Furthering America's Research Enterprise

DETAILS

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FURTHERING AMERICA'S
RESEARCH ENTERPRISE

Committee on Assessing the Value of Research
in Advancing National Goals

Richard F. Celeste, Ann Griswold, and Miron L. Straf, *Editors*

Division of Behavioral and Social Sciences and Education

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Preface

The America COMPETES Act,[1] which reauthorized the National Science Foundation (NSF), became law on January 4, 2011. The act required NSF to contract with the National Academies for a study to evaluate, develop, or improve metrics for measuring the potential impact of research on society. The language of the act is as follows:

> “SEC. 521. STUDY TO DEVELOP IMPROVED IMPACT-ON-SOCIETY METRICS.
>
> (a) IN GENERAL.—Within 180 days after the date of enactment of this Act, the Director of the National Science Foundation shall contract with the National Academy of Sciences to initiate a study to evaluate, develop, or improve metrics for measuring the potential impact-on-society, including—
>
> (1) the potential for commercial applications of research studies funded in whole or in part by grants of financial assistance from the Foundation or other Federal agencies;
>
> (2) the manner in which research conducted at, and individuals graduating from, an institution of higher education contribute to the development of new intellectual property and the success of commercial activities;

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[1] H.R. 5116, P.L. 111-358.

> (3) the quality of relevant scientific and international publications; and
>
> (4) the ability of such institutions to attract external research funding.
>
> (b) REPORT.—Within 1 year after initiating the study required by subsection (a), the Director shall submit a report to the Senate Committee on Commerce, Science, and Transportation and the House of Representatives Committee on Science and Technology setting forth the Director's findings, conclusions, and recommendations.

The origin of the study was an amendment introduced by Senator Amy Klobuchar of Minnesota, then chair of the Subcommittee on Competitiveness, Innovation, and Export Promotion of the Senate Committee on Commerce, Science, and Transportation, and Senator George LeMieux of Florida, then subcommittee ranking member.

In discussions with the leadership of NSF, the National Academy of Sciences, the National Academy of Engineering, and Senator Klobuchar's office, the limitations of metrics for the specific purposes of the legislation were noted. Accordingly, the decision was made to broaden the study while still addressing the intent of the legislation. The agreed-upon statement of task appears in Chapter 1.

With funding from NSF, the National Research Council (NRC) convened a committee to conduct a study responding to this charge. This report is the result of that study.

The committee met four times during 2013, sometimes calling on other experts to address specific topics. We also had the benefit of many contemporaneous conferences, workshops, and meetings involving committee members or staff. In addition, we benefited from myriad studies focused on quantifying the impacts of research, in particular in Australia, Canada, and the United Kingdom, which were summarized for and reviewed by the committee. A number of these studies are recent (see Appendix C). Moreover, previous NRC studies have addressed a similar charge, and we benefited from those studies as well.

The committee was fortunate to have a diverse and knowledgeable membership. The members brought many different perspectives to this study. Their expertise encompassed federal and state government policy making in research and innovation, research administration in academia and industry, and entrepreneurship in engineering and the life sciences. Members also represented a variety of academic research and expertise, including metrics, measurement, and statistics; the economics of technological innovation; the translation of university sciences into commercial technologies; and networks and the organization of research.

Despite the plethora of studies on the impacts of research, we believe this study brings to bear a fresh approach informed by a more holistic understanding of the research enterprise as a complex, dynamic system. As documented in this report, this understanding illuminates why America's research expertise has historically been so successful; where attention should be focused in examining the societal benefits of research investments; and how those who make decisions on the allocation of funds for scientific research will best carry out that task by understanding the many pathways by which those benefits are generated, the extent to which the potential to yield those benefits can be characterized if not quantified, and the usefulness and limitations of metrics for this purpose.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report: William F. Brinkman, Physics Department, Princeton University; E. William Colglazier, U.S. Department of State; Rita R. Colwell, Center for Bioinformatics and Computational Biology, University of Maryland; Gordon R. England, President's Office, E6 Partners LLC, Fort Worth, Texas; Donna K. Ginther, Center for Science Technology and Economic Policy, Institute for Policy and Social Research, University of Kansas; Robert L. Jervis, Department of Political Science, Columbia University; Paul L. Joskow, President's Office, Alfred P. Sloan Foundation; John A. Montgomery, U.S. Naval Research Laboratory; Arogyaswami J. Paulraj, Department of Electrical Engineering, Stanford University; Barbara A. Schaal, Department of Biology, Washington University in St. Louis; Jeannette M. Wing, Research International, Microsoft Research; Andrew W. Wyckoff, Economic Analysis and Statistics Division, OECD; and Richard N. Zare, Department of Chemistry, Stanford University.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the report's conclusions, nor did they see the final draft of the report before its release. The review of this report was overseen by Lawrence D. Brown, Department of Statistics, The Wharton School, University of Pennsylvania, and Susan Hanson, Department of Geography, Clark University. Appointed by the NRC, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Richard F. Celeste, *Chair*
Miron L. Straf, *Study Director*
Committee on Assessing the Value of Research
in Advancing National Goals

Acknowledgments

Many individuals and organizations contributed to this study. Special recognition goes to Charles M. (“Chuck”) Vest, who, as president of the National Academy of Engineering, played a critical role in the development of this study and the formation of the committee. He met with us and followed our work until his death in December 2013. A former president of the Massachusetts Institute of Technology, he understood the importance of research and of research universities.

We thank our sponsor, the National Science Foundation (NSF), and many on its staff for their support, as well as their assistance in the development and conduct of this study. We are particularly grateful for the leadership of Subra Suresh, former NSF director. Others on the NSF staff who contributed include acting NSF director Cora Marrett, David Croson, Joshua Rosenbloom, Jennifer Thornhill, and Joanne Tornow.

Robert D. Atkinson, president of the Information Technology and Innovation Foundation (ITIF), provided valuable advice in the development of the study. Together with Stephen Ezell and Kathryn Angstadt on the ITIF staff, he provided much helpful information.

A number of people directing National Academies boards or studies were especially helpful. Kevin Finneran, director of the Committee on Science, Engineering, and Public Policy (COSEPUP), and Stephen

A. Merrill, director of the Board on Science, Technology, and Economic Policy, worked with us from the formative stages of the study to the development of this report. Chair Richard N. Zare and other members of COSEPUP provided helpful advice, as did Constance F. Citro, director of the Committee on National Statistics.

The National Academies' Government-University-Industry Research Roundtable convened many conferences and webinars on topics in our purview, and its director, Susan Sauer Sloan, saw that we were represented at them. Anthony Boccanfuso, executive director of the University-Industry Demonstration Partnership, provided many helpful contacts and saw that we were informed about his organization's studies on university-industry partnerships. Kaye Husbands Fealing, director of the Committee on National Statistics' Panel on Developing Science, Technology, and Innovation Indicators for the Future, presented findings of that panel's study and provided other helpful information for this report. Others at the National Academies who helped us in our work include Maria Lund Dahlberg, COSEPUP research associate; Nancy F. Huddleston, communications director of the Division on Earth and Life Studies; and James C. Lancaster, director of the Board on Physics and Astronomy.

In addition to Chuck Vest, other leaders of the National Academies were helpful in developing and guiding this study. We thank in particular Ralph C. Cicerone, president of the National Academy of Sciences; C. Dan Mote, Jr., president of the National Academy of Engineering; and Robert M. Hauser, executive director of the Division of Behavioral and Social Sciences and Education.

Many others also contributed to this study. Those who made formal presentations to the committee are listed in Appendix D on the study process, which also lists the organizations of others who contributed. To these we add Richard C. Atkinson, president emeritus of the University of California; William B. Bonvillian, director of the Massachusetts Institute of Technology Washington Office; Laura Hillier, director, evaluation and outcome assessment, Canada Foundation for Innovation; Marina Volkov, acting director of the National Institutes of Health's Office of Science Management and Reporting; Andrew W. Wyckoff, director of the OECD Directorate for Science, Technology and Industry, and Yu Xie, Otis Dudley Duncan distinguished university professor of sociology, statistics, and public policy, University of Michigan.

We had the benefit of an exceptional staff led by study director Miron L. Straf. Our science writer, Ann R. Griswold, worked with us at all our meetings; summarized myriad studies for our review; and prepared drafts of this report based on presentations, discussions, text prepared by our members and staff, and her own research. Others on our staff who provided assistance were Steven Ceulemans, initially as Christine Mirzayan science and technology policy graduate fellow and later as a consultant; Meredith B. Blake, consultant; Viola Horek, manager of operations; and Mary Ann Kasper, senior program assistant. Kirsten Sampson Snyder marshaled our report through National Academies review, and the report was edited by Rona Briere.

Those involved in the review of our report are acknowledged in the preface. They made many constructive comments.

Finally, we acknowledge the service and contributions of our committee members, who freely gave of their time and effort as a public service.

We are grateful to all who contributed to this study and this report.

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Summary

The federal government has long supported scientific research for the benefit of society, far beyond the initial purposes of national defense. These investments have yielded manifest benefits that today include computers, the Internet, wireless communication, the laser, the global positioning system, and modern medicine, among many others—advances that have enabled the United States to achieve unprecedented prosperity, security, and quality of life.

Now, however, the United States faces increased global competition for new technologies and other innovations. In this context, Congress wants to further the benefits of science for the U.S. economy and the advancement of other national goals—in particular, keeping the nation in the forefront of the global competition for new technologies and other innovations. But it must do so in the face of growing economic exigencies.

In seeking to increase the returns on federal investments in scientific research, Congress asked the National Academies to study measures of the impacts of research on society. Of particular interest were measures that could serve to increase the translation of research into commercial products and services. The committee formed to conduct this study found that measures can usefully quantify research outputs for many specific purposes, but that current measures are inadequate to guide national-level decisions about what research investments will expand the benefits of science. That is because metrics used to assess any one aspect of the system of research in isolation without a strong understanding of the larger picture may prove misleading. With few exceptions, approaches to measuring the impacts and quality of research programs cannot depict the diffuse and interconnected pathways that lead from research to technologies and other innovations. The American research enterprise is indeed capable of producing increased benefits for U.S. society, as well as for the global community. To reap those benefits, however, will require new measures to guide federal research investments. To develop those measures, it is necessary to understand what drives the American research enterprise and what has made it so productive.

First and foremost, the American research enterprise is a system that must be viewed in relation to the innovation system in which the discoveries it produces are used to develop new technologies and other innovations. Without this system-level understanding, policies focused on relatively narrow objectives—such as increasing university patenting and licensing of research discoveries or reducing the funding for certain disciplines or types of research—could have undesired consequences. With this understanding, however, **the committee concludes that societal benefits from federal research can be enhanced by focusing attention on three crucial pillars of the research system: a talented and interconnected workforce, adequate and dependable resources, and world-class basic research in all major areas of science.**

- **A talented and interconnected workforce—**The importance of talent cannot be overstated. Talent benefits not only from traditional education and research training in science and engineering, but also from immigration; partnerships; supportive research environments; and the worldwide networks through which researchers connect with others, develop professional relationships, and share ideas and scientific resources. International collaborations are an increasingly important mechanism allowing the United States to rapidly apply knowledge gained through research investments in other areas of the world.
- **Adequate and dependable resources—**Stable and predictable federal funding encourages talented students to pursue scientific careers, keeps established researchers engaged over a career, and attracts and retains foreign talent. It also supports a diversity of institutions that both fund and conduct research, as well as essential scientific infrastructure—the tools necessary for conducting research. Stable resources are increasingly important to future competitiveness given the rising investments in research by other countries, particularly China and other Asian nations.
- **World-class basic research in all major areas of science—**Basic research, in which investigators pursue their ideas primarily for increased understanding and not necessarily toward a technologi-

cal goal, often provides the foundation of discovery and knowledge for future economically significant innovations. World-class basic research in all major areas of science is important for three major reasons:

- **Truly transformative scientific discoveries often depend on research in a variety of fields.** Maintaining broad expertise among those who conduct research also sustains the innovation system, because technological problems often arise in the development of an innovation that require research for their solutions. Research and innovation are symbiotic in this way. Similarly, many aspects of manufacturing contribute to and draw on research.
- **In today's highly connected world, a discovery made somewhere is soon known everywhere.** The competitive advantage may go not to the nation in which the discovery was made but to the nation that can use it more effectively to develop new technologies and other innovations by relying on a broad foundation of knowledge, talent, and capacity derived from diverse basic research.
- **A world-class basic research enterprise attracts scholars from around the world who in turn enhance excellence in research and create a self-reinforcing cycle.**

We also note that not all research achieves its intended goals. In particular, high-risk research inevitably results in some failures. Yet the transformative innovations that eventually result from some high-risk research can more than justify the investment in other such research that may fail. Moreover, even failures can lead to unanticipated discoveries and steer research in new directions. Only government has the broad social purpose and long horizon to invest in high-risk research so that society can reap its ultimate benefits.

The American research enterprise is a complex, dynamic system in part because it has evolved with many of the characteristics of free enterprise: it is decentralized, pluralistic, competitive, meritocratic, and entrepreneurial—major reasons why it has been so successful. In this complex system, it is impossible to predict what innovations may eventually result from research discoveries or which types of research would, in the absence of other types, lead to transformative innovations. Trying to make such predictions could have untoward effects. Attention to the pillars of talent, resources, and basic research will ensure that discoveries and innovations continue to emerge from the scientific research enterprise. Moreover, measures designed around these three pillars would promote a better understanding of the American research enterprise as a system.

These measures might include, for example, indicators of human and knowledge capital, indicators of the flow of knowledge in specific fields of science, indicators with which to track the flow of foreign research talent, portfolio analyses of federal research investments by field of science, international benchmarking of research performance, and measures of research reproducibility. Such measures could be used to guide federal research investments that would maximize the ability of the system to yield more of the societal benefits that have made it the world's premier scientific research enterprise.

1

Introduction

KEY POINTS IN THIS CHAPTER

- Scientific research furthers national goals in many arenas, including the economy, national security, energy, health, the workforce, the environment, technical infrastructure, and agriculture.
- The American research enterprise is a highly complex system. Given this complexity, a desired effect (for example, increased output of research discoveries with commercial value) is unlikely to be achieved by changing one or even a few components of the system without regard to its critical drivers and their interrelationships.
- Understanding the research enterprise as a system could inform policies designed to enhance the benefits of publicly funded research for U.S. society and the global community. Changes to individual components made without this understanding may result in unintended and undesirable effects.
- The societal benefits of federal research investments can best be enhanced by focusing attention on three fundamental drivers, or pillars, of the research system: (1) a talented and interconnected workforce, (2) adequate and dependable resources, and (3) world-class basic research in all major areas of science.

For more than 65 years, the United States has led the world in science and technology. Discoveries from scientific research have extended understanding of the physical and natural world, of the cosmos, of society, and of humans—their minds, bodies, and economic and other social interactions. Through these discoveries, science has yielded a broad range of benefits (see Box 1-1). For example, scientific advances have enabled longer and healthier lives, provided for better education through the science of learning, enhanced the national economy, and strengthened America's position in the global economy. These advances also have furthered national security and energy independence and, of particular note, have enabled the United States to remain at the forefront of global competition for commercially viable technologies and other innovations. Today, in the face of increasing competition from other nations, a highly effective and productive research enterprise is more essential than ever.

BOX 1-1
Some Benefits of Scientific Research

Economy—Provides high-tech, high-paying jobs, as well as hundreds of thousands of related jobs.
Contributions include sustained job creation by universities and other research institutions, marketable technologies and innovations, and increased economic competitiveness.

Energy—Produces efficient sources of energy and decreases the nation's dependence on foreign fuels.
Contributions include nuclear power, biofuels, and hybrid powertrain technology.

National security—Improves national security by enhancing the nation's ability to defend its shores and its cyberspace.
Contributions include better weapons systems, mechanisms for the rapid deployment of troops, compact explosive detectors, the Global Positioning System, and encryption technologies.

Environment and natural resources—Safeguards the nation's food and water supplies and protects its air quality; ensures abundant natural resources for present and future generations.
Contributions include cool roofing materials; shale oil recovery; and devices for detecting contaminants in water, food, and air.

Health—Enhances health care and therapies to improve health, lengthen lives, and reduce disabilities.
Contributions include computational chemistry in pharmaceutical development, personalized medicine, and nuclear magnetic resonance imaging.

In the current environment of budgetary austerity, many question why the federal government should continue to invest heavily in scientific training, capacity, and research given countless other pressing priorities. Congress and others have shown increased interest in measuring the economic and societal returns on federal research investments. These returns are reflected in part in the value of new goods and services and in the ability of new technologies to drive the American economy, increase the nation's standard of living, and create jobs. Because of the importance of scientific research and the new technologies and other innovations to which it leads, the Bureau of Economic Analysis and others have argued that research spending should be considered an investment rather than an expense (see Box 1-2).

While the contributions of scientific research are vast and multifaceted, influencing almost every aspect of daily life, the question arises of

Training and workforce—Develops and attracts people of talent, imagination, and intellect who enrich U.S. society and advance the nation's science enterprise.
Contributions include international research partnerships and collaborations, and greater sharing of research methods, techniques, and technical resources such as stock cultures.

Agriculture—Develops hybrid foods that enhance yields, improve nutrition, and alleviate global food shortages.
Contributions include genetically modified plants and remote sensing technology for site-specific fertilization and irrigation.

Infrastructure—Improves communications and interconnectedness among diverse peoples; improves human productivity and creates more leisure time as machines and technologies ease human workloads.
Contributions include the Internet, information retrieval and search technology, bioinformatics, and the Hubble space telescope.

Social innovation—Increases the speed of communication and collaboration among geographically distant individuals.
Contributions include crowdsourcing, social entrepreneurship, and social media informatics.

Policy—Enables analyses to support formulating, implementing, and evaluating public policies.
Contributions include methods for policy analysis and evaluation.

BOX 1-2
Treating Research as an Investment

Since July 2013, the U.S. Bureau of Economic Analysis, in its national economic accounts, has been treating business spending on research and development and the creation of intellectual property related to some creative and artistic works as investments rather than expenses. Calculations using the new definition showed that U.S. gross domestic product—the official measure of the market value of all goods and services produced in the United States—would have been an average of 2.7 percent larger each year during 1998 to 2007 than previously reported (U.S. Bureau of Economic Analysis, 2010).

whether these contributions can be measured in a meaningful and accurate way to guide future federal investments in the research enterprise. Is it possible to provide a clear picture of the returns on those investments? And how can analyses of such returns guide the development and implementation of policies designed to maintain the nation's global competitiveness?

PURPOSE AND SCOPE OF THIS STUDY

This study was requested by Congress in the America COMPETES Act (P.L. 111-358), which became law on January 4, 2011. Seeking to increase the returns on federal investments in scientific research, Congress asked the National Academies to study metrics that could be used to gauge the impacts of scientific research on society. Of particular interest were metrics that could serve the goal of increasing the translation of research into commercial products and services. Interest in measuring the benefits of federally funded research arose also in part from a desire to enhance accountability and to provide guidance for federal research investments in stringent budgetary times.

To carry out this study, the National Research Council of the National Academies formed the Committee on Assessing the Value of Research in Advancing National Goals. The committee's statement of task (see Box 1-3) reflects recognition of the limitations of metrics for the specific purposes set forth in the America COMPETES Act (as discussed further below). Accordingly, the committee was tasked with investigating some of the many pathways through which research contributes to the nation's economy and well-being, as well as other national goals. In particular, the committee was asked to address how research contributes to human and knowledge capital in government and private business through the training of a research workforce. In exploring these questions, the committee

BOX 1-3
Statement of Task

A diverse panel of distinguished experts would be appointed by the NRC to conduct the study. Its membership would reflect experience in science, engineering, business, education, and the public sphere. The panel would investigate some of the many pathways through which research contributes to our economy and well-being and serves other national goals. A particular pathway of interest is how research contributes to human and knowledge capital in government and private business through the training of a research workforce. For its investigations of these pathways, the panel may commission case studies, including one or more that trace a successful innovation back to the basic and other research discoveries and ideas that enabled its development. The panel would address the technical and other measurement issues for assessing (1) the quality of research output of universities and other research institutions receiving federal government support and (2) the potential societal impact of research in advancing national goals. For this purpose, the study would:

- Review and synthesize the broad variety of efforts to assess research output and impacts in industry and government, including those of the National Science Foundation (NSF) National Center for Science and Engineering Statistics and the NSF-National Institutes of Health STAR METRICS Program.
- Review the experiences of other countries, in particular the United Kingdom, in assessing the impacts of research.
- Draw upon relevant current and past NRC studies, including those of the Committee on Science, Engineering, and Public Policy.
- Explore various methodological approaches to measurement of research quality, productivity, and impact, including those that help to quantify the return on investment of research.
- Examine the explanatory power, predictive ability, and incentive effects of various measures of the potential impact of research on society, in particular to better understand the contributions and limits of these measures in science and innovation policy decisions.

The panel would also identify the research and data needed to develop measures or other means to assess the impact of research in advancing national goals and recommend priorities. The purview of the panel would be all federally supported research, but the panel may need to be selective in examining some research areas in depth. If so, the panel's choices would range from basic research, which contributes to fundamental understanding, to use-inspired basic research, as described in "Pasteur's Quadrant." The panel may also recommend how research could be better organized and supported to better contribute to national goals. For this purpose, the panel would be asked to think creatively about how the U.S. research enterprise can further adapt to a competitive and highly linked world with a globalized economy.

was charged with identifying the technical and other measurement issues entailed in assessing the quality of the research output of universities and other research institutions (e.g., laboratories operated by the federal government and private industry) that receive federal support.

In the America COMPETES Act, Congress explicitly asked how metrics could be improved or developed to measure the potential impact of research on society. In this regard, the wording of the committee's statement of task captures an important distinction. Whereas the legislative request for this study used the term "metrics," the statement of task uses the term "measures." The committee understands and uses the former term as a quantitative value, which may capture the performance of a system or of its outputs and outcomes at a point in time or over a period of time. We understand and use the term "measures" more broadly, encompassing not only quantitative but also qualitative values that, for example, provide a basis for rankings or comparisons, such as an assessment of the caliber of research performed in one country versus another.

As discussed in detail in Chapter 4, metrics have many uses, as well as significant limitations. Whereas metrics are commonly used to measure numbers of patents, publications, and other easy-to-count items, this report describes the broader, more useful applications of measures in assessing research portfolios—a research program, a collection of grants, or scientific research managed by a federal agency or private entity (see Chapter 5)—and the progression from idea to product in various phases of research. Although currently available metrics for research inputs and outputs are of some use in measuring aspects of the American research enterprise, they are not sufficient to answer broad questions about the enterprise on a national level.

Implicit in the request from Congress was a broader charge: assessing how well the United States is achieving the benefits of science. A holistic understanding of how these benefits arise can provide greater insight into the drivers of the system, and reveal how best to sustain and reap further benefits from the research enterprise. Specifically, it is necessary to understand how the discovery, dissemination, and application of knowledge gleaned from scientific research generate new technologies and other innovations, and how the ultimate value of these innovations depends on their widespread adoption and use. This understanding can be gained by taking a systems perspective—that is, by considering research and innovation as inextricably connected, yet distinct, systems of components that interact in unpredictable and often difficult-to-specify ways to shape the research enterprise and the nation's economy as a whole.

HOW A SYSTEMS PERSPECTIVE CAN HELP

From the scientific study of systems theory, researchers know that "emergent" phenomena[1]—effects sparked by interactions among components of a system—are enabled by the actions of the system as a whole; they cannot be explained by the behaviors or properties of its components. Therefore, all components of a system must be treated carefully to stimulate desirable effects while avoiding unintended and undesirable consequences that can arise from modifying one component without considering how the system might react (Jervis, 1997; Meadows, 2008).

The systems of research and innovation are no different. The research system is defined by the breakthrough discoveries that occur when many talented researchers and institutions generate knowledge in all scientific fields through basic and applied research. The innovation system produces advances—some of which may be revolutionary—both within the research system and beyond, relying on networks of institutions and researchers to integrate, transform, and disseminate discoveries in diverse fields (OECD, 1997). The innovation system also encompasses aspects of development, which enables the production of new technologies, products, processes, and other innovations of economic value. (See Box 1-4 for definitions of research, innovation, and development. See Chapter 3 for a more detailed description of the pathways from research to development.)

This report focuses on the benefits of federally funded research to society and on the various handoffs to and from the innovation system, including spin-offs, start-ups, technology transfer activities, proof-of-concept research, and public-private or regional partnerships. Chapter 2, for example, includes a discussion of how proof-of-concept research spans the gap between research and innovation. The report focuses primarily on basic and applied research, not on development as it may relate, for example, to the acquisition of venture capital, marketing, manufacturing, or other factors critical to the success of an innovation. However, some figures include both research and development in an effort to draw certain comparisons, and in some cases, the available data do not distinguish between research and development or are not broken down by type of research.

Intuitively one might think that basic science research should proceed directly to applied research, to an invention, and to an innovation that is developed and adopted to produce economic or other societal benefits. However, the progression from research to ultimate benefits encompasses

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[1] An example of an emergent phenomenon is superconductivity, the property of being able to carry electrical currents with no dissipation of energy, which is exhibited by some metals below a critical temperature. Its discovery ultimately enabled magnetic resonance imaging that revolutionized modern medicine (National Research Council, 2007a).

BOX 1-4
Definitions of Research, Innovation, and Development

"**Research** is defined as systematic study directed toward fuller scientific knowledge or understanding of the subject studied. Research is classified as either basic or applied according to the objectives of the sponsoring agency" (National Science Foundation, 2007).[a]

- "**Basic research** is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view" (OECD, 2002a).[b]
- "**Applied research** is original investigation undertaken to acquire new knowledge. It is, however, directed primarily toward a specific practical aim or objective" (OECD, 2002a).[c]

"An **innovation** is the implementation of a new or significantly improved product (good or service) or process, a new marketing method, or a new organisational method in business practices, workplace organisation, or external relations" (OECD, 2002a).[d]

The **national innovation system** has been defined slightly different by various groups, yet all of the definitions listed below share an emphasis on the interactions and relationships among multiple, divers, organizations or institutions (OECD, 1997):

- ". . . the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies" (Freeman, 1987, p. 1).

several interim steps and the development of multiple technology elements that combine to produce the eventual innovation. This process rarely, if ever, follows a linear progression. In fact, quite the opposite is frequently true.

For some research, it may be relatively straightforward to predict the near-term outcomes, yet it is extremely difficult to predict how research knowledge might be taken up and used, by whom, and in what ways, on the path to societal and economic benefits. One would have difficulty predicting, for example, when a feedback loop might carry findings from proof-of-concept research[2] back to the basic science laboratory bench

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[2] As we define and use the term later, proof-of-concept research is research conducted to establish the commercial viability of an invention.

- ". . . the elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge . . . and are either located within or rooted inside the borders of a nation state" (Lundvall, 1992, p. 2).
- ". . . a set of institutions whose interactions determine the innovative performance . . . of national firms" (Nelson, 1993, p. 4).
- "…the national institutions, their incentive structures and their competencies, that determine the rate and direction of technological learning (or the volume and composition of change generating activities) in a country" (Patel and Pavitt, 1994, p. 12).
- ". . . that set of distinct institutions which jointly and individually contribute to the development and diffusion of new technologies and which provides the framework within which governments form and implement policies to influence the innovation process. As such it is a system of interconnected institutions to create, store and transfer the knowledge, skills and artefacts which define new technologies" (Metcalfe, 1995, pp. 462-463).

"**Experimental development** is systematic work, drawing on existing knowledge gained from research and/or practical experience, that is directed to producing new materials, products, or devices; to installing new processes, systems, and services; or improving substantially those already produced or installed" (OECD, 2002a).[e]

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[a] Available: http://www.nsf.gov/statistics/nsb1003/definitions.htm [June 2014].
[b] Available: http://stats.oecd.org/glossary/detail.asp?ID=192 [June 2014].
[c] Available: http://stats.oecd.org/glossary/detail.asp?ID=120 [June 2014].
[d] Available: http://stats.oecd.org/glossary/detail.asp?ID=6865 [June 2014].
[e] Available: http://stats.oecd.org/glossary/detail.asp?ID=908 [June 2014].

to overcome an unexpected hurdle, which might then spark a new line of basic research, as well as require applied or further proof-of-concept research. Equally difficult is predicting whether that research will eventually lead to development, and even then, whether it will be successfully commercialized or embraced by society. And it is very difficult as well to predict how long this journey will take.

Clearly, the systems of research and innovation—and the many unpredictable pathways that connect them—are exceedingly complex. Yet while these pathways appear to be unpredictable almost to the point of being chaotic, one truth has been demonstrated time and again: from this complexity springs possibility; from this unpredictability, the systems give rise to transformative innovations.

Over time, then, the American research enterprise has evolved into a highly complex and dynamic system and it has adopted many of the characteristics of free enterprise. It is decentralized. It is pluralistic, with a diverse array of researchers, companies, institutions, and funding agencies. It is competitive, requiring researchers and organizations to compete for funding, for talent, for positions, for publications, and for other rewards. It is meritocratic, bestowing more significant rewards on those with highly competitive ideas and abilities through a built-in quality control system of peer review. And finally, it is entrepreneurial: it allows for risk taking, for facing the prospect of failure head on to reap potentially great rewards. This complexity and dynamism make the American research enterprise successful, but the poorly understood relationships among its many components mean that well-intentioned reforms (for example, favoring some scientific disciplines to increase the output of research discoveries of commercial value) could lead to unintended and undesirable effects.

THREE PILLARS OF THE AMERICAN RESEARCH ENTERPRISE

Understanding the American research enterprise requires knowledge of the fundamental drivers, or pillars, of the research system and their interrelationships. The committee identified three pillars on which we focus throughout this report: (1) a talented and interconnected workforce, (2) adequate and dependable resources, and (3) world-class basic research in all major areas of science. To understand how these pillars interact to produce research discoveries, one must understand how knowledge flows among networks of individuals and institutions; how research is influenced by the availability of funds and the methods, instrumentation, and other means used to conduct research; how accomplishing world-class basic research is affected by management, research environments, institutions, and peer review; and how these and other aspects of the pillars interrelate.

In using the term "pillars," we refer to broad components of a complex system, each of which encompasses many aspects. The pillars should not be mistaken for a model of research or innovation because relationships among them are constantly changing and because there are no dependent variables, as each pillar feeds back into the others. Since the pillars are critical drivers of the system of research and provide important preconditions for innovation, each proposed policy or other change to one pillar or any aspect thereof should account for the likely downstream effects on other pillars and on the system as a whole.[3]

The committee concluded that societal benefits from federal research can be enhanced by focusing attention on the above three crucial pillars of the research system: a talented and interconnected workforce, adequate and dependable resources, and world-class basic research in all major areas of science. We argue in this report for creating or adapting measures that can be used for this purpose. The pillars are described briefly here and in detail in Chapter 6.

A Talented and Interconnected Workforce

Talent encompasses not only science, technology, engineering, and mathematics (STEM) education and research training, but also many other aspects of the system, including inspiring young men and women to pursue STEM careers; attracting immigrants with technical skills; developing professional networks and partnerships; and supporting research environments that nurture the creativity, ingenuity, and passion of talented researchers. Highly trained talent is essential to sustain the American research enterprise. People amplify and expedite the nation’s capacity for innovation by generating knowledge; distributing it through colleges, universities, publications, and other means; and transforming it through networks of individuals with varying perspectives and creative ideas. Absent a strong pool of scientists and engineers familiar with research at the cutting edge, scientific research and its products are unlikely to be developed and applied in ways that create value for society.

Adequate and Dependable Resources

Certainly research depends on adequate and dependable funds. But resources encompass much more—in particular, access to scientific infrastructure, or the tools and organizations that allow for research excellence, including national and other laboratories, major research instruments such as the Hubble telescope and the General Social Survey, world-class research universities, and other research organizations. Adequate and dependable resources provide critical support for the process of research, encourage students to pursue STEM careers, encourage estab-

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[3] As discussed in Chapter 6, the “health” of different fields of the research enterprise is sensitive to trends in federal research funding, especially fluctuations that produce a research “feast and famine” cycle. Federal research funding influences the career choices of prospective future scientists, their employment prospects, and the decisions of university and other research administrators on complementary investments in research facilities and personnel. See, for example, Alberts et al. (2014).

lished researchers to continue in their careers, and attract foreign talent. Thoughtful public and private investment enables the United States to maintain cutting-edge information technology and other scientific infrastructure, to maintain the best possible pool of talent, and to sustain world-class scientific institutions and means of communication.

In short, the historically robust American research enterprise requires a stable, reliable stream of investment to sustain the continued flow of discoveries necessary to ensure the nation's welfare in both the near and distant future—a flow that can take years, often decades to prime and pump. And those investments must be broadly distributed across all major fields of science, not just those for which direct and near-term economic benefits are foreseen.

World-Class Basic Research

Basic research, in which investigators pursue their ideas primarily for fundamental understanding and not necessarily for a technological objective or other application, may advance national goals by leading directly to new technologies and other innovations, just as applied research occasionally leads to fundamental advances in scientific understanding. More often, however, basic research lays the foundation for economically significant future innovations. In addition, public investment in basic research contributes to the growth of a trained research workforce by developing their talent, abilities, knowledge, skills, experience, and professional connections, and enables American researchers and would-be innovators to exploit the worldwide networks of researchers who advance the scientific enterprise and open access to a vast stock of knowledge and technological approaches offering opportunities for commercialization.

ORGANIZATION OF THIS REPORT

This report presents the committee's argument for enhancing the societal benefits of federal research investments by focusing on the three pillars of talent, resources, and basic research:

- Chapter 2 presents an overview of the evolution of the American research enterprise.
- Chapter 3 describes some of the many ways in which research contributes to the nation's economy and societal well-being; examines the complex, lengthy, and often unpredictable pathways from research to innovation; and reveals how basic research plays a key role in the ultimate realization of societal benefits.

- Chapter 4 explores the usefulness and limitations of metrics in measuring the returns on research investments.
- Chapter 5 describes several studies that have attempted to measure research impacts and quality.
- Chapter 6 presents the committee's argument for cultivating a holistic understanding of the research system through a focus on talent, resources, and basic research.
- Chapter 7 presents the committee's overarching conclusion in the context of the key points of the report.

2

Evolution of the U.S. Research Enterprise

KEY POINTS IN THIS CHAPTER

- Federal funding plays an essential role in supporting research, particularly basic research. The figures presented in this chapter illustrate the mission-oriented allocation of research funds by federal agencies and for certain areas of science.
- Impediments to growth in the research and innovation systems include insufficient funding for proof-of-concept research and swings in federal research funding.
- The United States remains at the forefront of research and development (R&D) with the world's largest investment in R&D, the largest share of scientific publications, more than one-third of scientific publications cited in patents, and world-class research universities. However, this position is increasingly challenged by competition from many other nations, including China.

As discussed in Chapter 1, the U.S. research enterprise is a complex, dynamic system. This system is embedded within and evolving in conjunction with industry and market structures that are adapting to the intense competition resulting from globalization. Currently the strongest in the world, it has had a great deal of freedom in its development; researchers and investors have available numerous options that are not constrained by government. Perhaps for that reason, the complex of research universities, private industry, government, and nonprofit organizations and the rich web of interactions among them have evolved into a system that is difficult for other nations to emulate. This chapter presents an overview of the evolution of the U.S. research enterprise, addressing in turn the role of research in the national economy; the complementary roles of industry, government, and philanthropic funding; historical trends in research funding; the performers of scientific research; impediments to the research and innovation systems; and how the U.S. research enterprise compares with those of other nations.

RESEARCH AND THE NATIONAL ECONOMY

Over the course of its history, the United States has developed from a primarily agricultural to an industrial or manufacturing economy, and then to an economy in which services have grown in importance, and knowledge, information, and human capital play a larger role than ever before. The development of today's knowledge economy was enabled by research both directly and indirectly through the emergence of new sectors and the growing role of technology in production processes.

As noted in Chapter 1, the importance of public and private investments in R&D to the national economy was recently acknowledged by the government's decision to revise gross domestic product calculations. Previously, business expenses on R&D and on the intellectual property of some creative and artistic works were treated as intermediate expenses of production; they were not included with other investments, such as those in new plants and capital equipment, that are expected to contribute to the production and sale of future products and services. When R&D expenses are treated as investments rather than expenses, their contributions to the national economy are highly visible and significant. This shift represents an important step in measuring the value of research.

COMPLEMENTARY ROLES OF INDUSTRY, GOVERNMENT, AND PHILANTHROPY IN FUNDING RESEARCH

Recent plateaus in research spending by the government and private industry raise concern about the future of the U.S. research enterprise. Figure 2-1 indicates that industry's share of funding for U.S. research in 2009 was roughly at the same level as in 1953, while the federal share has declined since the early 1960s, partly because of reductions in the size of

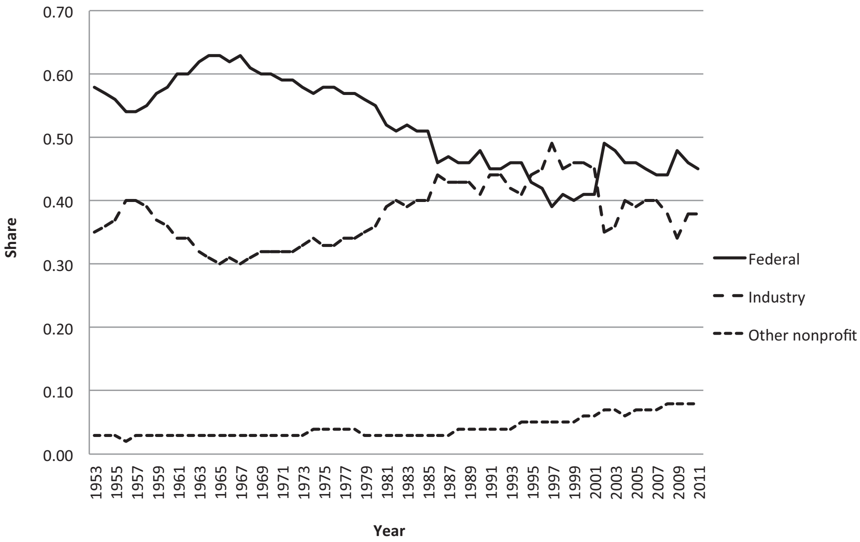

FIGURE 2-1 Federal, industry, and nonprofit shares of total funding for U.S. basic and applied research, 1953-2011. Excludes university and college (U&C)-funded research performed in U&Cs and research funded by other government entities (e.g., state governments) performed in U&Cs.
NOTE: The character-of-work estimates for business R&D were revised for 1998 and subsequent years; therefore, the data for 1997 and earlier years are not directly comparable. Furthermore, the character-of-work estimation procedures for higher-education R&D were revised in 1998 and again in 2010; thus, the data for 2010 and beyond are not directly comparable with those for 1997 and earlier years, or for 1998-2009.
SOURCE: Data from National Science Foundation (2014a), Appendix Tables 4-7 and 4-8.

federal investments in defense-related research.[1] Of particular concern is the future funding of high-risk, long-term research and of proof-of-concept research (described further in Chapter 6), which helps bridge the gap between research and development through the development of innovations. What are the roles of industry and government in funding such research?

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[1] The figures in this chapter are subject to the quality of existing data on research spending. For more information about R&D expenditures, see National Research Council (2005a, 2013c).

Industry funds a portion of the nation's basic research but places more emphasis than the government on leveraging internal funds, government contracts, and private support to create the end products of R&D. These end products encompass the manufacturing of chemicals, computers, electronics, aerospace and defense components, and automobiles, as well as the performance of services related to software, computers, and R&D. With a growing emphasis on applied engineering research, industry-funded research has become increasingly global and is not necessarily conducted in the United States, although it is far more likely than industry-funded development to be based in the United States (National Science Foundation, 2012). This difference between industry-funded research and development may reflect the substantial research infrastructure and budget that are supported by federal funds. In addition, the publicly supported U.S. research infrastructure and budget may attract foreign investments in U.S.-based industrial research.

The federal government, on the other hand, makes key investments in basic research, recognizing that the generation, distribution, and application of knowledge will prove fruitful in years to come by ensuring an eventual supply of marketable innovations and other societal benefits. Federally funded research is performed to benefit society and is intended to produce social returns more than private gains. Because others can benefit from those returns without sharing in the cost, the private sector has fewer incentives to produce them. This is particularly the case for basic research, which, as defined in Chapter 1, is scientific research conducted to increase fundamental understanding and not necessarily for a technological goal or other application. Moreover, government generally is better able than industry to tolerate the long wait—sometimes decades—for the transformation of knowledge into useful applications. Finally, in some cases the government funds research because it needs the end products for its own use to fulfill agency missions (e.g., for the development of defense weapon systems or of vaccines).

Increasingly, government is called upon to fund high-risk, long-term research and some types of applied research, particularly proof-of-concept research, at least to the point where the risks of investment in such research are reduced to attract private-sector funding. Inevitably, some high-risk research will not achieve its stated goals. Nevertheless, even failed research projects expand pools of talent and research capacity, can result in valuable redirection of research trajectories, provide valuable learning experiences for new researchers, and sometimes yield important but unanticipated discoveries. Regardless, government has a unique responsibility to support high-risk research because of its potential long-term benefits to society. Research portfolios can be pooled to reduce risk and allow a few transformative discoveries to emerge that more than justify the entire portfolio.

Today, a number of government programs provide direct funding for applied research, filling the gaps in which industry lacks incentives to do so. Much of this funding is focused on the handoff from research to development. Through programs such as the National Science Foundation's (NSF) I-Corps (discussed in Chapter 6), the government may be able to assist industry in bridging the gap between research and development, although few such programs have been rigorously evaluated to determine how well they accomplish this aim. These programs attempt to increase the efficiency of the transition from discovery to innovation through creative practices, most of which involve partnerships with industry. For example, I-Corps requires that academic researchers team with an entrepreneur possessing the skill sets and knowledge necessary to bring an invention to the market successfully.

The role of government in filling the gaps left by industry is illustrated by funding for so-called infratechnologies—the technical tools that enable the development and use of technologies. Examples include methods of measurement and testing for conducting research, for managing production for quality and unit cost, and for enabling marketplace transactions. The fact that these tools are in common use (e.g., as publicly owned standards in the semiconductor industry) results in underinvestment by private industry because no one company can capture all of their ultimate benefits. Accordingly, government agencies such as the National Institute of Standards and Technology, U.S. Department of Defense (DoD), and U.S. Department of Energy (DoE) invest in infratechnology research. Because of their nature, which requires government as well as industry funding, infratechnology research and some proof-of concept research are considered “quasi-public” goods.

The figures presented below highlight the critical role of federal funding in supporting research, particularly basic research. They illustrate the mission-oriented allocation of research funds by federal agencies, and they show how federal funding is allocated to certain areas of science.

Although industry and federal funding accounts for the majority of total U.S. research, shares of philanthropic funding are swiftly rising. Philanthropic funding shares of total U.S. research increased from 0.06 in 1953 to 0.12 in 2011 (see Figure 2-1), and this trend is expected to continue. Private foundations and wealthy individuals play a particularly important role in supporting scientific, medical, and engineering research at U.S. universities and colleges, where philanthropic contributions amount to an estimated $4 billion each year and provide nearly 30 percent of some institutions’ annual research funds (Murray, 2012). Much of this funding supports research operations, facilities, and endowments.

Despite the growing significance of philanthropic funding, these data are not widely reported, and relatively little is known about the patterns of private contributions to various fields of science and types of research. A recent analysis of science philanthropy at America's top 50 research universities (Murray, 2012) suggests that at the very least, one thing is clear: the role of funding from wealthy donors differs from the broadly understood roles of federal and industry funding. The most striking difference is that philanthropic funding often shapes research around the preferences of its patrons, rather than taking account of the needs of the research enterprise as a whole. Private donors support translational medical research far more than other types of research, and often neglect the critical need for basic research. As Murray (2012, p. 1) notes:

> The documented extent of science philanthropy and its strong emphasis on translational medical research raises important questions for federal policy makers. In determining their own funding strategies, they must no longer assume that their funding is the only source in shaping some fields of research while recognizing that philanthropy may ignore other important fields.

Private philanthropy does play an important role both in providing university endowments and in directly funding research. In some areas, such as translational medical research and astronomy,[2] this role is particularly important. Still, a recent article in *The New York Times* (Broad, 2014) questions whether the increasing support of research by wealthy individuals will ultimately privatize American science by shaping research programs around the preferences of philanthropists rather than around national priorities. It is worthwhile to note that, for now at least, philanthropic donations may be on the rise, but they continue to account for a small fraction of total U.S. research support.

HISTORICAL TRENDS IN FUNDING FOR RESEARCH

Assessing the trends in funding for research is difficult because of the variations in data reporting. Many of the data reported fail to distinguish between research and development, let alone between basic and applied research, and not all of the data are reported for a consistent fiscal year. Furthermore, calculations of research spending are sometimes inconsis-

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[2] One prominent example is the Giant Magellan Telescope, which has received more than $1 billion in support, mostly from philanthropic donors (see http://www.gmto.org/pressrelease11.html [August 2014]). Another example is the Sloan Digital Sky Survey, described in Box 6-5 in Chapter 6, which received funding from the Alfred P. Sloan Foundation and other organizations, including NSF, DOE, and the National Aeronautics and Space Administration (see http://www.sdss.org/ [August 2014]).

tent across federal agencies (National Research Council, 2005a, 2013c). These variations make it difficult to draw comparisons across fields of research or among nations.

As depicted in Figure 2-1, the majority of basic and applied research in the United States has been funded by the federal government. Substantial contributions also come from private industry and smaller contributions from nonprofit organizations that have grown significantly as a share of total research funding since the 1980s.

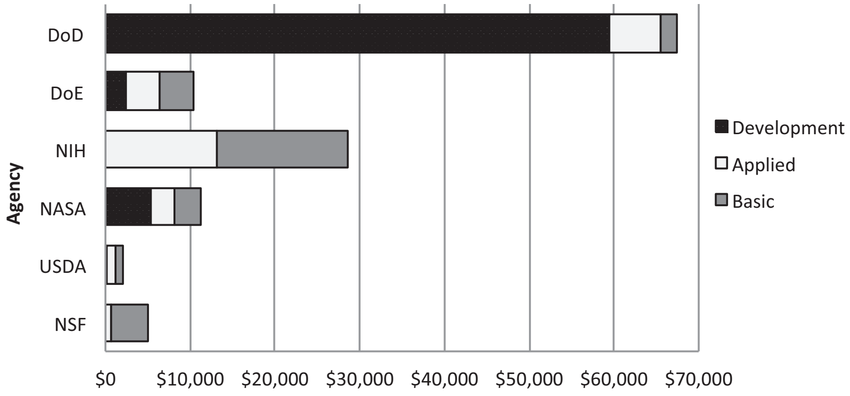
Within the federal budget, research spending is distributed among 20 agencies or departments, each with multiple programs that receive funds according to their missions and priorities. Spending on development is allocated in much the same way, but the final distribution of funds by each agency varies quite dramatically for research compared with development as a result of differences in the agencies' missions. Figure 2-2 shows how the shares of basic research, applied research, and development vary within the R&D spending of the top six federal R&D funding agencies. For example, NSF allocates the largest share of its R&D budget to basic research, while DoD allocates the largest share of its R&D budget to development.

In fiscal year (FY) 2011, federal funding for basic and applied research was $60 billion. In FY 2009, the National Institutes of Health (NIH) received more than half of the federal research investment, while NSF accounted for about one-tenth. These two agencies invest heavily in basic research.

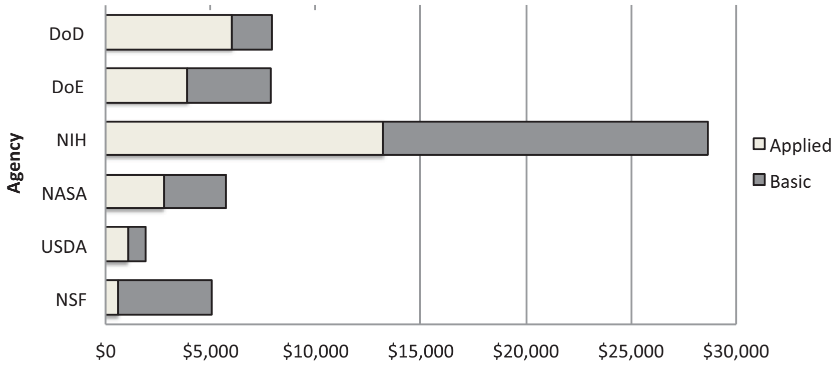
DoD, DoE, and the National Aeronautics and Space Administration (NASA) fund predominantly applied research that supports their agency missions. In addition, both DoD and NASA have been large-scale purchasers of products incorporating the results of their R&D investments.

Over the past 40 years, the NIH share of the federal research investment has increased dramatically, and the NSF share has increased to a lesser extent. Other federal agencies that invest heavily in research are shown in Figures 2-2a and 2-2b. Of the federal agencies and departments that invest heavily in *basic research*, NIH and NSF are most prominent (see Figure 2-2b). A portion of federal support for *applied research* is funneled through the defense budget, with the government acting as a customer. In this role, the government purchases research that will yield innovative technologies to help the nation prepare for the future.

Excluding funding from the American Recovery and Reinvestment Act between FY 1993 and FY 1999, federal support for research in the fields of physics, chemical engineering, geological sciences, and electrical and mechanical engineering declined by more than 20 percent in real terms, while funding for research in the biological and medical sciences increased by more than 20 percent in the same period. Funding



a. Allocations for research and development, in millions of 2014 dollars



b. Allocations for applied and basic research

FIGURE 2-2 Allocations for research and development (a) and total applied and basic research (b) by the top six federal funding agencies, 2013 (budget authority in millions of constant 2014 dollars).
NOTE: DoD = U.S. Department of Defense; DoE = U.S. Department of Energy; NASA = National Aeronautics and Space Administration; NIH = National Institutes of Health; NSF = National Science Foundation; USDA = U.S. Department of Agriculture.
SOURCE: Adapted from American Association for the Advancement of Science (2013b). Reprinted with permission.

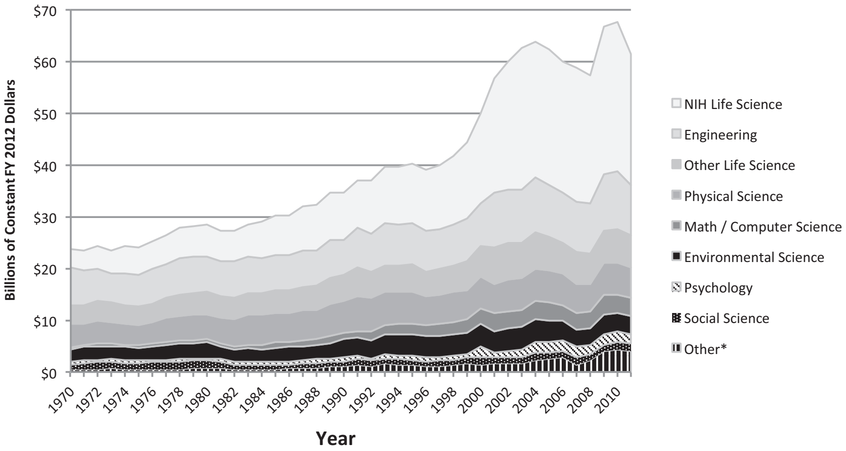


FIGURE 2-3 Federal research funding by discipline, 1970-2010—budget authority in billions of constant FY 2012 dollars. "Other" indicates research not classified (including basic and applied research, excluding development and R&D facilities).
NOTE: FY = fiscal year; NIH = National Institutes of Health.
SOURCE: Adapted from American Association for the Advancement of Science (2013b). Reprinted with permission.

for research in computer science was the major exception to this pattern of reductions in the share of physical sciences and engineering within federal research spending, rising by more than 60 percent (Merrill, 2013). Figure 2-3 shows trends in funding for individual fields of science, illustrating how federal funds for life sciences research have increased significantly since the 1980s such that this field now accounts for slightly more than half of all federal basic and applied research funding.

The various funders of U.S. research have each played key roles in the emergence of transformative innovations. An example is the Internet, presented as a case study in Box 2-1.

PERFORMERS OF SCIENTIFIC RESEARCH

The federal research investment flows to federal laboratories, universities, nonprofit institutes and hospitals, and contractors. Laboratories both produce agency mission-related outputs and conduct commercial activities, as described below. Universities produce new knowledge and an educated workforce trained in research, as well as other research outcomes, and likewise conduct commercial activities. Contractors, by and large, produce commercial products.

BOX 2-1
Case Study: The Internet

This case study illustrates the long time lag generally entailed in moving from an initial idea to a profitable product, the need for fluid movement across the public-private boundary, the critical roles played by supportive institutions, the benefits of sustained diverse government investment, and the unpredictability of the system of research.

The Internet's evolution from a small experimental network connecting three U.S. research facilities at speeds of 56,000 bits per second to a global network with more than 100 million hosts and a backbone capacity in excess of 2 billion bits per second relied heavily on federally funded innovations originating in the early 1960s, just years after scientists unveiled the world's first computer. Those early innovations were aimed not at connecting ordinary people on opposite ends of the earth, but at providing the U.S. Department of Defense (DoD) with a means of connecting and sharing the scarce computing resources available at the nation's top research centers.

Federal funding for R&D—particularly defense funding—enabled the creation of semiconductors, computers, software, and other information technologies on which the modern-day Internet is built. The 1960s research on packet switching, the Advanced Research Projects Agency Network, and protocols such as TCP/IP relied on a 15-year DoD investment in hardware and software. The NSF also played a key role, particularly in the 1980s, by funding the Computer Science Network, linking university computer scientists, and the NSFNET, connecting supercomputer centers across the United States at more than 1.5 megabits per second—a remarkable feat by 1988 standards. By 1991, the NSFNET had become the first national network operating at 45 megabits per second.

Federal funds also supported generations of future talent by strengthening universities' research capabilities in computer science; facilitating university "spin-offs" such as BBN and Sun Microsystems; and training the technical workers who helped develop, adopt, and commercialize the Internet.

Privately financed research played an important role as well, supporting basic

The differing priorities of industry and government are clearly reflected in the distribution of research performers supported by different federal agencies. Trends in the nation's total research investment (i.e., R&D investments from private as well as public sources) by performer reveal that industry performs most of the nation's research (see Figure 2-4). However, academic institutions have traditionally performed most of the nation's federally funded research (see Figure 2-5). When basic and applied research are considered separately, it becomes clear that industry performs most of the nation's federally funded applied research, while universities perform most of the nation's basic research (see Table 2-1). However, industry's share of applied research has declined networking technologies including networking hardware, Unix, and the Ethernet protocol. Start-up firms were crucial to the commercialization of Internet-related innovations. Equally important were the heavy investments in information technology (IT) by U.S. industry during the 1980s that supported the rapid diffusion of the TCP/IP network. But in many respects, this private investment complemented and responded to the incentives created by public policies and larger market forces.

In addition to providing funds, the U.S. government influenced the development and diffusion of the Internet through regulatory, antitrust, and intellectual property rights policies, encouraging rapid commercialization of Internet infrastructure, services, and content by new firms. The U.S. Internet explosion of the 1990s also relied on close university-industry links and an abundant supply of venture capital. As the focus shifted from development to application, defense R&D spending was largely overshadowed by private-sector R&D investment. The U.S. venture capital industry assumed a larger role in the commercial exploitation of the Internet than had been the case during the formative years of other postwar U.S. high-technology industries. Defense-related procurement, which had played a prominent role during earlier stages of the Internet's development, was not an important factor during the 1990s. Defense-related R&D investment in Internet-related fields, such as computer science, also declined modestly throughout the decade, although cutbacks in DoD R&D investments in computer science were more than offset by increased investments from other federal agencies, such as NSF and the Department of Energy (National Academy of Sciences, 1999, pp. 83-84).

The Internet has a history resembling that of other postwar IT innovations in that it was first commercialized primarily in the United States—the first country to deploy a large national research computing network; the first to standardize on TCP/IP; and the first to develop a large, competitive market for individual access. The United States remains an international leader in overall network penetration, and its national network continues to grow rapidly. And this history all began with basic research supported by federal investments—in technology and in talented people.

SOURCE: Adapted from Mowery and Simcoe (2002). More information is available from National Science Foundation (2003).

significantly in the past decade.[3] The share of federally funded research that is performed intramurally (i.e., within federal laboratories, whether operated by federal agencies or contractors) has declined significantly since the 1970s.

Among the performers of federally funded research, national laboratories, including 17 under the purview of DoE, invest heavily in scien-

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[3] Industry-funded basic research, although beyond the scope of this report, was extremely important to the evolution of the U.S. research enterprise. See, for example, Gertner (2012) for the many impacts of basic research at Bell Laboratories.

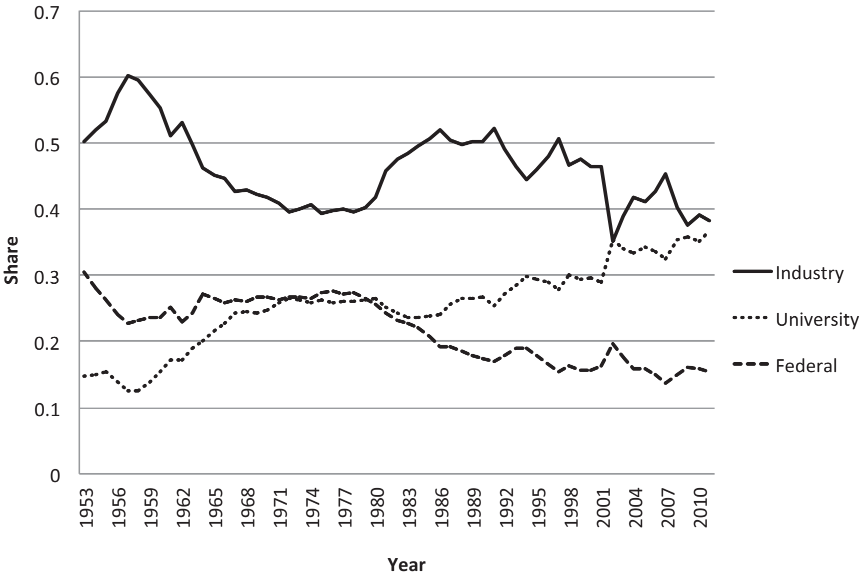

FIGURE 2-4 Federal, industry, and university performance shares of total U.S. research (basic and applied), 1953-2010.
NOTE: The character-of-work estimation procedures for academic and business R&D were revised in 1998; hence, these data are not directly comparable with data reported for earlier years. Furthermore, the methods of collecting data were revised in 2008 for business R&D and in 2010 for academic R&D; thus, these data are not directly comparable with data reported for earlier years. The federal shares include amounts for federally funded research and development centers. The sum of the shares does not equal 1 because these figures do not include university and college and other government (i.e., state) funding.
SOURCE: Data from National Science Foundation (2014a), Appendix Tables 4-3 and 4-4.

tific infrastructure. They carry out long-term scientific, technological, and operational missions with a direct focus on national priorities.

The national laboratories received much attention in the years before and immediately following the Bayh-Dole Act of 1980.[4] Along with universities, federal laboratories were explicit targets for initiatives, including Bayh-Dole, focused on developing and commercializing research discoveries. In the wake of the Bayh-Dole legislation, however, the commercial-

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[4] The Bayh-Dole Act allowed universities, small businesses, and nonprofit institutions to pursue ownership of federally funded research inventions. Prior to the act, most inventions were owned by the federal government, although research performers could and did negotiate with funding agencies for the rights to patent and license federally funded inventions.

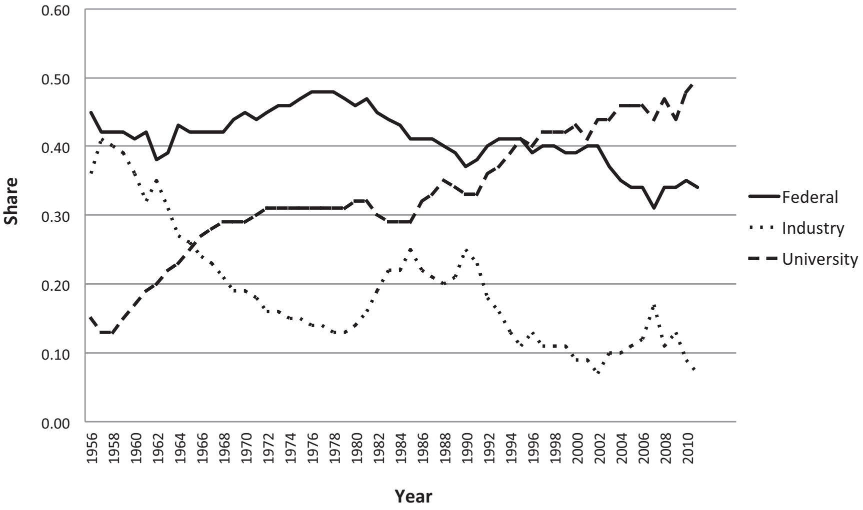

FIGURE 2-5 Federal, industry, and university performance shares of federally funded U.S. basic and applied research, 1953-2010.
NOTE: The character-of-work estimation procedures for academic and business R&D were revised in 1998; hence, these data are not directly comparable with data reported for earlier years. Furthermore, the methods of collecting data were revised in 2008 for business R&D and in 2010 for academic R&D; thus, these data are not directly comparable with data reported for earlier years. The federal shares include amounts for federally funded research and development centers. The sum of the shares does not equal 1 because these figures do not include university and college (U&C) and other government (i.e., state) funding.
SOURCE: Data from National Science Foundation (2014a), Appendix Tables 4-7 and 4-8.

ization of technology produced by federal laboratories has received only modest attention (see, for example, National Research Council, 2013b, 2013d), for several reasons. Some national laboratories perform confidential work that often is not shared with the broader research community, and compared with research universities, national laboratories have less flow of information through talent and fewer training opportunities.

National laboratories use a number of process indicators to track internally the performance of R&D. In particular, DoE manages these indicators via the Corporate Planning System (CPS), which tracks milestone achievements and financial performance each quarter at the project and contract levels. In addition, the Joule system tracks annual output measures, such as percent progress toward program goals and other sig-

TABLE 2-1 Total U.S. Research Expenditures by Performing Sectors, 1979-2011

Type of Work and Sector	Percent Distribution					
	1979	1989	1999	2004	2009	2011
Basic Research	100.00	100.00	100.00	100.00	100.00	100.00
Private industry	13.45	22.01	17.07	13.57	19.50	17.37
Federal intramural	14.20	10.55	8.60	8.14	7.18	6.50
FFRDCs	14.72	12.86	9.55	8.62	8.00	8.80
Universities and colleges	48.84	46.68	53.99	57.88	52.73	54.63
Other nonprofit organizations	8.79	7.90	10.79	11.79	12.60	12.70
Applied Research	100.00	99.99	100.00	100.00	100.000	100.00
Private industry	57.66	69.14	70.45	65.40	56.33	57.28
Federal intramural	19.97	11.05	10.63	10.73	10.80	9.40
FFRDCs	5.04	3.24	3.17	4.51	6.46	6.24
Universities and colleges	11.72	12.97	11.08	13.19	18.43	20.17
Other nonprofit organizations	5.62	3.59	4.67	6.17	7.98	6.91

NOTES: FFRDC = federally funded research and development center. “Other” includes research not elsewhere classified. The federal shares include amounts for FFRDCs. The character-of-work estimation procedures for academic and business R&D were revised in 1998; hence, these data are not directly comparable with data reported for earlier years. Furthermore, the methods of collecting data were revised in 2008 for business R&D and in 2010 for academic R&D; thus, these data are not directly comparable with data reported for earlier years. The federal shares include amounts for federally funded research and development centers.

SOURCE: Data from National Science Foundation (2014a), Appendix Tables 4-3 and 4-4.

nificant objectives. Finally, the Executive Information System (EIS) acts as a central repository that tracks project- and program-level financial, portfolio, scheduling, and performance information, as well as trends across the Office of Energy Efficiency and Renewable Energy (EERE) portfolio. The CPS, EIS, and EERE are described in detail in U.S. Department of Energy (2007).

IMPEDIMENTS TO THE RESEARCH AND INNOVATION SYSTEMS

Insufficient funding for proof-of-concept research can be an impediment to the translation of basic and applied research discoveries into innovations. In addition to the personal sacrifices of time and effort that academic researchers must make to translate their ideas into marketable innovations, entrepreneurs can find it difficult to advance their discoveries after federal research funding has ended and before sufficient capital can be attracted from private sources to support development and scaling up. Those early stages of spin-off development are the most risky. A lack of short-term gains, a low success rate, and steep competition from other companies discourage private investment (Ewing Marion Kauffman Foundation, 2012). Even a delay in funding can be devastating, as the success of an innovation may be limited by the speed with which it can be scaled up and brought to market.

A further impediment to growth in the research and innovation systems is the widely remarked absence of any executive or congressional entity overseeing the federal research portfolio and performing policy analysis for research.[5] NSF produces valuable data (e.g., *Science and Engineering Indicators*) that could be used in policy analysis. However, the role of its statistics agency, the National Center for Science and Engineering Statistics, differs from that of federal policy analysis agencies, such as the Office of the Assistant Secretary of Planning and Evaluation in the Department of Health and Human Services, as well as from that of statistics agencies that conduct policy analyses, such as the Bureau of Economic Analysis in the U.S. Department of Commerce and the Economic Research Service in the U.S. Department of Agriculture. In 1976, NSF established a Division of Policy Research and Analysis, which funded research on the returns to private and public R&D, but it was disbanded in 1995 (Hall et al., 2014). The lack of such an entity makes it difficult for various agencies to cooperate on common goals and strategies, as well as to foster more

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[5] In 2011, NIH established the Office of Portfolio Analysis to enhance the impact of its funded research by giving NIH administrators the means to evaluate and prioritize current and emerging research areas.

effective research pursuits (National Research Council, 2010b, 2012d; Government-University-Industry Research Roundtable, 2012).

Swings in federal research funding, such as those resulting from the American Recovery and Reinvestment Act and sequestration, also can be detrimental to the growth of the research and innovation systems (Freeman and van Reenen, 2008). This issue is discussed in more detail in Chapter 6.

HOW THE U.S. RESEARCH ENTERPRISE COMPARES WITH THOSE OF OTHER NATIONS

The United States differs from many other nations in that there is no central government administration exclusively in charge of research and innovation (Amsden, 1989; Chang, 2008; Mazzucato, 2011). China is attempting to transition from top-down control to a bottom-up "open door" policy focused on industry; nonetheless, a strong central government cohort largely sets strategic directions, objectives, and policy frameworks for research. In Canada, the prime minister and cabinet formulate overall science, technology, and innovation policy, which is implemented by Industry Canada and the Department of Finance. In East Asia, national governments have taken control of the transfer of research findings to development, targeting specific investments, creating barriers to foreign competition, and establishing industries in the international market.

OECD performed an international comparison of research funding and impacts (OECD, 2013), finding that:

> The U.S. remains the world's largest spender on R&D, accounts for a large share of scientific publications, and for over one third of scientific publications cited in patents. The U.S. still enjoys three distinct advantages: world class universities, a scale that is unmatched, being the central node in the global network of science, technology and innovation [STI] (OECD, 2013).

Compared with other nations, basic research in the United States is closely tied to research universities rather than private research institutes. Furthermore, a relatively high percentage of the U.S. adult population has a tertiary education, although the United States no longer leads other industrial economies in the share of college-age citizens enrolled in higher education. The United States leads in the overall production of scientific publications, producing more than 4 million publications from 2003 to 2011, double the output of second-place China (OECD, 2013). Nevertheless, challenges in U.S. K-12 education may impede the future growth of the U.S. research enterprise, and America's graduate- and faculty-level pools of STEM talent rely in part on the strength of K-12 education in other countries, such as China and India. As Gordon (2014) notes:

> The United States currently ranks 11th among the developed nations in high school graduation rates and is the only country in which the graduation rates of those aged 25-34 is [sic] no higher than those aged 55-64. . . . A UNICEF report lists the U.S. 18th out of 24 countries in the percentage of secondary students that rank below a fixed international standard in reading and math. The international PISA tests in 2013, again referring to secondary education, rated the U.S. as ranked 21st in reading, 24th in science, and 31st in math. A recent evaluation by the ACT college entrance test organization showed that only 25 percent of high school students were prepared to attend college with adequate scores on reading, math, and science.

The OECD comparison also reveals that the United States remains at the forefront of cutting-edge innovation, with a large and integrated marketplace and efficient capital and equity markets (OECD, 2012b, 2013). The United States is considered above average in business R&D expenditures and venture capital funding, although it is below the international average with regard to the share of university R&D that is funded by industry. However, a number of other studies have noted that the American university system works more closely with industry than is the case in many other economies, perhaps because of an overlap in federal funding that supports university-industry partnerships. (See the discussion of the university-industry relationship in Chapter 3.)

With respect to international collaboration between institutions in different countries, OECD (2013) finds that the United States is the “central node in the global network of science, technology, and innovation.” At the same time, the OECD report singles out the rise of China:

> As China invests in its institutions, expands its funding and becomes a more active participant in the global STI network, some of the inherent advantages the United States has enjoyed for decades may be reduced and a new node for STI will begin to form. This creates challenges for the U.S. system, especially given its dependence on highly skilled talent from abroad. To maintain its position, the United States needs to continue to invest and let its system evolve to encompass new developments ranging from sophisticated IT applications to greater recognition of the importance of nontechnological innovation (OECD, 2013, p. 6).

This observation suggests that as China invests in its research institutions, it will likely follow the pattern of development of such other Asian innovation powerhouses as Japan, Singapore, South Korea, and Taiwan by improving its performance in both research and innovation. Therefore, just as was the case during the 1980s and 1990s, the U.S. research system will be challenged by (and potentially be able to benefit from) the enhanced research and technological prowess of new competitors. It may become increasingly important to encourage foreign students who receive a Ph.D. in the United States to stay in the country and establish careers here.

NSF's *Science and Engineering Indicators* for 2014 notes that Asian countries—led by China—are performing an increased share of the world's R&D, rising from 25 percent in 2001 to 34 percent in 2011, while the share of the world's R&D performed in the United States and Europe has significantly decreased. An NSF press release for that report states (National Science Foundation, 2014c):

> Recognition on the part of national leaders that science and technology (S&T) innovation contributes to national competitiveness, improves living standards, and furthers social welfare has driven the rapid growth in R&D in many countries. China and South Korea have catalyzed their domestic R&D by making significant investments in the S&T research enterprise and enhancing S&T training at universities. China tripled its number of researchers between 1995 and 2008, whereas South Korea doubled its number between 1995 and 2006. And there are indications that students from these nations may be finding more opportunities for advanced education in science and employment in their home countries.

These observations drive home the point that the United States still dominates global research, but Asian nations, including China, are not far behind.

3

Understanding the Pathways from Research to Innovation

KEY POINTS IN THIS CHAPTER

- The benefits of scientific research—particularly basic research—include not only innovation but also contributions to a trained workforce and to the infrastructure that enables further research and the use of scientific discoveries.
- It is impossible to predict all of the outcomes or benefits to which basic research might lead. It is equally impossible to predict all the types of research knowledge that will contribute to a future transformative innovation.
- Maintaining a level of preparedness that will allow America to benefit from discoveries made elsewhere is essential. To maintain this level of preparedness, government needs to support world-class basic research in all major areas of science.
- Metrics for evaluating and policies for supporting the translation of university research into industrial innovations need to be varied and flexible to reflect the diversity of academic institutions and firms and their interactions.
- The translation of research discoveries into economically and socially viable innovations frequently is subject to a time lag that in many cases reflects the often prohibitive cost and risk associated with proof-of-concept research. As discussed in

Chapter 6, government support for such research may be essential to overcome this barrier to the development of innovations.

- The international flow of people and ideas plays an increasingly important role in the U.S. research enterprise. This flow is supported in part by worldwide networks of researchers that advance research and enable access to a vast stock of knowledge and technological approaches offering opportunities for commercialization.

The committee's implicit charge for this study was to identify ways of increasing the output of the U.S. research system. Although the desired outputs are numerous, Congress and others have placed particular emphasis on economic gains, so we give special attention to those contributions here, noting that these gains depend on numerous factors that cannot easily be predicted or controlled, such as the widespread adoption of an innovation. In exploring how the United States might enhance the economic benefits gained from science, we focus on one goal in particular: for the United States to be at the forefront of global competition for new technologies and other innovations. A framework for supporting this goal through a greater understanding of the system of research is described in Chapter 6. We focus on this goal not only because innovative technologies are profitable in and of themselves, but also because focusing on this goal enables one to understand how the research enterprise advances national goals in general. This chapter describes the complex, lengthy, and often unpredictable pathways that lead from research to innovations that yield economic and other benefits for U.S. society, illustrated by a set of detailed examples.

THE LINKS BETWEEN RESEARCH AND INNOVATION

As discussed briefly in Chapter 1 and in greater detail in Chapter 4, measuring the economic and other returns of research is not an easy task. Attempts to trace major innovations back to their original supporting research have rarely if ever revealed a direct flow of "money in, value out." In the majority of cases, such exercises illuminate a tangled and complex yet rich and fertile path from the original investment to the final impacts on society. They reveal layer upon layer of small impacts scattered across many places, as well as coincidental exchanges of information that gradually steered the path of everyday research toward a transformative breakthrough, one that could not have been predicted (Martin and Tang, 2006).

Yet if one looks more closely at the months, years, and decades preceding transformative breakthroughs, subtle clues emerge. It becomes clear that chance favors the prepared mind. Along the path to discovery, certain grounds become more fertile, and certain environments more conducive to major innovations. Recognizing particularly fertile avenues for research often requires a close familiarity with "dry wells"—dead ends or failures in the development of scientific knowledge. Scientific knowledge thus advances through failures as well as successes, a point emphasized throughout this report. In fact, every failure in science can be considered a discovery in the sense that the project may not have achieved its original goal, but the failure plays an important role by pointing research in a more productive direction and often by providing a foundation for new discoveries.

We offer a series of illustrations. Box 3-1 provides an example of how innovation flourishes in fertile ground; Boxes 3-2 through 3-4 present examples of transformative innovations that could not have been predicted at the time of the original research; and Box 3-5 describes a failed project that unpredictably gave rise to a revolutionary idea. This concept is also illustrated in a study by the U.S. Center for Technology and National Security Policy titled *The S&T Innovation Conundrum* (Coffee et al., 2005, p. 1):

> For example, the rapid advances in electronics and computer products over the past 50 years have created a general impression of continuous scientific breakthroughs. In reality, the breakthrough S&T innovations for electronics and computers took place in the 1940s and 1950s. The subsequent rapid advances in functional capability were the result of a brilliant and enormously successful program to exploit those early breakthroughs.

The key players in transformative breakthroughs often are well-trained researchers from diverse backgrounds who know the right people—and many of them. The right people are other talented researchers who can draw on their knowledge of diverse fields to bring fresh perspectives to stale problems. Mathematics, statistics, and computer science, for example, help advance discoveries in other scientific fields, while the social sciences provide information, incentives, and institutions that advance the use of research discoveries in all the sciences.

Once the above clues are assembled, they reveal the commonalities of most transformative innovations. Economic and other societal impacts begin with the generation of basic knowledge. Such research may be undertaken for no other reason than to satisfy curiosity. However, a broad and deep knowledge base is necessary for the development of new technologies. People and publications distribute basic scientific knowledge via networks and research institutions. Through its eventual incorpora-

BOX 3-1
Factors That Influenced the Spread of the Hybrid Corn Innovation

About 95 percent of corn now grown in the United States is hybrid corn, but this was not always the case. In the 1930s, almost no hybrid corn was grown. The father of hybrid corn, G.H. Shull, a geneticist at Cold Spring Harbor, New York, began experiments in 1906 to understand the genetics of corn. At the same time, E.M. East conducted similar experiments at Connecticut State College. Their studies provided an important basis for industry research and for research conducted at state and federally supported experiment stations and in corn research programs. Shull's research ultimately led to one of the most significant agricultural innovations as hybrid corn went from being unknown in the 1930s to being used by more than two-thirds of all farmers by the 1940s. Allowing farmers to produce more corn with increasingly less land, the investment in this research at agricultural experiment stations yielded a return of about 40 percent (Scott et al., 2001).

Analyzing information about the spread and adoption of hybrid corn among farmers in the United States, economist Zvi Griliches teased out key factors affecting the dispersal of innovation. The challenge with large-scale commercialization of hybrid corn was the need to customize the hybrid to a particular region based on growing conditions. While simply examining the initial and ultimate spread of commercial hybrid corn provided little information, an examination of multiple factors yielded a clearer picture of the factors involved. Locations with the best growing conditions were the first to market hybrid corn. When hybrid corn reached 10 percent of the total corn grown in the United States, superior hybrids and additional farm machinery for harvesting corn allowed other farmers to achieve profit by growing it. Further movement into each state was directly linked to the capabilities of the state's experiment station. While hybrid corn was adopted more rapidly in the north than in the south, for example, southern states with larger experiment stations, such as Florida, Louisiana, and Texas, adopted it more rapidly than other states in the region. Thus, the second major factor affecting adoption of hybrid corn was the proximity of and access to resources at state agricultural experiment stations, funded by the U.S. government. Griliches' study demonstrates the importance of regional factors to the adoption and diffusion of novel products and concepts, as well as the importance of federal funding in overcoming regional constraints.

SOURCE: Adapted from Griliches (1957).

tion into products, processes, and business practices—most readily in geographic hubs of innovation, where research institutions are located in close proximity to an external community of funders, human intellectual capital, skilled labor, supplier networks, manufacturers, vendors, and technology-oriented lawyers and consultants (Warren et al., 2006)—this knowledge generates economic and societal benefits.

BOX 3-2
The MASER, Forerunner of the Laser

For a decade-long stretch of his career, Charles H. Townes, the inventor of laser technology, had to fight to convince others of the possibility, and the value, of the seemingly obscure technique of amplifying waves of radiation into an intense, continuous stream. During his career, he received funding from the National Science Foundation and the U.S. Navy.

Townes, born in 1915 in Greenville, South Carolina, had earned his Ph.D. at the California Institute of Technology and then went to work at Bell Labs. Later, as a professor at Columbia University, he began work on generating a controlled, extended stream of microwaves through contact with an electron in an excited state. The project sounded frivolous even to his colleagues, who told him directly that they thought he was wasting the university's money.

In 1953, Townes, James Gordon and H.J. Zeiger built the first MASER (microwave amplification by stimulated emission of radiation). About 5 years later, Townes and Arthur Schawlow published a paper saying the MASER's principles could be extended to amplify radiation at the frequencies of visible light, thus introducing the principle of laser technology.

Even then, Townes encountered doubters who saw no value in the technology. Luckily, however, the scientific community began to grasp the technology's implications. In 1960, Theodore Maiman built the first laser.

The laser became the basis of countless technologies we use in our daily lives. Without lasers, the Internet and digital media would be unimaginable. Computer hard drives, CDs, digital video and satellite broadcasting would not exist. Nor would laser eye surgery or laser treatment for cancer.

SOURCE: Reprinted with permission from Golden Goose Award (2014).

THE RELATIONSHIP BETWEEN UNIVERSITY RESEARCH AND INDUSTRIAL INNOVATION

Universities in the United States have a long tradition of engagement with industry in research and other collaborative activities. This pattern of engagement has benefited from a two-way flow of ideas and people between academic and industrial research settings, and has included extensive patenting and licensing of university inventions to industry. Contributing to this pattern of collaboration have been both the historical structure of the national U.S. system of higher education and factors external to U.S. universities, such as relatively high levels of domestic interinstitutional mobility of researchers and new-venture financing from various private sources. But the connection between U.S. universities and innovation in industry throughout the 20th and 21st centuries has relied on a number of different channels, including, among others, the training

BOX 3-3
Green Fluorescent Protein

In 1962, an organic chemist named Osamu Shimomura, working in the Department of Biology at Princeton University, was interested in jellyfish and in learning how and why they glowed bright green under ultraviolet light. The recent Ph.D. graduate collected millions of jellyfish to isolate the source of their bioluminescence, and after many years of careful science, he finally succeeded in identifying the mechanism. He called the responsible protein "green fluorescent protein" or GFP. Beginning in the 1970s, Shimomura received funding from the National Science Foundation to explore the biochemistry of this luminescence further.

In the 1980s, Shimomura's studies attracted the attention of a young investigator at Woods Hole Oceanographic Institution named Douglas Prasher, who wanted to attach GFP to the bacterial proteins he was studying so they would glow brightly when expressed in a cell. Prasher sought $200,000 from the American Cancer Society to clone and sequence the gene for GFP. He succeeded in publishing the relatively short protein sequence, but he ran out of funding before he could actually use GFP as a tag on the bacterial proteins, and had to set the project aside. Although he failed to achieve his initial goal, Prasher did something even more valuable: he shared the cloned gene with hundreds of other scientists, including Columbia University biochemist Martin Chalfie, and University of California, San Diego biochemist Roger Tsien, who would later share the 2008 Nobel Prize in Chemistry with Shimomura for their work in honing the GFP technology.

Chalfie heard about GFP at a seminar and decided to ask Prasher for the sequence so he could use GFP to tag proteins in some of the worms (*C. elegans*) he was studying, using funds from the National Institutes of Health. On the opposite side of the nation, unbeknownst to Chalfie, Tsien applied his previous research on the chemistry of florescent dyes to alter the color GFP would produce when exposed to ultraviolet light, thus allowing protein tags of many different colors to be used at once. In 1996, a scientist at the University of Oregon, Jim Remington, collaborated with Tsien to determine the crystal structure of GFP, using funds from NIH.

With this new set of tools, biomedical scientists have opened up vast new capabilities in research. The applications of GFP are ubiquitous in both basic and applied research. Shimomura did not set out to revolutionize biology or medicine; he simply wanted to understand a complex creature. Chalfie wanted to find a way to understand the neurobiochemistry of a simple model organism in more detail, and was inspired by a seminar he attended in his department. Tsien saw the potential to improve the tools available to biologists.

According to a description of the award on NobelPrize.org, the work of these researchers has made it possible today to "follow the fate of various cells with the help of GFP: nerve cell damage during Alzheimer's disease or how insulin-producing beta cells are created in the pancreas of a growing embryo. In one spectacular experiment, researchers succeeded in tagging different nerve cells in the brain of a mouse with a kaleidoscope of colours."

SOURCE: Adapted from NobelPrize.org (2008).

BOX 3-4
Corning® Gorilla Glass®

Gorilla Glass® is in most people's pockets, but it started with a faulty furnace and spent nearly 40 years as a shelved idea. The idea for Corning's ultralight, ultrathin, and virtually indestructible glass—used on the surfaces of most modern mobile phones and laptop computers—emerged one morning in 1953, when chemist S. Donald Stookey accidentally overheated a sheet of lithium silicate photosensitive glass. Because of a faulty temperature controller, the furnace Stookey was using heated the glass to 900°C rather than 600°C. Instead of melting, however, the glass transformed to a milky white ceramic plate and bounced, rather than breaking, when it fell to the floor. Completely by accident, Stookey had discovered a new realm of high-temperature chemistry.

This was the start of Corning's Project Muscle—a research initiative focused on developing strengthened glass products. A key outcome was the realization that the glass could be strengthened through ion exchange by means of hot salt baths, with smaller sodium ions being traded for larger potassium ions. In 1961, Corning unveiled Chemcor glass—a highly durable ceramic that was quickly incorporated into the company's existing product lines.

But Corning could not find a consistent market for Chemcor; it was a solution in search of a problem. Both Chemcor and Project Muscle were shelved in 1971. Chemcor did not reemerge until 2007, when the widespread use of smartphones suddenly generated the need for strong, thin, lightweight, mass-produced glass. Apple's Steve Jobs is rumored to have rediscovered Chemcor's properties and to have requested further improvements. Previously, Chemcor had been produced around 4mm thick, was slightly cloudy, and was manufactured only in small batches. Jobs wanted it to be 1.3mm, clear, and stretchy at relatively low temperatures. And he needed it in 6 weeks for a new idea called the iPhone.

Adam Ellison and Matt Dejneka, two of Corning's compositional scientists, were given the task of adapting part of the Corning fusion production facility in Harrodsburg, Kentucky, to meet Apple's first request, as well as reformulating the composition of Chemcor itself. Corning's commitment to research—for which it is known and to which it has held true throughout its history—as well as its recognition of the sometimes delayed benefits of research, led to a product that can now be found in more than 750 commercial products and 33 brands worldwide.

SOURCE: Adapted from Gardiner (2012).

of students, faculty consulting, publication of research advances, and industry-sponsored research. These channels operate in parallel and are interdependent. Moreover, the relative importance of different channels of interaction and information flow between academic and industrial researchers appears to vary considerably among different research fields.

The so-called "Bayh-Dole era" that began in 1980 (discussed in Chapter 2) extended and expanded this engagement. Important as well was extensive federal support for research, notably in the life sciences, which

BOX 3-5
Failed Research That Inspired the Discovery of Novel Therapeutics: Antidepressants

In the early 1950s, researchers tested a new drug, iproniazid, for treatment of tuberculosis. It was not an effective treatment, but the researchers reported that the drug made a number of patients "inappropriately happy." This discovery ushered in a new era of biological research on depression, leading to the development of antidepressant drugs. Iproniazid became the first marketed antidepressant.

SOURCE: Adapted from Burns (1999).

produced important advances that sparked growth in university patenting and licensing, increasingly managed directly by U.S. universities, during the 1970s. There is little evidence that increased faculty engagement in entrepreneurial activities during the post-1980 period, including the formation of new firms and patenting and licensing of inventions, negatively affected the scholarly productivity of leading researchers (Ding and Choi, 2011). Nonetheless, the efforts of U.S. universities to manage their intellectual property more directly for revenue purposes have sparked criticism from U.S. firms, especially those engaged in information technology. In response to this criticism, some U.S. universities have experimented with new approaches to the management of patenting and licensing that take into account the differences among research fields in the importance of patents relative to other vehicles for information exchange and technology transfer. Research universities can contribute to or inhibit faculty start-ups through their reward systems. Some academic departments look askance at patents in tenure consideration, while others regard patents more highly. In recent years, institutions such as the University of Maryland have begun formally counting patents and commercialization in tenure reviews (Blumenstyk, 2012). Similarly, Massachusetts Institute of Technology (Ittelson and Nelsen, 2003) and Carnegie Mellon University (Simmons, 2013) have been recognized for encouraging entrepreneurship and faculty start-ups through supportive policies.

Reflecting the complex roles of university technology transfer programs in regional and U.S. national economies, an array of institutional goals can be pursued through such programs. But these goals are not always mutually consistent or compatible, so that policy priorities must be established for these programs and clearly linked to current policies. Revenue-maximizing licensing strategies may be shortsighted (Ewing Marion Kauffman Foundation, 2012).

Metrics for evaluating the performance of universities in transferring technology and supporting industrial innovation are informative when they are aligned with the specific goals of a given university or research institute and account for the full breadth of channels through which university research influences industrial innovation, including the training and placement of students, faculty research publications, faculty- or student-founded firms, patents, and licenses. Given the lack of data covering these various channels for most U.S. universities, as well as the need for metrics to be tailored to the goals and environments of individual universities, it appears unrealistic and unwise for federal agencies or other government evaluators to impose a single set of metrics for measuring the technology transfer performance of all U.S. universities. Trying to apply an evaluation framework that does not take adequate account of the diverse channels of university influence or the differences among universities would only serve to diminish the institutional heterogeneity that historically has been a strength of the U.S. system of higher education.

This institutional heterogeneity also implies a need for flexibility and variety in the policies used by U.S. universities to support interactions with industry and the commercialization of academic research advances. The Bayh-Dole Act and other relevant federal policies do not specify any single institutional structure for managing patenting, licensing, and related activities in university-industry collaborations. But U.S. universities have been slow to implement and evaluate different approaches to managing these activities during the three decades since the act’s passage. Such experimentation, combined with efforts to assess the effectiveness of alternative approaches, is not likely to advance to the extent that would be desirable without the encouragement of federal agencies, industry, and other stakeholders. Nonetheless, no single approach is likely to prove feasible or effective across the numerous and diverse academic institutions and private firms engaged in federally funded research and industry collaboration. Appendix B elaborates on the relationship between university research and industrial innovation.

THE UNPREDICTABLE TIMELINE FROM RESEARCH TO SOCIETAL IMPACT

In many cases, a significant time lag separates the original research from the commercialization of an innovation incorporating the knowledge generated by that research. Sometimes this time lag represents the long wait between an original research finding and its sudden and unexpected relevance to a breakthrough innovation. The basic science research that enhanced understanding of the mathematics of nonlinear control theory, for example, eventually made it possible to create electrical power grids that rarely fail.

This time lag occurs, however, even when a research finding has readily apparent applications. This is the case because many research discoveries intended for future development and commercialization, such as the technology used to develop efficient fuels, must first cross the so-called "valley of death"—the often prohibitive cost and risk associated with proof-of-concept research. In some cases, the industry and venture capital support needed to develop a concept or invention vastly exceeds the funding for the original concept or invention.

Only after crossing this valley can the technology be incorporated into a concept model or laboratory prototype that provides a platform for the subsequent applied research and development needed for a product to compete in the marketplace. But technology concept models and laboratory prototypes must be achieved quickly, before others can exploit the discoveries on which they are based for commercial advantage. In that sense, the time lag associated with proof-of-concept research is particularly important in the race to commercialize research discoveries with immediately obvious applications.

The complexity of modern technologies has increased the difficulty of translating basic science advances into economically and socially valuable technologies. Universities, industry, and government are all investing in crossing the "valley of death" within the limitations imposed by the time lag, expense, and risk that characterize the path from basic science to the industrial laboratories where innovations are created. As discussed in Chapter 6, government support for proof-of-concept research may be essential to overcome this barrier to the development of economically and socially viable innovations.

CONNECTING THE DOTS FROM RESEARCH TO INNOVATION

Research universities have the primary goal of generating knowledge and dispersing it through the nation's most talented people. One of the greatest benefits of research universities is the workforce they train—their talent, abilities, knowledge, skills, and experience and the networks of professional connections they have made. Students trained in research develop critical thinking skills and an ability to help solve some of the most complex problems facing society, ranging from the technical (energy efficiency, climate change, cybersecurity) to the social (the economy, crime, an aging population, immigration).

The funding provided to research universities is therefore crucial to the societal benefits derived from the research enterprise. An example of research funding used to develop new approaches to training is the

National Science Foundation's (NSF) 2002-2005 Department-Level Reform Grant Program, which funded 20 engineering departments to transform their undergraduate teaching from a stovepiped approach, focused solely on teaching engineering concepts, to an approach providing an education in the context of achieving societal goals. The specifics of the approaches taken by each of the departments differed, but they all included partnerships with nonengineering departments, service learning projects, and hands-on application of the concepts learned. Other interdisciplinary programs followed. The focus of these programs on theory, application, and interdisciplinary experiential education has been deemed effective, although the programs' long-term effectiveness, including the impact on students' careers, has not been fully evaluated (Shipp et al., 2009).

The *flow* of knowledge occurs when talented people forge new connections with other talented people and migrate both geographically and intellectually between positions in academia, private industry, and the government. This flow is channeled through networks and partnerships, aided by publications, citations, and other correspondence, so that bits of knowledge emerge when and where they are needed most. With the increasingly important role of the Internet in scientific research, these networks are expanding and enabling virtual collaborations. As knowledge emerges at different times and in different places, it evolves and expands. People with diverse backgrounds transform it and present it in new ways, with fresh perspectives. Networks of researchers and institutions enable discoveries, ideas, instrumentation, and analytical methods to be shared among the world's best talent, inspiring the ultimate use of knowledge from research. These networks can also encompass scores of volunteers working with scientists on real-world research projects—a movement known as Citizen Science (Bonney et al., 2014).[1] In addition, the ready availability of knowledge enables serendipity and increases the potential for transformative innovations.

Increasingly, these flows of people and ideas occur internationally and play an important role in research and innovation in the United States. Private industry now invests in research laboratories abroad, and the findings from these laboratories feed back into U.S. research and innovation. Encouraging the mobility of researchers across national boundaries as well as among domestic research institutions remains a challenge for most nations; however, a UK Royal Society report indicates that Australia, Canada, the United Kingdom, and the United States attracted the

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[1] Citizen Science has been defined by the Cornell Laboratory of Ornithology at Cornell University in Ithaca, New York, which helped pioneer the concept, as "projects in which volunteers partner with scientists to answer real-world questions." More information is available at: http://www.birds.cornell.edu/citscitoolkit/about/definition [June 2014].

largest numbers of highly skilled migrants[2] from OECD countries in 2001, followed by France and Germany (OECD, 2002b). China perhaps experiences the most extreme challenges with mobility (Ministry of Science and Technology of the People's Republic of China, 2007). While it produced 1.5 million science and engineering graduates in 2006, 70 percent of the 1.06 million Chinese who studied abroad between 1978 and 2006 did not return to China (GOV.cn, 2010). In 2008, the Chinese government established the Thousand Talents Program, which brought more than 600 overseas Chinese and foreign academics back to their native country (The Royal Society, 2011).

Today, knowledge from basic science moves more rapidly than ever across international borders, and research findings can be shared in a public forum (e.g., the GenBank database of genetic and proteomic findings) to become immediately accessible to all researchers worldwide. A study by Griffith and colleagues (2004) suggests that foreign research and development can spill over domestically and have an impact on productivity. As discussed in greater detail in Chapter 6, the United States needs to educate and attract the scientists and engineers who understand and can advance these findings by conducting world-class basic research in all major areas of science, with "major areas" being defined as broad disciplines of science, their major subdisciplines, and emerging areas such as nanotechnology (National Academy of Sciences, 1993).

This requirement is emphasized in a 1993 report of the National Academy of Sciences (NAS), *Science, Technology, and the Federal Government: National Goals for a New Era*, which emphasizes the importance of the United States being among the leaders in all major areas of science (National Academy of Sciences, 1993). In particular, the report is noted for its argument that maintaining a world-class standard of excellence in all fields will help ensure that the United States can "apply and extend scientific advances quickly no matter when or where in the world they occur" (*Experiments in International Benchmarking of U.S. Research Fields* [National Academy of Sciences, 2000, p. 5], in reference to the 1993 NAS report). To this end, the federal investment must be vigorous enough to support research across the entire spectrum of scientific and technological investigation. Because of the interconnection among fields, neglect of one field such that the capabilities and infrastructure in that field are exceeded elsewhere could impede domestic progress in other fields or stifle innovation. The importance of nurturing all fields of scientific research to foster transformative innovations is illustrated by the case study in Box 3-6.

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[2] Highly skilled migrants are defined by OECD as workers who have completed education at the third level in a science and technology (S&T) field of study, or who are employed in an S&T occupation in which that level of education is typically required.

BOX 3-6
Genomics and the Big Bang Theory

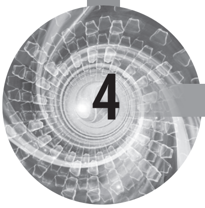
In 2001, three astrophysicists published in *Science* a confirmation of the Big Bang theory of the creation of the universe (Miller et al., 2001a, 2001b). They studied the imprint of so-called acoustic oscillations on the distribution of matter in the universe and showed it to be in concordance with the distribution of cosmic microwave background radiation from the early universe. This discovery not only provided support for the Big Bang theory but also yielded an understanding of the physics of the early universe that enabled predictions of the distribution of matter from the microwave background radiation forward and backward in time.

The discovery was made using a statistical method—the false-discovery rate—to detect the oscillations. The impetus for this method was the development of technologies that allowed for the rapid collection and analysis of data on a large number of distinct factors.

Collaborating with the astrophysicists, a statistician developed the method further for their research. Using this method, the authors were able to make their discovery and publish it in *Science* while others were still wrestling with the plethora of data. Based on the method's applications to cosmology, statisticians conducted research to improve it, and it is now used in many other applications. This method has been applied in genomics, for example, so that for a small sample of individuals, thousands of genes can be tested simultaneously to determine how they differ in affecting a biological condition.

The possibility of innovation is enhanced when tools and resources considered "missing" in some fields of science can be handed over by colleagues in other fields at the precise moment that they matter most (see Box 2-5 in Chapter 2). When investments in research create a fertile environment for innovation, the United States has a greater capacity to build scientific infrastructure, generate knowledge and human capital, and reap economic and other societal benefits. When the environment is fertile for innovation, the nation is better prepared for an uncertain future.

A wise investment in America's future, therefore, is an investment in *knowledge*: in the researchers who generate it, in the research colleges and universities that disseminate it, and in the networks of scientists and engineers who transform and ultimately use it. The value of knowledge becomes most evident through its eventual applications, which often cannot be predicted. Nonetheless, investing in the generation, dissemination, and use of knowledge will better ensure that research leads to applications that benefit society, some in transformative ways. Many research findings will eventually have unexpected applications that differ from a project's original goal. The task for government management of research is not to predict, much less control, the future but to allow discoveries to emerge from these investments.



4

The Usefulness and Limitations of Metrics in Measuring the Returns on Publicly Funded Research

KEY POINTS IN THIS CHAPTER

- Currently available metrics for research inputs and outputs are of some use in measuring aspects of the American research enterprise, but are not sufficient to answer broad questions about the enterprise on a national level.
- The impacts of scientific research can best be determined not by applying traditional metrics such as counts of publications and patents, but by cultivating an understanding of the complex system that is the U.S. research enterprise to determine how all of its component parts interrelate, a theme that is explored in detail in Chapter 6.
- Ongoing data collection efforts, including Science and Technology for America's Reinvestment: Measuring the Effect of Research on Innovation, Competitiveness and Science (STAR METRICS), could potentially be of great value if these datasets could be linked with other data sources and made more accessible to researchers.

Metrics often are used to assess quantitatively how well a project or a research-performing institution measures up. Is it performing as well as it should? Is it producing the expected results? Is it a worthwhile investment?

Of particular interest to Congress for this study was whether metrics could be used to quantify one particular aspect of the U.S. research enterprise: the transfer of scientific discoveries at research universities and government laboratories into commercial products and services for societal benefit (a process discussed at length in Chapter 3). The committee found, however, that technology transfer is only one small piece of the picture (see Chapter 3 and Appendix B on the relationship between U.S. universities and industrial innovation). In fact, the very term "technology transfer" connotes specific institutionalized mechanisms for the movement of technical knowledge, whereas in reality knowledge moves through numerous informal channels and institutional frameworks—perhaps most importantly through people—and moves in many directions between universities, industry, and other laboratories, or between basic and applied research. It is also important to note the subtle difference between "measuring inputs to and outputs from the research enterprise" and "evaluating the impacts of the research enterprise": the former focuses on the measurement of external factors that modulate the process of research and on the measurement of intermediate research outputs, such as publications and patents; the latter focuses on how research ultimately affects society.

This chapter reviews in turn existing measures; the uses and limitations of a commonly used input indicator and a commonly used output indicator; the challenges of data collection to inform measurement tools, with a focus on the STAR METRICS Program; the limitations of existing metrics; and the need to move beyond current indicators. Chapter 5 explores how the impacts of the research enterprise have been evaluated by various groups, including universities, private industry, private nonprofits, government agencies, and other nations.

EXISTING MEASURES

Although no single measure can provide an accurate representation of the full picture of the returns on research investments, some currently available tools—particularly the metrics and indicators of research inputs and outputs described below—can help answer specific questions about aspects of the overall picture. Both techniques and methods, as well as metrics that are used to measure a system's performance quantitatively, and indicators, which reveal trends or facts about a system, can provide value.

A report by Guthrie and colleagues (2013) explores how various methods (e.g., data mining, visualization, site visits, economic analyses), metrics, and indicators can be used and describes key challenges related to each. The following are some examples:

- *Bibliometrics* are a quantitative measure of the quantity, dissemination, and content of research publications. They reveal the volume of outputs from the research system, and can shed light on pathways of knowledge transfer and the linkages among various scientific fields. However, the use of citations as a measure of quality or impact varies among fields and individual scientists, making this a difficult metric to apply across the research system.
- *Case studies* are useful in capturing the complex and varied inputs that influenced a particular output. This method is a valuable way to reveal the context of a discovery, but case studies often provide examples and generalizable information rather than definitively linking research to a particular output or outcome.
- *Economic analysis* can be used to understand the relationship between costs and benefits, compare possible outcomes among a range of alternative strategies, and reveal the cost-efficiency of an approach. This method is useful whenever it is possible and appropriate to assign a monetary value to both costs and benefits.
- *Logic models* provide a visual interpretation of the trajectory through which inputs contribute to a particular output, and can be useful for planning, monitoring, and evaluating research programs. The limitation of logic models is that a trajectory can change in unexpected ways. Moreover, these models tend to disregard the counterfactual, or the most likely scenario had the research program not existed.
- *Peer review* is a method based on the idea that experts in a field are best suited to determining the quality of work in that field. Some have criticized peer review for discouraging the funding of high-risk research or radically new research approaches. Moreover, as further discussed in Chapter 5, others have recently criticized how the National Institutes of Health (NIH) organizes, funds, and selects study sections, suggesting that it leads to the dilution of expertise in the review process. See, for example, Alberts et al. (2014).
- *Statistical analysis* is a valuable, albeit time-consuming way to identify patterns in existing datasets. This method depends greatly on access to and the quality of existing data.

The next two sections describe indicators of the broader systems of research and innovation from two different perspectives—research inputs and research outputs. These indicators are commonly used to assess the competitiveness of the American research enterprise.

INPUT INDICATOR: RESEARCH AND DEVELOPMENT (R&D) AS A PERCENTAGE OF GROSS DOMESTIC PRODUCT (GDP)

A frequently used indicator of a nation's investment in science is the ratio of spending on R&D to GDP. It is a crude measure that allows for international comparisons of the levels of national investment in R&D, investments that are correlated with overall innovative performance. Nonetheless, like many widely used metrics for R&D investment, R&D/GDP ratios conceal a great deal of cross-national heterogeneity. In the United States and some other countries, for example, a large share of the national R&D investment is devoted to defense, and most of such spending is on the development and testing of military equipment.[1] Differences in the proportions of defense and nondefense funding in the public R&D investments of each nation make comparisons of the United States' R&D/GDP ratio with those of other nations potentially misleading. The mix of public and private R&D investment that is included in the numerator also varies considerably among nations. Moreover, of course, this ratio measures only inputs, and says nothing at all about the efficiency with which the investment in R&D is translated into basic knowledge and/or innovations.

Despite these limitations, the ratio and its numerator (i.e., the amount of R&D spending) are important indicators of where the United States may face future competition. As reported by the National Science Foundation (NSF) (2014a, Table 4-4), in 2011, the R&D share of GDP for the United States was 2.9 percent. For Japan, it was 3.4 percent, and for South Korea, it was 4.0 percent. For China, the share has increased consistently since the mid-1990s, reaching 1.8 percent in 2011. According to the most recent OECD data, the United States ranks 10th among nations on this indicator.

Moreover, NSF notes (pp. 4-18):

> Most of the growth over time in the U.S. R&D/GDP ratio can be attributed to increases in nonfederal R&D spending, financed primarily by business. This growth may also indicate an increasing eagerness by business to transform new knowledge into marketable goods. Nonfederally financed R&D increased from about 0.6 percent of GDP in 1953 to about 2.0 percent of GDP in 2011. This increase in the nonfederal R&D/GDP ratio reflects the growing role of business R&D in the national R&D system and, more broadly, the growing prominence of R&D-derived products and services in the national and global economies.

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[1] In 2010, 60 percent of U.S. federal R&D spending was for defense, but only a very small fraction of that spending (about 2 percent) was for basic research (National Science Foundation, 2012, Tables 4-28 and 4-29).

As this statement suggests, much of the growth in industry-funded R&D during the post-1953 period reflects increased industry spending on applied research, as well as development, rather than on basic research.

The ratio of R&D to GDP does not account for how effectively each nation manages its investment, nor does it capture cross-national differences in the mix of public and private funding within the numerator or in the division of labor among different institutional performers (government, universities, and industry). Moreover, combining data on national investments in research and in development does not allow for cross-national comparisons of research investments alone, presenting a significant barrier to examining the effects of federal research investments. Therefore, further data and analysis are necessary to understand the components of R&D spending and enable a better understanding of how the United States compares with other countries in this regard.

NSF calculates a similar ratio for individual industries and sectors. In this case, the ratio is R&D divided by net sales.[2] This measure, called "R&D intensity," shows another aspect of the results of federal funding for basic and proof-of-concept research. The opportunity for a business to be successful in conducting R&D is influenced by the availability of a science base and platform technologies from proof-of-concept research. The better government does in supplying these inputs, the higher is the return to industry on its prospective investments in R&D, and the more industry invests in innovation. In other words, higher R&D intensities should be expected for industries supported in this way.

From a metrics perspective, the output of government support for science and technology platforms is what economists call an "intermediate good," in that industry builds upon these platforms and the general stock of scientific knowledge to create innovations. For the most part, there are no markets for these knowledge-based intermediate technology goods, which makes impact assessment difficult.[3] Nonetheless, they are essential to the productivity of applied R&D.

OUTCOME INDICATOR: RETURN ON INVESTMENT

A popular indicator for assessing research outputs as a means of justifying further research investments is return on investment. This indicator has been used for medical research (Passell, 2000), manufacturing prac-

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[2] A portion of an industry's sales is its "value added." The sum of the value added by all domestic industries is GDP.

[3] Other government policies, such as the R&D tax credit, apply to the entire R&D cycle. Further, mission agencies, notably the National Aeronautics and Space Administration (NASA), fund applied R&D as well. The discussion here applies to government investment in research in support of economic growth objectives.

tices, information technology (IT) (Dehning and Richardson, 2002), and other elements of the research and innovation systems.[4,5] Using this measure correctly, however, presents methodological challenges in terms of both alternative conceptual models and the requirement for quality data.

Two main approaches have been described for measuring the private economic returns on R&D investment. The first relates current output (measured as sales or net revenue) to conventional inputs (labor, capital, purchased materials and services) and a measure of the stock of knowledge available to a firm. The second is more forward looking and incorporates future expectations, but relies on the efficiency of financial markets in evaluating the future prospects of a firm. It relates the stock market value of the financial claims on the firm's assets to the underlying assets, again including a measure of the knowledge stock. This second approach is not suitable when the unit of observation is anything other than a publicly traded firm, so it is not useful for measuring the returns on federal R&D investments.

Constructing a measure of the knowledge stock available to a firm is challenging. The earliest work, by Griliches (1980), Mansfield (1965), and Terleckyj (1980), simply used research intensity (the R&D to sales ratio), relating it to the growth in output adjusted for input change (that is, total factor productivity, or TFP). This approach is appropriate when the depreciation rate for R&D is zero and the impact of R&D on output is immediate. Subsequent researchers, led by Griliches, have used a stock of R&D constructed by analogy to ordinary capital, with a depreciation rate arbitrarily chosen to be 15 percent. Work by Hall (2005) using the market value of private firms suggests that the appropriate private depreciation rate may be larger than 15 percent and will vary over time and sector, depending on competitive conditions. In a social sense, however, knowledge generated by private-firm R&D may depreciate more slowly than these rates suggest. The reason is because the technical knowledge base of an industry or entire economy expands over time, retaining and building on knowledge produced in earlier technology life cycles. That is, such knowledge may remain useful even if it is no longer possible for an individual firm to extract monetary value from it directly. Even with respect to new knowledge, firms benefit from R&D done by others because of its quasi-public good nature. Thus several researchers have included mea-

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[4] See the survey in Hall (1996) on the private and social returns on R&D investments.

[5] A large body of literature from NIST's Advanced Technology Program proposes and demonstrates multiple approaches to conducting studies that measure societal impact, including return on investment (http://www.atp.nist.gov/eao/eao_pubs.htm [August 2014]).

sures of the stock of potential spillover R&D in the production function to obtain measures of the social return on R&D investments.[6]

Hall and colleagues (2010) survey a large literature using the above production function approach to measure the returns on R&D investment. These authors also discuss in detail the many measurement issues that must be addressed when using this methodology. They then report on studies conducted at the firm, sector, and country levels, including those that incorporate measures of the spillover stock of R&D. They conclude that private rates of return generally have been positive and usually higher than those for ordinary capital. In addition, social rates of return often have been substantially greater than private rates, while returns on government R&D investments are lower, as one would expect for reasons given below.

Aside from the many measurement issues identified in the literature, interpreting results on rate of return in the R&D context poses a central problem: the outcome of individual R&D projects or indeed a collection of R&D projects is highly uncertain, and the projects' revenue or sales success depends on a number of other factors that are difficult to control. Hence past results are not a certain guide to future success, although they may be informative. In other words, the "rate of return on R&D investment" is not a parameter or universal constant—it will vary over time, country, firm, or technology. One might naturally expect it to be positive at the firm level on average, since profit-maximizing firms choose to spend money on such investments, but there will be great variability. Indeed, at any given point in time, returns are so variable that one might not even expect the average returns across firms to be equal to the cost of R&D capital that the firms face. Economic theory says that in general, a firm will invest in R&D to the point where the expected returns equal its cost of capital, but there is no guarantee that this equality holds *ex post*.

It is tempting to try to transfer the methodology for computing private returns on R&D investment to the assessment of economic returns on federal research investments. But this is generally a mistake. Besides the

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[6] R&D spillovers are defined as the knowledge acquired from R&D done by others (including governments) that is not paid for. Examples are increased understanding of scientific processes useful for one's own product development that is obtained from reading scientific publications or attending scientific meetings. In addition to spillovers from public R&D, firms and others frequently benefit from observing the introduction of new products and processes by their competitors. Although an actual product may be protected by one or more patents, some of the knowledge that accompanies its development is inevitably diffused to the rest of the industry. A number of researchers have explored ways of constructing stocks of knowledge relevant to a particular firm or sector by using spatial or technological distance measures to weight the R&D conducted by others. See Hall et al. (2010) for further development of these ideas.

interpretive drawback mentioned above, the central problem is that the computation of rate of return is appropriate when the entity making the investment is reaping its rewards and when the goal of the research is to maximize economic returns. This is not the case for most federal research, for a number of reasons.[7] In addition, unlike the situation for private firms, little if any of the output of the agencies responsible for much federal R&D spending (e.g., national security, public health, environmental quality) is priced in conventional markets, making the measurement of output, a cornerstone of the production function approach discussed earlier, infeasible (Griliches, 1979, 1994).

The relevant output for most federal research is not revenue but a variety of public goods, some but not all of which will be reflected in economy-wide productivity growth but will not be directly traceable to any particular R&D spending.[8] On the applied research side, these outputs include improvements to agricultural productivity, aeronautics, and energy production and efficiency. Such output may enhance the productivity of private firms, but it will be difficult to capture these impacts given their diffuse nature. For basic research, the problem is even more difficult because of long and variable time lags between the research and its impacts (see Chapter 3) and the fact that one cannot predict the areas impacted by particular fields of research very well (e.g., the role of mathematics and basic computer science research in genetic research).

The diffuse nature of the output of federal research has led some researchers to attempt measurement at the aggregate level by relating aggregate total factor productivity, or TFP, to various types of R&D spending across countries (Guellec and van Pottelsberghe de la Potterie, 2001; Westmore, 2013). The results are fairly encouraging and can reveal something about which policies and institutions appear to work better than others. However, these studies are somewhat fragile because of the great differences across countries and the increasingly international nature of R&D spillovers (which implies that one country may free-ride to some extent on the R&D spending of others). These studies also provide no specific guidance on the allocation of government R&D across fields. In principle, given enough data, it might be possible to estimate average returns across countries in various fields during the past, but it remains true that

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[7] A report of the National Academy of Sciences (1995) identifies about half of federal R&D spending as being devoted to nonresearch programs, including end development and testing of aircraft and weapons by the U.S. Department of Defense, nuclear weapons development by the U.S. Department of Energy, and mission operations and evaluation at NASA. Excluding this spending, the balance of federal spending is arguably for basic and applied research.

[8] For more information about the economics of scientific research, see President's Council of Advisors on Science and Technology (2012).

past performance is not necessarily indicative of future results. In any case, for most countries, it is simply impossible to construct the full input-output matrix from research in different scientific fields to downstream industry use and the accompanying feedbacks from industry to science.

These issues have been discussed thoroughly in several previous National Research Council (NRC) and other publications listed in the annotated bibliography in Appendix C. Most authors have reached the conclusion that standard economic rate of return analysis is not suitable for evaluation of federal research investments, and that a variety of methods—such as bibliometrics (supplemented by peer review), international benchmarking, and expert review of applied research projects—are necessary for the evaluation of scientific output.[9]

In summary, the outputs of federal research are intermediate knowledge-based goods, which industry combines with its own investments to produce proprietary technologies (innovations). The productivity of federal research must therefore be measured in terms of its partial contribution to the eventual commercialization of proprietary technologies. Thus, whether the output of federal research investments is science, technology platforms, or infratechnologies, the nature of the impact is to leverage the productivity of industry-funded R&D.

CHALLENGES OF DATA COLLECTION TO INFORM MEASUREMENT TOOLS

Interest in measuring the impacts of government-funded research has increased around the world, and a number of data collection efforts to this end are under way in the United States and other nations. Table 4-1 describes major data programs of Australia, Canada, the United Kingdom, and the United States (Guthrie et al., 2013). A key challenge is to establish the most appropriate set of metrics for achieving the goal of the data collection effort. Programs currently under way include the Research Excellence Framework in the United Kingdom, which is intended to measure the performance of universities and determine funding allocation based on the wider nonacademic impacts of research; the Excellence in Research for Australia framework, which uses bibliometrics and other quantitative indicators to measure research performance for accountability and advocacy purposes, and potentially for allocation of funds; and the Canadian Academy of Health Science Payback Framework, which relies on several indicators of research impact and incorporates a logic model for health

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[9] For an example of how bibliometric measures can be used to help evaluate research impacts, see Lichtenberg (2013).

TABLE 4-1 Research Impact Frameworks Used by the United States and Other Nations

Framework	Origin and Rationale	Scope
Research Excellence Framework, UK	Evolved from its predecessor, the RAE, and the RQF. Intended to be low burden, but pressure from researchers led to changes. Includes wider societal impact.	Assessment at subject level on three elements: quality of research outputs, impact of research (not academic) and vitality of environment.
STAR METRICS, U.S.	Key aim to minimize burden on academics. Helps to meet U.S. federal accountability requirements.	Two levels: Level 1, number of jobs supported; Level 2, range of research funded researcher interactions and wider impacts.
Excellence in Research for Australia, Australia	Perceived need to include assessment of quality in block funding allocation (previously volume only). Advocacy purpose to demonstrate quality of Australian research.	Assesses quality, volume, application of research (impact), and measures of esteem for all Australian universities at disciplinary level.
Canadian Academy of Health Sciences Payback Framework, Canada	Draws on well-established ‘payback’ framework. Aims to improve comparability across a disparate health research system, Covers wide range of impacts.	Five categories; advancing knowledge; capacity building; informing policies and product development; health and health sector benefits; broader economic benefits.

Measurement	Application to Date	Analysis	Wider Applicability
Assessment by subject peer review panel of list of outputs, impact statement and case studies, and statement on research environment.	Piloted 2009. First round of assessment 2014; results will determine funding allocation.	Burden not reduced, but adds wider impact to evaluation. Originally metrics based, but this was dropped as too unpopular.	Suitable for similar cross institutional assessment of performance. High burden in institutions, arguably expensive. Best for significant funding allocation uses.
Data mining approach, automated. At present, only gathers jobs data. Methodologies for Level 2 still being developed.	Level 1 rolled out to 80 universities. Level 2 still under development. Voluntary participation so full coverage unlikely.	Feedback generally positive, but feasibility of Level 2 not proven.	Potentially very wide depending on success of Level 2. There has been international interest, e.g., from Japan, EC.
Indicator approach; uses those appropriate at disciplinary level. Dashboard provided for review by expert panel.	First round in 2010, broadly successful. Next round 2012, with minor changes. Intended for funding allocation, but not used for this as yet.	Broadly positive reception. Meets aims, and burden not too great. Limitation is the availability of appropriate indicators.	Should be widely applicable; criticism limited in Australian context. Implementation appears to have been fairly straightforward.
Specific indicators for each category. Logic model has four research 'pillars': biomedical, clinical; health services; social cultural, environmental and population health.	Used by public funders; predominantly CIHR (federal funder), but there has also been some uptake by regional organizations (e.g., Alberta Innovates).	Strengths: generalizable within health sector; can handle unexpected outcomes. But understanding needed at funder level—may limit uptake. Early stages hard to assess.	Breadth, depth, and flexibility mean framework should be widely applicable. However, it only provides a guide and needs significant work to tailor to specific circumstances.

continued

TABLE 4-1 Continued

Framework	Origin and Rationale	Scope
National Institute of Health Research Dashboard, UK	Aim is to develop a small but balanced set of indicators to support strategic decision making, with regular monitoring of performance.	Data collected quarterly at programme level on inputs, processes, outputs and outcomes for three elements: financial, internal process and user satisfaction.
Productive Interactions, Europe	Measures productive interactions, defined as interactions with stakeholders that lead to change. Eliminates time lag, easier to measure than impacts. Assessment against internal goals intended for learning.	Intended to work in a wide range of contexts, best applied at research group or department level where goals are consistent.

NOTES: CIHR = Canadian Institutes of Health Research; EC = European Commission; NIHR = National Institute for Health Research; RAE = Research Assessment Exercise; RQF = Research Quality Framework.
SOURCE: Reprinted with permission from Guthrie et al. (2013, Appendix A, p. 37).

research translation in an effort to provide consistency and comparability among institutions in a research system with multiple regional funders.

One data collection program in the United States—STAR METRICS—is designed to collect a number of measures of the impacts of federally funded research.[10] This program is a joint effort of multiple science agencies (NIH, NSF, the U.S. Department of Energy, the U.S. Environmental Protection Agency, and the White House Office of Science and Technology Policy) and research institutions. Its objective is to document the outcomes and public benefits of national investments in science and engineering research for employment, knowledge generation, and health.

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[10] See the STAR METRICS Website: https://www.starmetrics.nih.gov/ [August 2014].

Measurement	Application to Date	Analysis	Wider Applicability
Programme specific data can be pooled to provide a system level dashboard; 15 indicators selected, matching core aims, collected quarterly.	Launched July 2011 NIHR-wide, with data to be provided by the four coordinating centres, analyzed and aggregated centrally.	Designed to fit strategic objectives, so in that sense likely to be effective. However, only just launched, so detailed analysis premature.	Should be applicable to other national health research funders. Performance indicators selected can be tailored to assessment needs.
Three types of interaction: direct personal contacts, (e.g., via a publication) and financial. Engages users; findings assessed against internal goals.	Piloted across diverse disciplines and contexts in four European countries and at EC level. No plans to roll out more widely at present.	Tailored, so should help improve performance. No comparative ranking. Requires significant work from participants to generate their own set of goals and indicators.	Indicators developed to meet goals, so widely applicable, but does not produce comparison between institutions, so not appropriate for allocation, and could be challenging to use for accountability.

The data collection program, which began in 2010, was to proceed in two phases using readily available information. In Phase I, the program identified workers supported by scientific funding, drawing on the internal administrative records (e.g., awards, grants, human resources, finance systems) of researchers' (mainly academic) institutions. Phase II is currently gathering information on scientific activities from individual researchers, commercial publication databases, administrative data, and other sources. The information gathered by STAR METRICS will allow various calculations, such as the total number of individuals supported by research funding, along with the number of positions supported outside universities through vendor and subcontractor funding. The STAR METRICS Program is intended to help federal policy makers, agency officials, and research institutions document the immediate economic effects of federal investments in scientific research.

While the program is relatively new, it takes two interesting steps: (1) automating and aggregating standardized reporting of grant payment information from university administrative records, and (2) creating a dataset that can plausibly reorient the analysis of federal R&D investments away from a focus on grants and toward a focus on investigators by assessing the impact of federal R&D spending on job creation. Programs akin to STAR METRICS are beginning to gain traction in Japan, Australia, and the European Union nations, offering the eventual possibility of international comparisons.

The committee evaluated the STAR METRICS Program (see Appendix A) in an effort to determine its potential utility for assessing the value of research in achieving national goals. Although STAR METRICS represents a valuable step toward developing detailed, broadly accessible, and nationally representative data that would allow systematic and scientific analysis of the organization, productivity, and at least some of the economic effects of federally funded research, it is currently deficient in a number of respects. To fulfill its considerable promise, the program requires several changes and expansions.

First, as of this writing, STAR METRICS data are largely inaccessible for research use; the data could be used in more informative ways if steps were taken to ensure broad and open access. Second, data collection could usefully be expanded to include more universities and other performers of federally funded research, such as national laboratories and teaching hospitals. This expansion would enable better coverage of both federal expenditures on basic and applied research and key aspects of the scientific workforce. Finally, STAR METRICS data would be more useful if steps were taken to ensure that the data can be flexibly linked to other relevant data sources, including but not limited to those maintained by the federal statistical and science agencies, as well as proprietary data sources such as the Institute for Scientific Information's Science Citation Index, recognizing that data emanating from such databases have very different meanings from field to field. Creating a robust and linkable dataset may require the addition of individual and organizational identifiers to the current STAR METRICS data.

The ability to capture, store, and analyze massive amounts of data offers opportunities for the further development of indicators. A recent NRC report, *Frontiers in Massive Data Analysis*, outlines the challenges of using today's massive data and suggests statistical approaches for addressing these challenges (National Research Council, 2013a, p. 70). Big data will require the use of advanced statistical methods and machine learning algorithms to optimize the data's usefulness and understand the challenges involved. Big data cannot answer all the salient questions with the push of a button; there is a need to vet the algorithms used to analyze these data. Human input will still be needed to decide what data to use, how they might be sampled, and how to integrate them with complementary existing data sources and models.

In addition to STAR METRICS, NIH is engaged in other efforts to collect data on its research: the Research Portfolio Online Reporting Tools, the Scientific Publication Information Retrieval and Evaluation System, and the Electronic Scientific Portfolio Assistant. These programs, however, collect data on shorter-term outputs, such as citations and patents, for management purposes, and were not established to track longer-term outcomes. The data collected through these efforts could potentially prove valuable in the design of a more powerful database.

The 2013 NIH report *Working Group on Approaches to Assess the Value of Biomedical Research Supported by NIH* (National Institutes of Health, 2013) describes how three of the agency's new administrative data collection efforts—the Research Performance Progress Report (RPPR), the SciENcv database, and the World RePORT database—can improve the quality of data collected on NIH-funded research projects and investigators. Indeed, much of the data needed to develop metrics about the research enterprise is housed in various administrative datasets across the federal government. The RPPR will collect information about research performance in a uniform format across all federal agencies, allowing greater integration across agencies. Moreover, it will link to other data-tracking systems, including the SciENcv database, which tracks researcher profiles. Finally, the World RePORT database will plot information about NIH-funded projects onto a geographic map to facilitate greater coordination among public and private funders.

LIMITATIONS OF EXISTING METRICS

The committee's review of many current metrics for research inputs and outputs revealed them to be lacking. In Chapter 5, we point to ways of improving existing metrics and making their use more effective, in particular by using them to identify where improvements are needed. Ultimately, however, metrics used to assess any one aspect of the system of research in isolation without a strong understanding of the larger picture may prove misleading.

Many currently available metrics are used in an attempt to reveal the value of research through the measurement of research outputs. They look at individual pieces of the big picture, for example, by counting patents and licenses and various other outputs. But a holistic understanding of the research system is needed if the goal is to increase the likelihood that innovations will emerge. Existing metrics give some indication of how well the system is performing, but the ultimate impacts, the emergent phenomena that truly matter to society—such as an abundant supply of natural gas enabled by fracking technology, communications and commerce enabled by Google and the Internet, and medical advances enabled by genomics—depend on a number of critical components, and the relationships among them, in the complex systems of research and innovation. These components often are intangible, including opportunities and relationships that are not captured by most data collection programs and cannot be measured by any method available today. The challenge, which has yet to be met, is to capture and articulate how these intangible factors enable the success of the research enterprise. A report by the National Bureau of Economic Research (Corrado et al., 2006) suggests that the challenges of accounting for intangible factors lead to the exclusion of nearly $3 billion of business intangible capital stock and significantly modulate the patterns of U.S. economic growth.

Numerous approaches have been used to measure the impacts and quality of research programs. With a few notable exceptions, such as the cost-benefit studies conducted for the National Institute of Standards and Technology (NIST) (Polenske and Rockler, 2004), these approaches cannot depict the diffuse and interconnected pathways that lead from research to technologies and other innovations. We particularly agree with a common finding that metrics of research impacts must be viewed with considerable caution and that assessments, therefore, require both metrics and professional judgment. The Australian Group of Eight (Rymer, 2011) explores this issue in depth in the report *Measuring the Impact of Research: The Context for Metric Development*, issuing strong warnings about the limitations of metrics. The report describes how the impacts of scientific research can be grouped into eight broad categories: effective teaching; advances in knowledge; encouraging additional investment by other parties; financial returns; and economic, social, environmental, and intangible (e.g., national reputation) outcomes. The Group of Eight assessed impact in these categories using several measures, including bibliometrics, benchmarking, peer review, and surveys, to determine patents and spin-offs (Rymer, 2011, pp. 11-17). The authors emphasize that none of the current metrics can provide definitive results.

In addition, data on the outcomes of each of the many steps in a complex research project or technological innovation often are lacking, and the appropriate performance metrics may differ in different phases of a technology's development. Appropriate metrics also may differ for each type of research and field of science.

Moreover, multiple areas of research often contribute to the development of a technology, so that different measures and data may be needed to evaluate outcomes in such areas as productivity, output, or overall societal benefit. Such measurement and analysis require expertise that is not evident in many federal agencies.[11]

Federal agencies must guard against the temptation to try estimating outcomes, or impacts, directly from a specific federal research program. Each research program makes a direct contribution to an outcome that might be measured in terms of outputs, such as publications, patents, and trained scientists and engineers, for example. But in the vast majority of cases, these outputs are inputs into further development. It is virtually impossible to extrapolate the impact of a single research program forward through multiple levels of development and commercialization because of the resulting technology's combination with other technologies to make an eventual impact on economic growth or some societal goal. But for research toward a broad technology goal, such as clean energy, assessment of the relative contributions of research projects or programs can be made at a level sufficient to track progress toward the broad objective.

Because multiple technologies often need to be investigated in the early phases of an R&D project, support for a diverse portfolio of research is beneficial. Indeed, multiple technologies may eventually be combined into a final technology system. To manage diverse research studies at an early stage of technological development, prospective analysis is essential. That is, strategic planning is as important as retrospective impact analyses. Strategic planning studies that examine the entire technology base in question can also identify gaps in the existing technology platforms and infratechnologies.

Another crucial issue with the use of metrics to assess research quality and impacts, one stressed throughout this report, is that knowledge from basic research often underpins applied research. In this way, the benefits of basic research—the discoveries, the infrastructure, the networks, and the scientific workforce—enable applied research, with multiple feedback loops. The value of applied research is in part the value of the underlying scientific knowledge from basic research. This point is illustrated by the decades of basic research leading up to the discovery of an algorithm for Google's search technology (see Box 4-1), which followed the emergence of a series of university-developed and government-funded Web browsers such as Lycos and Netscape. Knowledge from basic research allows for the continuous evolution of science. Today's research is performed in dramatically different ways than it was 10 years ago, thanks to enhanced

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[11] One exception is NIST, which has conducted many prospective and retrospective economic studies, as well as studies of impact assessment methodology. More recently, the U.S. Department of Energy has invested in the development of an evaluation framework to guide future impact studies.

BOX 4-1
Case Study: Google's Page-Ranking Algorithm

On the morning of January 10, 1997, there were no festivities to mark the world's transition into the age of Google. Only a U.S. provisional patent application filed by Stanford University Ph.D. student Lawrence Page marked the occasion. The patent had a somewhat obscure title (*Method for Node Ranking in a Linked Database*) that blended with those of the other technical applications filed that day. But 16 years later, the page-ranking algorithm underlying Google's search technology has transformed people's daily lives.

It is clear from Page's original patent application that he did not invent the algorithm overnight. The invention drew heavily on multiple discoveries spanning nearly 45 years of social and information sciences research—discoveries made possible by research and development (R&D) funding from four federal science agencies and protected by a handful of seemingly unrelated patents awarded to a university (Carnegie Mellon), corporations (AT&T, Libertech, Lucent, Matsushita), and industrial laboratories (AT&T Bell Laboratories).

Much of the supporting research depended on federal research funds. The original patent application acknowledges support from a National Science Foundation (NSF) grant to the Stanford Digital Libraries project. That acknowledgment was eventually expanded to include three earlier NSF grants that extend back to 1974 and span fields of science as seemingly abstruse as centrality measures, analyses of prominence in international article citation networks, and methods for crawling and cataloguing websites. Twenty research articles cited by Page, covering highly abstract topics such as hypertext link structures, information retrieval, databases, bibliometrics (citation analysis), and social networks, were supported by federal funds from NSF, the National Library of Medicine, the National Institutes of Health, and the National Aeronautics and Space Administration.

The citations in Page's patent application illustrate the timeless nature of scientific research. The underlying logic of Google's page-ranking algorithm, for example, is analogous to the 1953 idea that people's social status increases when they are acknowledged by others who are themselves of high status. In 1965, a researcher examined connections among people to identify flows of social influence and then used those measures to identify social cliques. In 1986, a group expanded this work to differentiate between social statuses that are reflected back *through* a relationship and those that are derived *from* a relationship. Unbeknownst to these early scientists, their research would one day form the underpinnings of one of the most transformative innovations in recent history.

instrumentation, advances in high-throughput data, the evolution of business models, and the emergence of platforms such as the human genome database and open-access databases.

Maintaining the expertise of those who conduct world-class research also sustains the innovation system because technological problems frequently arise in the development of an innovation that must be solved through research. In this way, research and innovation are symbiotic, as illustrated by the case study in Box 4-2. Similarly, many aspects of manufacturing contribute to and draw on research (Pisano and Shih, 2012).

Is it possible that scientists who laid the groundwork for Google or wireless communication or their peers, or any metrics available today for that matter, could have predicted the multimillion dollar value of their original work? Is it possible to predict which projects undertaken today will lead to unfathomable transformations in the lives of future generations? Will metrics help protect seemingly obscure projects that could one day hold the key to these transformations, or will they encourage their dismissal? These are the kinds of questions raised by the case studies in Boxes 4-1 and 4-2.

Bibliometrics, for example, would not have flagged the supporting citations in the patent application for Page's Google search algorithm (see Box 4-1) as particularly high impact during the years surrounding the initial appearance of those publications. Page's discovery of the algorithm itself was first reported in *Computer Networks*, an archival journal with a relatively low impact factor (a measure of the average number of citations of articles published in the journal) of 1.2, as determined by the Institute for Scientific Information.

What, then, about metrics for talent? Clearly, the importance of talent cannot be overstated. But it also cannot be fully captured by metrics available today, particularly by counts of academic degrees. Page, for

BOX 4-2
Radio Astronomy and Wireless Communication

This case study illustrates how an application of research—the processing of signals over telephone lines—led to basic research on more efficient processing methods, which led in turn to discoveries in radio astronomy and to many innovations, including wireless communication.

The fast Fourier transform, a statistical technique, was developed by James W. Cooley and John W. Tukey at Bell Laboratories for the efficient analysis of sound waves to improve the transmission of conversations over telephone lines. The technique enabled the solution of signal processing problems in real time, at the rate at which the signal was received.

The technique was later used by radio astronomers to discern signals from background noise. John O'Sullivan developed a key patent of the technique as the result of a failed experiment aimed at detecting exploding mini black holes. The technique later enabled wireless transmission, whose development had been impeded because of the interference of signals with their reverberations off of objects in their path.

example, is as talented as they come, but he never earned a Ph.D., leaving Stanford with a master's degree before assuming the role of Google's founding CEO.

The committee found that no high-quality metrics for measuring societal impact currently exist that are adequate for evaluating the impacts of federally funded research on a national scale. We reviewed many metrics designed to measure the societal impacts of research, including those proposed and used by other countries, and found them to be useful for certain purposes but of limited utility for drawing broad conclusions about the American research enterprise as a whole. Each metric describes but a part of the larger picture, and even collectively, they fail to reveal the larger picture. Moreover, few if any metrics can accurately measure important intangibles, such as the knowledge generated by research and research training.

Furthermore, previous studies have shown that innovation and failure go hand in hand—another key point emphasized throughout this report—and that metrics can limit the possibility of transformative innovation by fostering an avoidance of failure to make the metrics look good. A study by Azoulay and colleagues (2010) compared 73 Howard Hughes Medical Institute (HHMI) investigators and a matched control group of similarly accomplished NIH-funded researchers. The authors initiated the study to test the hypothesis that NIH-funded researchers were deterred from taking risks because of that institution's rigid expectations of outcomes, its short review cycles of about 3 years, and grant renewal policies that discourage taking risks that could result in failure. By contrast, HHMI researchers have greater flexibility in their efforts; are encouraged to focus on long-term outcomes; and work in 5-year cycles, which are more tolerant of failure. The HHMI researchers also undergo a more engaging and informal first review after 5 years. Azoulay and colleagues standardized publication outputs from these two groups of researchers using statistical methods.[12] They discovered that HHMI researchers produced 96 percent more high-impact papers and 35 percent more low-impact papers compared with NIH researchers. In addition, HHMI researchers were awarded six times as many grants and introduced more new keywords into their fields of science. These findings suggest that flexibility and stability in funding, along with a culture that tolerates failure, may inspire researchers to pursue riskier and more innovative research with a greater chance of failure but also a greater likelihood of transformative impact. More formal qualitative judgments about relative risks assumed by dif-

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[12] Using a combination of propensity-score weighting and difference-in-differences estimation strategies.

ferent research programs or portfolios could potentially enable similar evaluations.

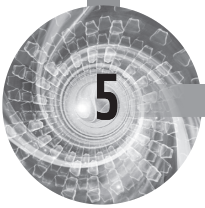
Finally, metrics are only as good as the questions to be answered. They are most effective when their definitions and specific uses have been spelled out clearly in advance.

THE NEED TO MOVE BEYOND CURRENT INDICATORS

There are countless indicators of research performance. As described in Chapter 5, the success of research universities, for example, can be measured by examining university enrollment, NRC research rankings, and graduation statistics. The extent to which scientific knowledge is exchanged can be assessed through bibliometric and social network analyses, which rely on journal publications and citations. In the presence of clear university-defined goals, measuring the patents, licenses, and other products of university technology transfer offices can help identify areas for improvement when these measurements are compared among multiple universities or followed over time.

The real challenge, however, lies in assessing the value of knowledge itself. And the ultimate value of knowledge is equivalent to the people using it and the ways in which it is being used. While scientific impacts must be measured according to the final products of knowledge generation—the commercialization of research discoveries, for example—we suggest that these impacts might be further enhanced by focusing greater attention on the means to these ends. Achieving this focus requires more than counting publications, patents, and other traditional measures of research productivity: it requires cultivating a better understanding of the complex system that is the U.S. research enterprise to determine how all of its component parts interrelate, a theme that is explored in detail in Chapter 6.

In the next chapter, we describe some efforts to evaluate the impacts of research and innovation. We also outline the studies that need to be carried out to improve the ability to assess research impacts.



5

Measuring Research Impacts and Quality

KEY POINTS IN THIS CHAPTER

- Metrics are used by various nations, by various types of organizations (e.g., public research universities, private industry), and for various purposes (e.g., to measure research impacts retrospectively, to assess current technology diffusion activities, to examine the return on investment in medical research). However, no metric can be used effectively in isolation.
- Industry tends to rely heavily on metrics and expert judgment to assess research performance. Because the goals of the private sector are different from those of the public sector, however, metrics used by industry may not be appropriate for assessing public-sector research activities.
- Universities often use metrics to make the case for annual budgets without infrastructure to analyze research outcomes over time. Alternative measures focus on presenting the income earned from and expenditures devoted to technology transfer activities, tracking invention disclosures, reporting on equity investments, and tracking reimbursement of legal fees.
- Many problems can be avoided if evaluation is built into the design of a research funding program from the outset.

Chapter 4 details the challenges of using existing metrics and existing data, even data from large-scale programs such as Science and Technology for America's Reinvestment: Measuring the Effect of Research on Innovation, Competitiveness and Science (STAR METRICS), to measure research impacts and quality. Despite these challenges, a number of attempts have been made to make these measurements. In preparing this report, the committee drew on a number of relevant studies in the literature. Among the most useful was a recent study (Guthrie et al., 2013) by the RAND Corporation, *Measuring Research: A Guide to Research Evaluation Frameworks and Tools*, which is summarized in Appendix C and cited frequently in Chapter 4. We also relied on previous National Research Council (NRC) reports, including a report on innovation in information technology (IT) informally known as the "tire tracks" report (National Research Council, 2012a) and a summary of a recent workshop (National Research Council, 2011b) on measuring the impacts of federal investments in research. In this chapter, we review some of the relevant studies; we also examine the use of metrics by selected governmental, industry, and nonprofit organizations, pointing out the purposes for which these metrics are useful, as well as those for which they are not.

USE OF METRICS BY OTHER NATIONS

Many nations other than the United States, such as Australia, Canada, and the United Kingdom, and have struggled with the challenge of measuring research returns, and the committee drew substantially on the literature on those efforts. As noted in Chapter 3, the benefits of scientific research require extensive time to percolate and may not come to fruition for decades or even centuries. Canada's National Research Council states:

> No theory exists that can reliably predict which research activities are most likely to lead to scientific advances or to societal benefit (Council of Canadian Academies, 2012, p. 162).

This conclusion is particularly accurate because science is constantly changing in unpredictable directions. For example, progress in the IT field may depend on economics and other social science research on keyword auctions, cloud pricing, social media, and other areas. Economics and other social sciences are becoming even more critical fields of research with the increasing importance of understanding human and organizational behavior, which is needed to enable the adoption of new technologies. As a result, the social sciences are valuable contributors to interdisciplinary research and education.

Metrics have been developed that span multiple disciplines and countries. Nonetheless, the development of universal evaluation systems has proven challenging, in particular because of variations in policies, research funding approaches, and missions (National Research Council, 2006). The United Kingdom's Council for Industry and Higher Education describes three other factors that complicate the accurate assessment of publicly funded research impacts: (1) the influence of complementary investments (e.g., industry funding); (2) the time lag involved in converting knowledge to outcomes; and (3) the skewed nature of research outcomes, such that 50-80 percent of the value created from research will result from 10-20 percent of the most successful projects (Hughes and Martin, 2012). This last constraint might be addressed by analyzing the funding portfolios of each funding agency by research and development (R&D) phase/type and by assessing the behavior of individual researchers in addition to using outcome-based assessments (Hughes and Martin, 2012).

The Australian Group of Eight (Rymer, 2011) notes additional barriers to assessing research impacts: research can have both positive and negative effects (e.g., the creation of chlorofluorocarbons reduced stratospheric ozone); the adoption of research findings depends on sociocultural factors; transformative innovations often depend on previous research; it is extremely difficult to assess the individual and collective impacts of multiple researchers who are tackling the same problem; and finally, it is difficult to assess the transferability of research findings to other, unintended problems. Equally difficult to measure is the ability of research to create an evidence-based context for policy decisions, which is important but poses a formidable challenge (Rymer, 2011; National Research Council, 2012e).

Even when effective indicators and metrics are developed, their use to determine which research projects should be funded inevitably inspires positive and negative behavioral changes among researchers and research institutions (OECD, 2010), an issue noted also in Chapter 4. In Australia, Norway, and the United Kingdom, incorporating the number of publications into the grant review process led to a significant increase in publication output (Butler, 2003; Moed et al., 1985; OECD, 2010). This might be viewed as a positive effect except that in some cases, this increase in output was followed by a decline in publication quality as researchers traded quality for volume. (The quality of a research publication often is assessed by the quality of the journal in which it is published, which may depend on how widely cited the journal is. This can be problematic because the top research in some fields is presented at conferences, not published in journals, and not every study published in high-impact journals is exemplary of high-quality or high-impact research.) This negative effect was more pronounced in Australia than in Norway or the United Kingdom, as the latter nations rely on metrics that account for quality as well as quantity (Butler, 2003).

While metrics based on both quantity and quality have generally proven useful to other nations, two issues have arisen: the potentially subjective definition of a "high-quality" journal, and the difficulty of determining whether widely cited journals are in fact better than specialized or regional journals (Council of Canadian Academies, 2012). For instance, China provides strong incentives to publish in international and widely cited journals; researchers receive 15 to 300 times larger financial bonuses for research published in *Nature* or *Science* compared with that published in other journals (Shao and Shen, 2011). As described by Bruce Alberts in an editorial in *Science* (Alberts, 2013), however, the San Francisco Declaration on Research Assessment[1] acknowledges the potential of journal impact factors to distort the evaluation of scientific research. Alberts asserts that the impact factor must not be used as "a surrogate measure of the quality of individual research articles, to assess an individual scientist's contributions, or in hiring, promotion, or funding decisions."

Serious consequences—both positive and negative—can occur when governments use metrics with the potential to change researchers' behavior. Researchers and institutions can focus so intently on the metric that achieving a high metric value becomes the goal, rather than improving outcomes. In some cases, there is documented evidence of researchers and institutions resorting to questionable behavior to increase their scores on metrics (Research Evaluation and Policy Project, 2005). A recent survey published in *Nature* revealed that one in three researchers at Chinese universities have falsified data to generate more publications and publish in more widely cited journals. Some Chinese researchers report hiring ghostwriters to produce false publications (Qiu, 2010). Aside from ethical concerns, such practices have presented serious problems for other researchers in the field, who unknowingly have designed their own research studies on the basis of false reports in the literature. Another negative though less serious outcome occurred when the Australian Research Council incorporated rankings for 20,000 journals, developed through a peer review process, into its Excellence for Research in Australia (ERA) initiative (Australian Research Council, 2008). One year after being developed, the ranking was dropped from ERA because some university research managers were encouraging faculty to publish only in the highest-ranking journals, which had negative implications for smaller journals (Australian Government, 2011).

Additional concerns regarding the development and implementation of metrics have revolved around training and collaboration. The United Kingdom found that use of the Research Assessment Exercise (RAE), a peer-reviewed tool for assessing research strength at universi-

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[1] The Declaration is available from http://am.ascb.org/dora/ [August 2014].

ties, significantly affected researchers' morale as certain researchers were promoted as being "research active," while some departments were dissolved because of poor reviews (Higher Education Funding Council of England, 1997; OECD, 2010). Researchers also have noted that the RAE discourages high-risk research because of its focus on outputs, and that it also discourages collaboration, particularly with nonacademic institutions (Evaluation Associates, Ltd., 1999; McNay, 1998; OECD, 2010). Another commonly used metric, previous external research funding, has been criticized by the Council of Canadian Academies as being subjective because of the nature of previous expert judgment and funding decisions (Council of Canadian Academies, 2012). Using funding as a criterion also poses the risk of allowing outside money to drive research topics (e.g., pharma funding for positive drug evaluation), as well as rewarding inefficient and costly researchers who ask for more money. Additional indicators, such as previous educational institutions attended by students and esteem-based indicators (e.g., awards, prestigious appointments) have been criticized as being subjective in countries such as Canada and Australia. Performance on these indicators may be influenced by external factors such as geographic location and personal choice rather than the institution's quality, and the quality of a researcher's work at the time of funding of a previous award may not characterize his or her current accomplishments (Council of Canadian Academies, 2012; Donovan and Butler, 2007).

IMPACT ASSESSMENTS IN THE UNITED KINGDOM

A review of UK research impact studies by the chair of the Economic and Social Research Council (ESRC) Evaluation Committee notes that so-called "knowledge mobilization"—defined as "getting the best evidence to the appropriate decision makers in both an accessible format and in a timely fashion so as to influence decision making"—can help overcome major impediments that would otherwise limit the economic and social impacts of high-quality research (Buchanan, 2013, p. 172). Beginning in the 1990s, a growing body of evidence in the United Kingdom (Griffith et al., 2001; Griliches, 1992; Guellec and van Pottelsberghe de la Potterie, 2004) suggested that the economic returns of research were limited by researchers' weak attention to knowledge transfer. A 2006 report (Warry Report, 2006) strongly urges research councils to take the lead on the knowledge transfer agenda, to influence the knowledge transfer behavior of universities and research institutes, to better engage user organizations, and to consider metrics that would better demonstrate the economic and social impacts of scientific research. These metrics, it is argued, should assess research excellence as well as the relevance of research findings to user needs, the propensity for economic benefits, and the quality of the relationship between research findings and their likely users (Warry Report, 2006, p. 19).

A report commissioned by Universities UK (2007) and a related paper (Adams, 2009) suggest that the research process might be aptly evaluated by being considered in terms of "inputs–activity–outputs–outcomes." Moreover, indicators for one field of science may not be strong tools for assessing other fields. For example, bibliometric tools were found to be strong indicators of performance in some areas of the social sciences, such as psychology and economics, but not in more applied or policy-related areas. Publication counts were found to be similarly problematic, as they give an idea of a researcher's output volume but do not reflect research quality or the potential for social or economic impact (Adams, 2009). In recognition of these findings, the Research Excellence Framework (REF) assessment[2] in the United Kingdom will consider citation data in science, technology, engineering, and mathematics fields but not in the social sciences.

The ESRC issued a report (Economic and Social Research Council, 2009) identifying several drivers of research impact, including networks of researchers, the involvement of users throughout the research process, and the supportiveness of the current policy environment. A subsequent ESRC report suggests a more comprehensive picture of the interactions between researchers and policy makers might aid efforts to track the policy impacts of research (Economic and Social Research Council, 2012).

On the basis of this literature, the ongoing effort to develop an REF assessment promotes greater knowledge mobilization by compelling academic researchers to engage with the public and demonstrate more clearly the economic and social implications of their work. Current efforts are aimed at ensuring that the quality of research is not compromised by the emphasis on impact and open-access data. It remains to be seen whether and how this latest introduction of new incentives and measurement schemes in a highly centralized national research funding system will create perverse incentives for UK researchers, leading gifted scientists to devote more time to lobbying policy makers or industry managers, or whether it will enhance the impacts of the country's publicly funded research. Nonetheless, these new evaluation measures likely have some potential to distort researchers' behavior and reduce rather than increase positive research impacts.

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[2] In 2007, the United Kingdom announced plans to establish the REF to gauge the quality of research in the nation's institutions of higher education. According to the REF's official website (http://www.ref.ac.uk/faq/ [August 2014]), the 2014 version of the REF will replace the nation's former system, the RAE.

USE OF METRICS TO EVALUATE THE ECONOMIC RETURNS OF MEDICAL RESEARCH

Some major studies have sought to measure the economic returns on investments in medical research. In the United States, the Lasker Foundation supported a study leading to the 2000 report *Exceptional Returns: The Economic Value of America's Investment in Medical Research* (Passell, 2000). In this report and a subsequent volume (Murphy and Topel, 2003), a number of economists describe the "exceptional" returns on the $45 billion (in 2000 dollars) annual investment in medical research from public and private sources and attempt to estimate the economic impact of diagnostic and treatment procedures for particular diseases.

The economic value of medical research was assessed by monetizing the value of improved health and increased life span (i.e., by adapting data from work-related studies performed in the 1970s-1990s), then isolating the direct and indirect impacts of medical research from gains unrelated to R&D (i.e., by accounting for the total economic value of improved survival due to technologies and therapies). The report offers the widely criticized calculation that increases in life expectancy during the 1970s and 1980s were worth a total of $57 trillion to Americans, a figure six times larger than the entire output of tangible good and services in 1999 (the year prior to the report's publication). The gains associated with the prevention and treatment of cardiovascular disease alone totaled $31 trillion. The report suggests that medical research that reduces cancer deaths by just one-fifth is worth approximately $10 trillion to Americans—double the national debt in 2000. The report states that all of these gains were made possible by federal spending that amounted to a mere $0.19 per person per day. Critics of the report note that it simply attributes outcomes in their entirety to investments in medical research without considering, for example, how the returns on medical research in lung cancer might compare with the equally poorly measured returns on education in smoking cessation.

Researchers in Australia (Access Economics, 2003, 2008) sought to replicate this U.S. study. The first such study, which used the same value for a year of life as that used in the U.S. study, led to some anomalies. By using disability-adjusted life years (DALYs), a measure that accounts for extended years of life adjusted for the effects of disability, this study suggests that the value of mental health research was negative because of the decline in DALYs for mental health. A second Australian study used a different methodology, comparing past research investments with projected future health benefits and basing the value of life on a meta-analysis of studies.

In the United Kingdom, the Academy of Medical Sciences, the Medical Research Council, and the Wellcome Trust commissioned research to assess the economic impact of UK medical research. According to the report:

> The overall aim of the work was to compare the macroeconomic benefits accruing from UK medical research with the cost of that research—ultimately to give a quantitative assessment of the benefit of medical research to the UK. It was also expected that the research would critically appraise both the selected approach and previous attempts to estimate the economic returns from research. In this way, the goal was not to obtain a definitive answer about the returns on the investment in UK medical research, but to generate a piece of work that would help to move this young field forward and inform methodologies for future assessments (Health Economics Research Group et al., 2008, p. 3).

The study focused on cardiovascular disease and mental health. It used a "bottom-up" approach based on evidence on the "effects and costs of specific research-derived interventions, rather than [on] macro-level, temporal changes in mortality or morbidity" (p. 5).

These and other studies, including work by the Canadian Academy of Health Sciences (Canadian Academy of Health Sciences, 2009) and for the World Health Organization (Buxton et al., 2004), raise many issues concerning the valuation of research aimed at improving health:

- *Measuring the economic returns on research investments*—Approaches include using a benefit/cost ratio (ratio of the value of health benefits to the costs of research), a return on investment (ratio of the amount by which health benefits exceed research costs to research costs), or an internal rate of return (IRR, the rate of return for which net present value is zero or alternatively, the discount rate at which the net present value of research costs equals the net present value of health benefits over time). The UK study used IRR.
- *Valuing health benefits*—Examples include using a monetary value for a year of life or a quality-adjusted year of life, direct cost savings for health services, indirect cost savings when improved health leads to productivity increases, or increases in gross domestic product or other economic gains. These efforts, however, are widely criticized.
- *Measuring the costs of research*—Questions that arise include how costs of research are determined; how infrastructure is accounted for; whether measures of public and private research costs are comparable; and how the effect of research failures, which, as noted earlier, may advance knowledge, can be accounted for.

- *Time lag*—The appropriate time lag between research and health benefits must be determined.
- *Global benefits*—Issues include identifying the global health benefits from U.S. research and the health benefits that accrue to the United States from research in other countries, and determining how such international transfers of research knowledge should be accounted for.
- *Attribution*—It is difficult to disentangle how much of health improvement can be attributed to health care, as opposed to improved hygiene, diet, and other behaviors; to what extent behavior changes to improve health can be attributed to behavioral and social science research; and how the contributions of behavioral and social science research to improved health can be distinguished from those of medical research on therapeutics.
- *Intangibles*—The extent to which research in a health care system increases the system's capacity to use research findings is difficult to understand (Belkhodja et al., 2007).

USE OF METRICS IN ECONOMIC IMPACT ASSESSMENTS OF FEDERAL PROGRAMS

Given that, as noted earlier, the results of basic research are largely public goods, the federal government funds a large portion of this research in the United States. There are also reasons why government funding may be needed for some technologies that have both public and private characteristics. These reasons include long gestation periods; the inability to capture the full economic value of an R&D investment; broad scopes of potential market applications; coordination difficulties among the various private-sector entities that must conduct the R&D and eventually integrate the resulting component into the final technology system; and the inability (often due to small firm size) to price an innovation at a level sufficient to rationalize the investment, assuming the generally large technical and market risks associated with R&D investments (Tassey, 2014).

As previously discussed, the typical industrial technology is a complex system combining multiple hardware and software technologies. Many of these component technologies are derived from multiple areas of science and developed by a range of public and private entities. The complex genealogy of many innovations of great economic value reflects the fact that private firms may lack sufficient incentives (e.g., assurance of a return on their investment) to support the development of technological knowledge of a quasi-public good nature, including standards and research infrastructure, or "infratechnologies" (see Chapter 2). Without adequate and timely investment in these technology elements, industry's investment in proprietary technologies or other innovations will be both inadequate and inefficient.

Federal R&D policy has implicitly embraced investment to overcome these market failures for agencies whose R&D targets social objectives such as defense (U.S. Department of Defense [DoD]), health (National Institutes of Health [NIH]), and energy (U.S. Department of Energy [DoE]). Thus, DoD funds technology platform research through the Defense Advanced Research Projects Agency, and DoE funds similar research through the Advanced Research Projects Agency-Energy. DoE also funds considerable research in measurement infratechnology and standards.

The National Institute of Standards and Technology (NIST), part of the U.S. Commerce Department, also focuses on infratechnology research. NIST undertook economic impact studies in the 1990s to demonstrate the value of its research. Over the past 20 years, it has conducted 40 such retrospective studies across a wide range of technologies that it supports. To undertake such studies, NIST had to choose a set of metrics from among three basic alternatives (see Figure 5-1):

- measures to guide public R&D policies such as allocation of resources, including those that influence investment decisions by firms and businesses (a process measure);
- measures to guide private industry investments in R&D, such as net present value, return on investment, and benefit-cost ratio (an output measure); or
- measures with which to evaluate the research and innovation systems, such as productivity growth, employment growth, and other economic and societal impacts (an outcome measure).

Because the focus of impact assessment was at the program level and evaluation budgets were limited, NIST chose the middle ground—the set used in corporate finance. Under the circumstances (no government-wide guidance and limited resources), this approach yielded the most useful quantitative impact data. NIST's impact reports also provide considerable qualitative analysis, which is essential for interpreting the quantitative results and placing them in context.

USE OF METRICS TO EVALUATE DEPARTMENT OF ENERGY (DOE) FOSSIL FUEL R&D PROGRAMS

At the committee's third meeting, Robert Fri of Resources for the Future discussed a retrospective study that looked at DoE-sponsored research from that agency's inception through 2000 (National Research

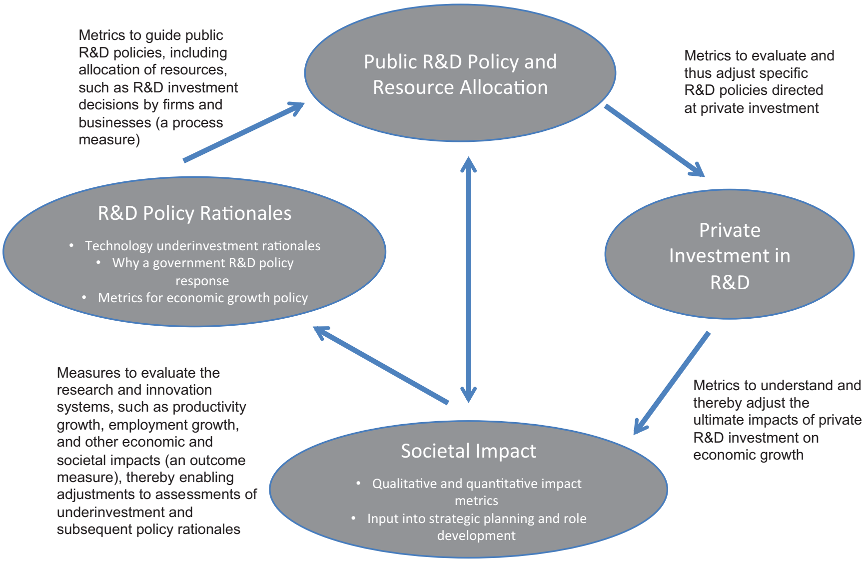

FIGURE 5-1 Influences of processes, outputs, and outcomes on research impact. NOTE: Role rationalization and impact assessment are part of a recursive process. Both must be modeled correctly and their interactive nature recognized, as depicted in this figure. The conceptual argument for federal R&D funding (the existence of market failure) must be tested through economic analyses of industry investment patterns and the causes of any underinvestment trends determined. Such analysis leads to the design and implementation of policy responses, which are followed by periodic economic impact assessments. The results of these assessments then feed back into adjustments of existing policies and associated budgets, as indicated in the figure.

Council, 2001), as well as two prospective evaluations of DoE applied R&D (National Research Council, 2005b, 2007b). The 2001 NRC study in particular used an evaluative framework that emphasized three types of benefits from DoE-sponsored R&D in energy efficiency and fossil fuels: (1) the economic benefits associated with technological advances attributed to the R&D; (2) the "option value" of the technological advances facilitated by the R&D that have not yet been introduced; and (3) the value of the scientific and technological knowledge, not all of which has yet been embodied in innovations, resulting from the R&D. Like most such retrospective studies, the 2001 study faced challenges in attributing these three types of benefits to specific DoE R&D programs, since substantial investments in many of the technologies were made by industry. An important source of the estimated economic benefits of DoE R&D pro-

BOX 5-1
Shale Oil Recovery

The potential importance of shale oil and gas has been known for more than a century, but only in the past decade have oil companies been able to access this vast resource. The booming industry that exists today was built on technologies that took decades to amass.

Today's industry arose largely from federal investments in research and development (R&D), and two investments in particular: (1) a government-industry partnership known as the Gas Research Institute, and (2) a series of programs (e.g., the Eastern Gas Shales Program) developed by the present-day U.S. Department of Energy (DoE) to support research on high-risk energy sources. The three technologies at the core of the DoE investment were horizontal drilling, fracturing technology, and 3D seismic imaging.

The federal government invested approximately $187 million in the above programs, which generated an estimated $705 million in revenues to the gas industry (in 2001) and $8 billion in savings to consumers (National Research Council, 2001). This technology is not without controversy, however. Although natural gas is cleaner than coal, environmental problems still exist. Along with the increased benefits of shale oil extraction may come increased risks to society, including possibly disruption to the water table, which scientists today are exploring (Council of Canadian Academies, 2014; National Research Council, 2013e, 2013f).

grams was the programs' contributions to accelerating the introduction of the innovations studied.

The attempt in the 2001 report to highlight the "options value" of technological advances points to another type of benefit that is difficult to capture in retrospective evaluations of R&D investments but is important nonetheless: in a world of great uncertainty about economic, climatic, and technological developments, there is value in having a broad array of technological options through which to respond to changes in the broader environment.[3] The DoE programs examined in the 2001 study produced a number of innovations that were not introduced commercially simply because their characteristics and performance did not make them competitive with existing or other new technologies. But there is a definite value associated with the availability of these technological alternatives or options in the face of an uncertain future (see Box 5-1 for a discussion of shale oil extraction technologies, many of which benefited from DoE and other federal R&D but have been applied only in the past decade).

Deriving a quantitative estimate of the "option value" of such inno-

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[3] Other academic studies of the options value of R&D investments include Bloom and van Reenen (2002) and McGrath and Nerkar (2004).

vations, however, is very difficult precisely because of the uncertainty about conditions under which they might be of use (this is an important difference between the value of financial and technological options). As with other retrospective evaluations, however, it was impossible to incorporate any quasi-experimental elements into the assessment scheme for these DoE programs. No effort was made to examine the question of what would have happened had these programs not existed (e.g., whether similar investments in R&D would have come from other sources). There was also no attempt to compare firms that exploited the results of DoE R&D with some type of "control" population, for obvious reasons. These limitations are hardly critical or fatal, but they illustrate the challenges of developing designs for R&D program evaluation that approximate the "gold standard" of randomized assignment of members of a population (of firms, individuals, institutions, etc.) to treatment and control groups.

The 2001 report also includes a detailed set of case studies of DoE R&D programs in the areas of energy efficiency and fossil fuels. Overall, the report states that in the area of energy efficiency, DoE R&D investments of roughly $7 billion during the 22-year life of this program yielded economic benefits amounting to approximately $30 billion in 1999 dollars. DoE fossil energy programs during 1978-1986 invested $6 billion in R&D (this period included some costly synthetic fuels projects) and yielded economic benefits of $3.4 billion (all amounts in 1999 dollars). DoE fossil energy programs during 1986-2000, by contrast, accounted for an investment of $4.5 billion and yielded economic benefits estimated at $7.4 billion (again in 1999 dollars). Many other significant conclusions in the 2001 report concern qualitative "lessons" for program design based on observations of successful and less successful programs.

An important source of estimated economic benefit for the DoE R&D programs examined in the 2001 NRC and related studies was the fact that the innovations that benefited from these federal R&D investments were in use, and their economic payoffs could be estimated relatively directly. Nevertheless, the efforts in these studies to at least highlight (if not quantify) the "options" and "knowledge" benefits of federal R&D investments are highly relevant to the present study.

The 2001 NRC and related studies further conclude that there is a need for broadly based incentives for the private sector to invest in basic research across a wide range of disciplines to increase the odds of success. The government plays an important role in sponsoring high-risk, mission-driven basic research; funding risky demonstration projects; partnering with industry-driven technology programs; and encouraging industry's adoption of new technology.

USE OF METRICS BY PRIVATE INDUSTRY: IBM'S PERSPECTIVE

In his presentation to the committee, John E. Kelly, III, director of research for IBM, noted that metrics are essential tools for ensuring continued growth and competitiveness. To stay on the leading edge of technology, IBM designs metrics and processes around four primary missions: (1) seeing and creating the future, (2) supporting business units with innovative technologies for their product and service roadmaps, (3) exploring the science underlying IT, and (4) creating and nurturing a research environment of risk taking and innovation. In general, most research funding decisions made by IBM rely more heavily on judgment than on quantitative metrics, although the relative importance of qualitative versus quantitative data shifts during the transition from long-term research to near-term development.

Although industry's goals for research differ from those of the government, strategic planning is a valuable way to identify gaps in existing platforms and infratechnologies, as discussed earlier in this chapter. IBM relies largely on a process called the Global Technology Outlook (GTO) to fulfill its mission of seeing and creating the future. Every year, it initiates a corporate-wide effort to look years into the future and shift its strategy based on the technology changes it foresees. As a result, IBM has been inspired to create new businesses, acquire companies, and divest itself of others. The GTO process has proven invaluable in efforts involving long lead times, such as architecture, where a correct or incorrect decision can have profound effects on a company. Metrics are used in the GTO process in an attempt to quantify how many future technology disruptions and business trends will be identified and how many will be missed. These predictive metrics emphasize qualitative information, relying heavily on the judgment of experienced managers and scientists.

To fulfill its mission of supporting business units with innovative technologies for their product and service roadmaps, IBM continually focuses on creating new technologies—innovative hardware or software features—to integrate into its product lines over 2- and 5-year horizons. The metrics used here include near-term and relatively easy-to-quantify outcomes such as product competitiveness and market share. IBM also measures the intellectual property being generated through counts of patents and other means.

According to Kelly, IBM believes a deep understanding of science is essential to making sustained progress; through this understanding, IBM fulfills its mission of exploring the science underlying IT. The company supports large research efforts in hardware, software, and service sciences (i.e., people and technologies organized in a certain way to produce a desired impact). Some of these efforts are enhanced by partnerships with universities, government, and industrial laboratories around the world.

Metrics used to assess progress toward fulfillment of this mission include those pertaining to key publications, recruiting and retention of top scientists, and impact on various scientific disciplines.

Finally, IBM supports its mission of creating and nurturing a research environment of risk taking and innovation by focusing on inputs. It makes a concerted effort to hire the best people and provide them with a large degree of freedom to pursue innovative ideas. According to Kelly, one cannot manage research the way one manages development or manufacturing. When it comes to research, micromanagement is counterproductive to growth, innovation, and competitiveness.

USE OF METRICS BY PRIVATE NONPROFITS: BATTELLE'S PERSPECTIVE

In his presentation to the committee, Jeff Wadsworth, president and chief executive officer of Battelle Memorial Institute, noted that metrics are critically important for guiding research investments and monitoring the success of R&D. Battelle uses metrics throughout the R&D process—from tracking the long-term success rate of its project selection process, to improving the productivity (and therefore capital efficiency) of its R&D activity, to tracking the financial contributions of its innovation system with lagging metrics such as percentage of sales from new products.

However, Wadsworth noted that while certain private-sector management approaches—such as DoD's use of the business process improvement approach known as Lean Six Sigma or the national laboratories' use of private management and operations contractors—may lend value to government research activities, many public-sector research activities require different measures from those used by the private sector since the latter are defined almost exclusively by economics (Cooper, 1986). Wadsworth suggested that economic analysis combined with analyses of future impacts can be used to measure the impact of public-sector research. For example, Battelle's 2011 and 2013 studies suggested that the economic returns of the Human Genome Project have approached a trillion dollars (Batelle, 2013). That analysis, however, has not been universally accepted, in part because it examined only economic activity and not the impact on human health, and it attributed the economic returns to the government's investment when other factors, including private investments in genomics, have contributed (Brice, 2013; Wadman, 2013a).

USE OF METRICS TO EVALUATE THE REGIONAL ECONOMIC IMPACTS OF RESEARCH UNIVERSITIES

Many public research and education institutions have conducted studies of their impact on local, regional, and state economies. Some institutions, such as Massachusetts Institute of Technology (MIT), have commissioned economic impact reports to illustrate these returns. Like many retrospective evaluations, however, such reports contain useful data but are rarely able to address the counterfactual issues that loom large: For example, what would have happened in the absence of a specific set of policies or channels for economic interaction between university researchers and the regional economy?

A 2009 study, *Entrepreneurial Impact: The Role of MIT* (Ewing Marion Kauffman Foundation, 2009), analyzes the economic impacts of companies started by MIT alumni. The analysis is based on a 2003 survey of all living MIT alumni and revenue and employment figures updated to 2006. The study concludes that if all of the companies (excluding Hewlett-Packard and Intel) were combined, they would employ 3.3 million people and generate annual revenues of $2 trillion, representing the 17th-largest economy in the world (Ewing Marion Kauffman Foundation, 2009). In addition, the study offers the following conclusions:

- An estimated 6,900 MIT alumni companies with worldwide sales of approximately $164 billion are located in Massachusetts alone and represent 26 percent of the sales of all Massachusetts companies.
- 4,100 MIT alumni-founded firms are based in California, and generate an estimated $134 billion in worldwide sales.
- States currently benefiting most from jobs created by MIT alumni companies are Massachusetts (estimated at just under 1 million jobs worldwide from Massachusetts-based companies); California (estimated at 526,000 jobs), New York (estimated at 231,000 jobs), Texas (estimated at 184,000), and Virginia (estimated at 136,000).

This study provides an accounting of the economic effects of firms founded by alumni of one research university, MIT. It does not isolate or highlight the mechanisms through which the economic benefits were realized, so one cannot conclude that some of the benefits would not have occurred otherwise. Moreover, research universities contribute to the production of knowledge for the development of new technologies and firms in many ways other than through alumni.

USE OF METRICS TO MONITOR TECHNOLOGY TRANSFER FROM UNIVERSITIES

Universities use various metrics to track the diffusion of technology resulting from the research they conduct (see Appendix B). Most of the metrics widely used for this purpose (e.g., inputs such as collaborations, intermediate outputs such as innovation creation and knowledge acceleration, and final impacts such as qualitative outcomes or economic development) have been criticized as ignoring some of the more important formal and informal channels of knowledge flow to and from universities (Walsh et al., 2003a, b). Examples of these channels include the flow of trained degree holders, faculty publications, sabbaticals in university laboratories for industry scientists, faculty and student participation in conferences, and faculty consulting. It should be noted as well that at least some metrics proposed or implemented for faculty evaluation at some universities, such as patenting, could have effects similar to the use of publication counts in China and other economies: if faculty perceive an incentive to obtain more patents, they are likely to file for more patents; however, the quality of these patents could well be low, and the legal fees paid by academic institutions to protect the rights to a larger flow of patent applications could increase.

Moreover, the appropriateness of commonplace metrics depends largely on whether the goal of the university's technology transfer office is to increase the university's revenue through licensing, to assist university entrepreneurs, to support small firms, to support regional development, to attract and retain entrepreneurial faculty, or any number of other goals. A disconnect often exists between the selection of metrics and the university's broader strategic goals, which can make it difficult to use the metrics to analyze performance or draw comparisons among universities. Box 5-2 elaborates on the value of university technology transfer metrics.

EVALUATION OF RESEARCH FUNDING PROGRAMS

A fundamental question with which the committee grappled was how to assess which research funding programs are effective and how to choose among them to maximize returns to society (i.e., what areas of research should be funded and through what agencies). Addressing this question leads to evaluation of the effectiveness of the wide variety of programs adopted by research funding agencies in the United States to select individuals and groups for research support. The agencies employ two types of approaches—one for selecting recipients of research funding (i.e., prospective assessment) and another for evaluating the performance of those funded (i.e., retrospective evaluation).

Evaluating the effectiveness of a research funding program requires

BOX 5-2
Value of University Technology Transfer Metrics

To assess the value of technology transfer metrics and their utility for assessing the value of research, it is important to understand the nature of many technology transfer offices and the environment in which they operate.

Data from a survey conducted by the Association of University Technology Managers show that, even before subtracting expenses for patenting and staff costs, technology licensing and spin-out equity income averages less than 3 percent of the amount universities spend on research (Nelsen, 2007). Many more than half of university technology transfer programs bring in less money than the costs of operating the program, and only 16 percent are self-sustaining, bringing in enough income that sufficient funds are available to cover the operating costs of the program after distributions to inventors and for research have been made. Most universities that generate technology transfer revenue do so from a limited number of technology licenses, which typically are concentrated in biomedical disciplines (Abrams et al., 2009). Some technology transfer offices operate as service centers aimed at supporting the faculty who are interested in patenting their inventions and seeing them make a difference in the marketplace. As a result, patents are sometimes filed with no expectation of revenue.

Metrics are needed each year to justify budgets, but universities do not have the infrastructure in place to track outcomes over time, except perhaps anecdotally. Output measures are used as proxies in an attempt to assess longer-run outcomes. Measuring outcomes is expensive and requires commitment (staff and funds). Alternative measures focus on identifying the income earned and expenditures devoted to technology transfer activities, tracking invention disclosures, and

a different strategy and different forms of data gathering from those typically used by research funding agencies and program managers. As we have noted, neither the Executive Branch nor Congress has an institutional mechanism for attempting cross-field comparisons or undertaking an R&D budget portfolio analysis.

Moreover, few federal agencies dedicate resources within programs for retrospective evaluation. NIH has a separate evaluation staff that provides guidance to programs, but expects each program to implement its own evaluations. NIH programs tend to fund external research organizations to conduct both process and outcome evaluations early in the program and at about the 5-year point, respectively. Evaluations are rarely conducted beyond this point. The National Science Foundation (NSF) requires an evaluator for some of its grant programs, such as the 10-year Industry-University Cooperative Research Center Program and some of its educational grant programs. The outputs of these evaluation efforts are descriptive statistics and case studies, which are useful for describing reporting on equity investments. These approaches may prove more useful and less expensive than measuring outcomes. As proxies for the success of technology transfer, they help set the stage for informed decision making by stakeholders, although they omit or overlook many of the most important channels through which universities "transfer" knowledge to and from industry.

It is interesting, however, to contrast the approach taken by the Massachusetts Institute of Technology (MIT) study discussed in the text (Ewing Marion Kauffman Foundation, 2009) with the use of "outcome measures" such as those discussed in the previous paragraph. The MIT study, an attempt to provide a long-term evaluation of MIT's economic effects on the U.S. and regional economies (an evaluation that lacked a rigorous experimental design), largely overlooks the intermediate measures captured by most university technology transfer data. Indeed, the MIT study looks solely at a set of outcomes that are fairly removed from the sorts of technology transfer activities that preoccupy so many current critics and supporters of university-industry collaboration. The MIT study contains little information, for example, on the contributions of conventionally measured technology transfer to the establishment of the new firms that are central to the study's measures of economic effects.

Even with its flawed design (which is nearly inevitable in a retrospective study), the MIT study highlights the value of a broad approach that avoids the myopic focus on patents, licensing fees, and invention disclosures that dominates many current discussions of the economic contributions of U.S. universities. Indeed, it is arguable (and ultimately unverifiable) that had MIT focused more narrowly on maximizing institutional licensing revenues during the period covered by the study, the institution's catalytic effects on the formation of new firms by alumni and researchers might have been weaker.

the programs but rarely yield insights valuable for measuring impact. For other programs, NSF follows the same model as NIH and contracts with research organizations to conduct process and outcome evaluations.

Program managers at NIH generally are open to program evaluation. Accessing data is time-consuming and bureaucratic, but once access is obtained, NIH has more data in structured format, which facilitates data analysis. Obtaining access, however, may take several months. As previously noted, in addition to STAR METRICS, NIH research data systems include the Research Portfolio Online Reporting Tools, the Scientific Publication Information Retrieval and Evaluation System, and the Electronic Scientific Portfolio Assistant. NSF data often must first be "scraped" and computer programs (e.g., Python) used to create variables from unstructured text data.

Government-wide mandates such as the Government Performance and Results Act (GPRA) and the Program Assessment Rating Tool have been implemented with good intent, and their language focuses on measuring outcomes and impacts. However, implementation focuses on measuring short-term outputs because they can be measured more easily than longer-term outcomes. Without staff resources dedicated to evaluation, it is difficult to do more. (See National Academy of Sciences [1999, 2011] for discussion of how GPRA has led to federal agency measurement of the performance of research.)

We distinguish between two types of comparison for program evaluation: (1) comparing different research areas, and (2) comparing proposals submitted by individuals or groups of researchers within a research area, either retrospectively or prospectively. The two approaches present very different analytic challenges.

In the committee's judgment, comparisons involving the allocation of funding among widely varied research areas and those involving the assessment of different researchers or groups within a given research field or specialty are conceptually different tasks, and treating them as related or somehow similar is a source of confusion. Programs that allocate funds among different research areas, such as NSF's Science and Technology Centers Program, are more difficult to evaluate than programs that allocate funds among researchers in a specific research area, such as economics research supported by NSF. One reason for this greater difficulty is the many alternative research funding programs with which the program under consideration should be compared. Even the attribution of outcomes may not be clear: If a new research program stimulates a research proposal that is funded by another program, to which program should the outcomes be attributed?

Further complication is introduced by efforts to measure the success of a program, even assuming that a clear set of agreed-upon outcome measures exists. Impact or outcome measures are ideal, but require data that may be impossible or very difficult to obtain at reasonable cost. Finally, it is not always clear that specific outcomes can be attributed to a research funding program when many other factors influence impact.

Guthrie and colleagues (2013) provide a synthesis of existing and previously proposed frameworks and indicators for evaluating research. They note that research evaluation aims to do one or more of the following:

- *Advocate:* to demonstrate the benefits of supporting research, enhance understanding of research and its processes among policymakers and the public, and make the case for policy and practice change
- *Show accountability:* to show that money and other resources have been used efficiently and effectively, and to hold researchers to account
- *Analyse:* to understand how and why research is effective and how it can be better supported, feeding into research strategy and decision making by providing a stronger evidence base

- *Allocate:* to determine where best to allocate funds in the future, making the best use possible of a limited funding pot (pp. ix-x).

In particular, Guthrie and colleagues (2013) reviewed 14 research evaluation frameworks, 6 of which they investigated in detail, and 10 research evaluation tools such as STAR METRICS. Most of these frameworks require data on inputs and outputs, as well as information about the scientific process.

While such evaluation approaches are valuable for many purposes, they do not address the fundamental question that faced the committee: What would have happened without the research funding program, or if the resources had been used on other programs or had been allocated in different ways within the program? Instead, these frameworks look at the allocations within programs and attempt to measure scientific productivity or even innovation, often using publications, patents, or related output measures. These are useful for performance measures (see the discussion in Chapter 6), but even if the outputs are assumed to be surrogates for eventual outcomes, they do not provide an evaluation without a counterfactual.

Research funding programs in which evaluation is built in from the outset are superior to those that attempt evaluation retrospectively, as the latter evaluations often are more prone to unmeasurable biases of various sorts. Few studies or approaches consider the role of formal statistical field studies or experiments with randomization used to control for biases and input differences.

The standard review mechanism for prospective evaluation of research grant and contract proposals is some form of peer review and assessment. Some have criticized peer review for discouraging the funding of high-risk research or radically new research approaches, but more recently, others have criticized it for the dilution of expertise in the NIH review process:

> Historically, study sections that review applications were composed largely of highly respected leaders in the field, and there was widespread trust in the fairness of the system. Today it is less common for senior scientists to serve. Either they are not asked or, when asked, it is more difficult to persuade them to participate because of very low success rates, difficulties of choosing among highly meritorious proposals, and the perception that the quality of evaluation has declined (Alberts et al., 2014, p. 2).

Yet despite the need for improvements in the peer review process, and especially in light of the decreasing success rate for research proposals, there is limited experience with the widespread use by public agencies of alternative mechanisms, and little existing evidence suggests that there is generally a better mechanism. The committee cautions that peer review is not designed to assess overall program effectiveness, but rather investigator qualifications and the innovativeness of individual projects within a given research program. Thus, peer review typically is most appropriate as a means of awarding funding rather than assessing performance. There have been cases, however, in which panels of experts have assessed the outputs of research programs using peer review and other approaches (Guthrie et al., 2013; National Academy of Sciences, 1999, 2011). Some interesting evaluation studies also have been conducted using the methodologies reviewed by Guthrie and colleagues (2013), but they appear to be limited both in focus and in implementation. Other evaluations, such as that by Jacob and Lefgren (2011) using a regression continuity design, appear to be internally focused (i.e., not comparative) and subject to many possible biases.

As an example, consider the NSF Science and Technology Centers Program, aimed at developing large-scale, long-term, potentially transformative research collaborations (National Science Foundation, 2014b). Efforts to evaluate this program have focused primarily on individual center reviews, both for the selection of centers for funding and for the assessment of ongoing effectiveness. Evaluation in this case does not attempt to compare the performance of different centers, nor does it assess the performance of centers funded versus those not funded by NSF (Chubin et al., 2010). Comparing funded centers with those not funded might somehow help, but such a comparison would be limited to an examination of this one program. To our knowledge, there have been no systematic reviews of unfunded center proposals and the research output of the investigators involved in these proposals. Nor has there been any counterfactual analysis of what would have happened had there been no Science and Technology Center funding or of what benefit for science might have been gained had the dollars been spent differently (i.e., on other programs).

Similar to the report by Azoulay and colleagues (2010) mentioned in Chapter 4, a study by Lal and colleagues (2012) evaluates the NIH Director's Pioneer Award (NDPA). The authors set out to answer the following questions: To what extent does the research supported by the NDPA (or the "Pioneer") Program produce unusually high impacts, and to what extent are the research approaches used by the NDPA grantees (or the "Pioneers") highly innovative?

Inevitably the answers to such questions are comparative. Lal and colleagues (2012) conclude that the performance of the first three cohorts of Pioneer Award winners was comparable or superior to that of most other groups of funded investigators—excluding Howard Hughes Medical

Institute investigators, whose performance exceeded that of the Pioneers on some but not all impact indicators (e.g., on number of publications, number of citations per awardee, and journal rankings). Lal and colleagues set out to compare the effects of different funding programs using retrospective matching. Retrospective matching is inevitably inferior to prospective randomization as an evaluation design, and the analyses that use it cannot control adequately for the award mechanisms of the various programs and for the multiplicity of sources of funding that teams of investigators seek and receive. Nevertheless, this study was the best one could do after the fact, given the available information. Building evaluation into the program prospectively might have yielded quite different results.

We have discussed two types of comparison used in research program evaluation—comparing different research areas and comparing proposals submitted by individuals or groups of researchers within a research area, either retrospectively or prospectively. A third type is seen in international benchmarking, which uses review panels to assess the relative status of research fields among countries or regions (National Academy of Sciences, 1993, 1995, 2000). Although international benchmarking can be used to assess whether the United States is losing ground compared with other countries in certain research areas, it is not designed to assess the effectiveness of federal research programs in forestalling such declines. Instead, international benchmarking can only measure outcomes that may be loosely connected with the funding or management of research programs. Moreover, the selection of outcome measures in international benchmarking is even more difficult and controversial than in the other types of comparison.

All three types of comparison also face challenges of attribution of observed outputs, outcomes, or performance. The fundamental statistical tool of randomized experiments could play a role in these comparisons, but it may be feasible only for the first type—comparison of individuals or groups within a research area. Even so, very little evaluation has been conducted through randomized experimentation, and we believe there are both small and large opportunities for wider use of this method. We encourage continuing to experiment with modifications of this approach to evaluation for both prospective and retrospective assessments.

One opportunity for randomization would be to evaluate peer review. Awards could be randomized among proposals near the cut-off point for funding, and the results of both those funded and not funded could be followed up. Or randomization could be used among reviewers of proposals, because once the outliers of exceptionally good- or bad-quality proposals have been determined, variation among reviewers may exceed the variation among proposals.

Regardless of what approach to prospective evaluation of a research funding program is explored, it is preferable to build evaluation into the program from the very beginning. Doing so helps clarify goals and expectations and allows for the collection of important data that might otherwise be missed. If counterfactual models appropriate for the evaluation are defined in advance, data that allow for comparisons with those models can be identified for collection. Advance planning allows for interventions in the program that can be part of the evaluation.

The ideal design of an experiment for an evaluation may be achievable if it is built into new programs, but this approach requires the commitment of scarce funds and talent within federal research programs, including staff trained to carry out, or at least oversee, its implementation. Other requirements of a research program may compete for resources needed for evaluation. A program may be required to allocate all of its funds to awards for research, leaving none for evaluation. In some cases, programs may receive set-aside funds for evaluation, but only years after the program has begun.

Despite the difficulties, evaluation can be built into the design of a research program, as is illustrated by the Advanced Technology Program (ATP) in the Department of Commerce. That program conducted a number of evaluations, including comparisons with firms that had not applied for an ATP grant and with applicants that had applied but not been funded (Advanced Technology Program, 2005; Kerwin and Campbell, 2007). Evaluation was built into the design of the program, with data being collected throughout the life of a project and into its postfunding period.

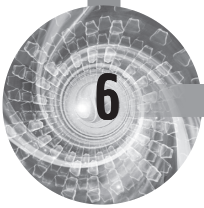
Finally, evaluation can be conducted retrospectively. With this approach, an outcome is observed, and assuming that reasonable evaluators agree on its importance and measurement, the question for evaluation is whether this outcome was due to the research funded by the program. To answer this question, a different form of counterfactual analysis, sometimes referred to as "causes of effects," is necessary. The potential outcomes of alternative treatments (e.g., program structures or portfolios), or at least a framework for speculating about them, need to be specified. This approach often requires many qualifications and assumptions (Dawid et al., 2013).

Regardless of what approach is used for evaluation, it is important to keep in mind the need for careful, controlled, systematic measurement of well-defined concepts:

> Research that can reach causal conclusions has to involve well-defined concepts, careful measurement, and data gathered in controlled settings. Only through the accumulation of information gathered in a systematic

> fashion can one hope to disentangle the aspects of cause and effect that are relevant (National Research Council, 2012e, p. 91).

Investment in scientific research propelled the U.S. economy to global leadership during the Industrial Revolution and again in the more recent Information Revolution. Today, the amount and composition of these assets are changing at an increasingly rapid pace, presenting leading economies, such as the United States, with challenges to maintaining competitive positions in a sufficient number of industries to achieve national economic growth goals, especially in employment and income. The levels, composition, and efficiency of federally funded research need to be adjusted to meet today's circumstances. Better metrics can be developed to inform policy decisions about research. This can be the charge of a government unit with the capability to systematically evaluate the research enterprise, assess its impact, and develop policy options for federally funded research. As noted, however, no federal agency or department currently is tasked with performing policy analysis for research. And as observed in Chapter 2, while NSF's National Center for Science and Engineering Statistics produces valuable data (e.g., *Science and Engineering Indicators*) that could be used in policy analysis, NSF's role differs from that of federal policy analysis agencies or statistics agencies such as the Bureau of Economic Analysis or the Economic Research Service that conduct policy analysis. Therefore, the committee's judgment is that no such institutionalized capability currently exists within the U.S. government.



6

Understanding the Research Enterprise as a Complex System

KEY POINTS IN THIS CHAPTER

- With a holistic understanding of the system of research, government can enable greater benefits from research through policies that address three pillars of the research system: a talented and interconnected workforce, adequate and dependable resources, and world-class basic research in all major areas of science.
- New and existing measures could be used to assess each of the three pillars. These measures might include, for example, indicators of human and knowledge capital, indicators of the flow of knowledge in specific fields of science, indicators with which to track the flow of foreign research talent, portfolio analyses of federal research investments by field of science, international benchmarking of research performance, and measures of research reproducibility.

The committee's findings reveal that the pathways from research to innovation are multiple, diffuse, and interconnected. As described in Chapter 1, innovation is an emergent phenomenon, consistent with the principles of systems theory, which depends on the actions of the system as a whole rather than those of one or two components in particular. Making a change to one component of a complex system can affect other components, often in unpredictable ways. On the other hand, a desired change in the behavior of a system—for example, increased output of new technologies—is unlikely to be achieved by changing one or even a few components without regard to the critical pillars of the system and the relationships among them. That is why a focus solely on technology transfer at universities or on which particular research disciplines to fund might not result in the desired effect and could have potentially undesirable consequences.

We hold that the highly productive American research enterprise rests on three critical pillars—a talented and interconnected workforce, adequate and dependable resources, and world-class basic research in all major areas of science. To understand how these pillars interact to produce research discoveries, one must also understand how knowledge flows among domestic and global networks of individuals and institutions; how research is influenced by the availability of scientific infrastructure, funds, and other resources; how the quality, including the usefulness, of research discoveries is affected by management, research environments, institutions, and peer review; and how all of these aspects interrelate. These topics are not well understood and need to be addressed with future research. Nonetheless, we attempt in this report to enhance understanding of these elements.

As if the complexity of the research system were not challenging enough, it is also necessary to understand how that system interrelates with the innovation system if the development of innovations from research discoveries is to be enhanced. But the story does not end even there. Both the research and innovation systems interact with manufacturing, commercial, legal, political, economic, and other systems.

Despite all this complexity, however, patterns do emerge that can inform policies aimed at achieving further societal benefits from research, and in particular at keeping the United States at the forefront of global competition for new technologies and innovations. Moreover, measures can be developed to guide the effective implementation of those policies. Taking this perspective reveals promising opportunities to increase the benefits of federally funded research to society. This chapter presents an argument for cultivating a greater understanding of the research system through a focus on talent, resources, and basic research, and suggests how measures might be created or adapted to support these three pillars.

UNDERSTANDING THE SYSTEM OF RESEARCH

A complete understanding of the system of research may be elusive, but there are many important aspects of the system that, with proper measures and assessments, can be better understood. Within this understanding, the role of failure must be properly valued. As discussed in Chapter 4, scientific research projects that fail to achieve their original objective nonetheless play extremely valuable roles in the overall research system by providing important training experiences, by contributing to the stock of scientific knowledge, and by redirecting research in what ultimately may be transformative directions.

The committee finds that the key to understanding the research system is how knowledge is

- *Generated*—Research produces value through the generation of a stock of knowledge, which occurs at research universities and other organizations, such as government and industry laboratories, and through team-oriented collaborative mechanisms, such as research consortia and clusters. This knowledge stock is a societal resource whose value depends on developments in the uncertain future. Which knowledge will ultimately prove useful may not be immediately clear, but all knowledge—including that from failures—must remain accessible.
- *Utilized by well-trained and highly talented people*—The workforce trained at research universities—their talent, abilities, knowledge, skills, and experience and the networks of professional connections they have made—is one of the most valuable products of the system of research. These people make use of the stock of knowledge and adapt it to their specific needs, often to society's benefit.
- *Disseminated through networks of researchers and institutions*—The stock of knowledge becomes valuable when it flows to, from, and among people engaged in all forms of research and development (R&D) and when it flows at the right times to the particular places where it is needed most. This flow is made possible by partnerships and networks, as well as by dissemination of information through publications and at conferences. Much knowledge in the early phases of the R&D cycle is somewhat tacit in nature and often is embodied in individual researchers and transferred through interpersonal contact. However, knowledge also is codified to varying degrees in published papers, formal databases, and patents as a research field matures.
- *Affected along the way by external variables*—By producing talented people, networks, partnerships, and other assets, the systems of research and innovation provide almost everything needed to ensure the continued generation, flow, and use of knowledge. But external variables—such as investment and infrastructure, intellectual environment, management, motivations, and incentives—

can enhance or hinder the ultimate success of the research enterprise. And many of the factors that influence the translation of research advances into societal benefit (e.g., labor markets, financial factors, regulation) are themselves well beyond the boundaries of most conventional definitions of the research system.

- *Absorbed and used for economic and other societal benefits*—New societal benefits are realized through a diverse range of public and private entities that provide the complementary assets needed to transform knowledge into products and services and then penetrate markets.

The key to an understanding of the innovation system is how knowledge is used effectively to produce new technologies and other innovations of economic value.

SUPPORTING THE THREE PILLARS OF THE RESEARCH SYSTEM

With a more nuanced understanding of the system of research, government can enhance the public returns on its research investments through policies that address the system's three pillars: a talented and interconnected workforce, adequate and dependable resources, and world-class basic research in all major areas of science. As described by the National Research Council's (NRC) Committee on Science, Engineering, and Public Policy (National Academy of Sciences, 2000) and noted earlier in this report, "major areas" refers to broad disciplines of science and their primary subdisciplines, as well as emerging areas of science. Each of the three pillars supports the research system as a whole, rather than a particular type of research (e.g., basic, applied, or proof-of-concept). The ultimate economic and societal impacts of the research system depend largely on wise and coordinated investment in and management of each of these pillars.

A research system based on talent of high-caliber, adequate and dependable resources, and excellence in basic research is necessary for successful innovations, but it is not sufficient. Also necessary is an innovation system that supports a culture of innovation within firms and among individuals, so that firms and entrepreneurs value creative and unconventional ideas and are willing to take risks, in particular with research investments, and accept failures (Mote, 2013).

Metrics and other measures could be developed to help in understanding whether the government is supporting the three critical pillars successfully. Whereas existing metrics provide limited assistance in answering broad questions about the research system on a national scale (see Chapter 4), the measures described in the following sections could provide valuable insights into trends, gaps, and opportunities for each pillar. In particular, it may be useful to develop a national set of research portfolios and refine existing methods of international benchmarking to better assess the relative global leadership of the United States in these three critical areas.

Many measures for assessing the performance of policies intended to strengthen the three pillars of the research system are identified in the National Research Council (2014) report *Capturing Change in Science, Technology, and Innovation: Improving Indicators to Inform Policy*. That report provides guidance to the National Science Foundation's (NSF) National Center for Science and Engineering Statistics (NCSES) on how its data collection could be improved to guide research and innovation policy and in particular to allow for international comparisons. In this chapter, we draw heavily on that report's discussion of data gaps and measure development, particularly with regard to the strength of the nation's knowledge and human capital.

Below, we describe in more detail the three pillars of the research system. We also present potential measures for assessing the vitality of each.

A Talented and Interconnected Workforce

A talented and interconnected workforce is a critical input to the research system. The U.S. domestic pool of talent relevant to innovation includes individuals that benefit from science, technology, engineering, and mathematics (STEM) education and training, as well as career-technical (i.e., vocational) training. But it also encompasses many other aspects of the system as well, including immigration, professional networks and partnerships, and a supportive and creative research environment that nurtures the creativity and ingenuity of talented researchers (National Academy of Engineering and National Research Council, 2012; National Research Council, 2008, 2010a, 2011a, 2012b; OECD, 2012a). The interconnectedness of this talented workforce, as discussed below in the section on networks, also is key to the success of the research enterprise.

To compete globally, the United States must be able to leverage the expertise of world-class researchers, which will in turn amplify and expedite the nation's capacity for innovation. This can be accomplished by maintaining a strong pool of scientists and engineers familiar with research at the cutting edge, whose networks can broaden their expertise. A large body of empirical and theoretical economic literature has linked innovation activity, including the absorption of technologies discovered elsewhere, to the levels (Benhabib and Spiegel, 2005) or the composition (Manca, 2011; Vandenbusche et al., 2006) of the human capital of an economy. The translation of research findings into new technologies requires people who truly understand research in diverse fields; can make unexpected connections; and can devise counterintuitive solutions to problems related to health, defense, communication, the environment, the economy, and other areas of national concern. A critical variable is the flow of talent from abroad to U.S. research institutions and firms, which can be affected by such variables as the research environment and immigration policies.

The STEM Workforce

American research universities differ from the centralized university systems in many other nations. They must supply highly trained STEM graduates in the numbers and fields needed to support the demand of the U.S. research enterprise. Their ability to do so depends in turn on the pool of K-12 students who prepare for and pursue careers in science and on the foreign students and workers who can be attracted to study and remain in the United States. Their contributions to the U.S. research enterprise further its world-class nature, thus creating a self-reinforcing cycle.

The balance of talent in the STEM workforce remains a controversial topic. Federal agencies such as NSF and the National Institutes of Health (NIH) track information on scientists who receive training awards, but insufficient data are available for determining how best to balance STEM talent by field of science, for example. Some large information technology (IT) firms have encouraged the immigration of people with technology expertise to the United States, claiming a shortage of STEM talent. However, opinions on this strategy differ, and there is ample room for further study of the issue, as evidenced by recent publications (National Research Council, 2012c; The Research Universities Futures Consortium, 2012; Salzman et al., 2013; Stephan, 2012; Xie and Killewald, 2012). An article in *Science* notes the increasing difficulty of retaining students in STEM fields, as many students start but do not finish college with a STEM major (Graham, 2013). Weaknesses in the domestic K-12 system, including those that have the effect of excluding historically underrepresented groups from benefiting from postsecondary STEM education, ultimately diminish the diversity and viability of this talent pool.

Networks

As discussed earlier, basic and applied research leads to the development of national and international networks of researchers, which increase the system's connectivity by linking research groups, disciplines, and institutions across and within national boundaries. For example, one of the important assets of a new graduate is the network of researchers that he or she has developed. Ideas, instrumentation, and analytical methods often are freely shared through these networks. Industries draw on what they learn from these networks to develop new technologies and other innovations and to obtain new ideas and approaches for addressing technological problems they might not otherwise pursue. Research networks increase the stock of knowledge and broaden the range of technological opportunities available for commercialization. And through research networks, particularly peer-to-peer collaborations, the nation can draw on the results of research conducted throughout the world. For a nation to tap into this stock of knowledge effectively, however, it must maintain an enterprise of scientists and engineers conducting world-class research.

Measures for Assessing Talent

The NRC report on science, technology, and innovation indicators (National Research Council, 2014, pp. 6-14) provides guidance on the development and use of metrics to measure networks, as well as human and knowledge capital. It may be possible to create indicators of human and knowledge capital based on existing longitudinal data from agencies and organizations such as the U.S. Census Bureau, NCSES, and the U.S. Bureau of Labor Statistics. Doing so, however, would require the ability to link datasets from each agency.

Indicators could be generated, for example, to track the flow of knowledge in specific fields of science. In addition, indicators of STEM labor mobility could help answer questions about the career progression of scientific researchers and recent STEM graduates by following the movement of individual researchers to posts in industry, government, and academia. In addition, data from full-text dissertation databases could be mined to create indicators for emerging research topics. Doing so might allow for a better match between STEM training and the demand for particular skills.

Adequate and Dependable Resources

Certainly research depends on adequate and dependable funds. But resources encompass much more—in particular, scientific infrastructure, or the tools that allow for research excellence, and world-class research universities, national laboratories, and other research institutions. Dependable resources thus provide critical support for the research process. Resources make it possible for the United States to maintain cutting-edge IT and other scientific infrastructure, the best possible pool of talent, and world-class scientific institutions and means of communication. The case study in Box 5-1 in Chapter 5 illustrates how the combined resources of government and industry can drive an innovation’s success.

Key Features of Adequate and Dependable Resources

Key features of adequate and dependable resources include government support for proof-of-concept research, resource stability, and resources to support all fields of science.

Government support for proof-of-concept research. Policies providing businesses with incentives to undertake long-term or high-risk research, in particular, can help support the pathway from research to innovation. Private industry has a good sense of short- and medium-term needs for which proof-of-concept research would be useful. Government regulations, policies, or incentives, as well as increased public-private partnerships, may encourage private industry to help fill the gap between a research discovery and investment in its use by industry. Industry often is reluctant to fund proof-of-concept research when the risk is high, although there are exceptions, such as the insulin inhaler Exubera® developed by Pfizer and withdrawn from market within the first year of sales (Johnson, 2007). In the current climate, a number of federal research funding agencies have assumed increased responsibility for supporting applied research, particularly high-risk and proof-of-concept research, to bridge this gap (see Box 6-1).[1] The government's role also includes continued support for research that leads to technologies such as those needed by the Departments of Energy and Defense (Mazzucato, 2011).

Some examples of government support for proof-of-concept research are described in Box 6-2. Although Box 6-2 includes a number of these programs, most are relatively new, and their ultimate effectiveness (or survival) is uncertain. Moreover, few such programs that have been in existence for more than 5 years have been rigorously or systematically evaluated to determine their effectiveness.

Resource stability. Policies that help maintain the predictability and stability of federal research funding can boost the infusion of talent into the U.S. research enterprise by encouraging students to pursue STEM careers and discouraging established researchers from leaving their careers. Stable federal funding also helps the U.S. research enterprise attract and retain

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[1] In fact, federal programs such as the R&D and extension programs of the U.S. Department of Agriculture (USDA) have long supported R&D in more applied areas that is designed in part to accelerate the adoption as well as the creation of new technologies. And in the field of aeronautics, the National Advisory Committee on Aeronautics, established in 1919 and the forerunner of the National Aeronautics and Space Administration (NASA), supported "proof-of-concept" R&D in civilian and military aircraft that underpinned such major technological advances as the DC-3. See Ruttan (2001) for a discussion of USDA agricultural R&D or Mowery and Rosenberg (1982).

BOX 6-1
Public-Private Funding and the 3D Printing Boom

The technology for creating three-dimensional objects from a digital model, known as "3D printing," has existed since the 1980s. In 2012, however, this innovation achieved a new level of commercial success thanks to a $70 million combined investment from the federal government and private industry that established the Midwestern town of Youngstown, Ohio, as a manufacturing innovation hub.

In 1984, an engineer named Chuck Hull developed a technology called stereolithography, which uses a robot to stack layer after layer of a material such as plastic, resin, or titanium in an additive process until it produces a three-dimensional object. Hull later cofounded 3D Systems Corporation, which in the early 1990s produced the first stereolithographic machine. The original printer used an ultraviolet laser to solidify each layer of photopolymer, and it demonstrated that complex objects could be manufactured in a matter of hours. By the late 1990s and early 2000s, 3D Systems had established collaborations with academic researchers in North Carolina to create synthetic human organs.

The 3D printers are now used to create everything from synthetic human tissues to footwear, even food. Companies such as General Electric use the printers to create turbine components. A free and open-source software printer produced by the RepRap Project can print individual parts of the printer that can be assembled to generate a continuous supply of the machines. And the company Defense Distributed offers a printable AR-15-type rifle. *The Economist* (2011) has predicted that the long-term impacts of 3D printing will be akin to those of the printing press in the 1400s, the steam engine in the 1700s, and the transistor in 1950.

In 2012, the technology's already booming commercial success was boosted still further when private industry and five federal agencies, led by the Department of Defense, established Youngstown as a hub for 3D manufacturing as a pilot program of the National Network for Manufacturing Innovation, initiated by President Obama to spur the development and adoption of pioneering manufacturing technologies. The program aims to "help to strengthen the competitiveness of existing U.S. manufacturers, initiate new ventures, and boost local and state economies."* The hub in Youngstown is expected to attract venture capitalists and research professionals to the area.

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*More information is available at http://manufacturing.gov/nnmi.html [August 2014].

foreign talent. Stability is particularly important in the wake of fluctuations in research funding due to the American Recovery and Reinvestment Act of 2009 (ARRA) and the recent sequester (see Box 6-3).

Resources to support all fields of science. Priorities for funding research must be established with care so as to sustain the entire U.S. research enter-

BOX 6-2
Federal Government Support for Proof-of-Concept Research

- **National Institutes of Health (NIH), National Center for Advancing Translational Sciences (NCATS)** (budget request, fiscal year [FY] 2013: $639 million): Established in 2011, NCATS initiates collaborations among government, academia, industry, and nonprofit patient organizations to enable faster and more effective translational interventions that improve human health.
- **NIH-Larta Partnership** (budget request, FY 2013: not available): NIH has partnered with Larta to design and deliver a program that helps accelerate Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Phase II awardees' commercialization outcomes. Larta's mentors (mainly venture capitalists) are matched with NIH awardees to develop and deploy business plans for commercializing their NIH-funded technology. Larta also has a Web portal for participating companies that serves as a repository for program deliverables and performance tracking, and provides tools, communications, and updates.
- **National Science Foundation (NSF), Industry/University Cooperative Research Program (I/UCRP)** (NSF contribution, FY 2011: approximately $15 million):* NSF's I/UCRP Program allows industry, government, and other organizations to leverage R&D investments with more than 60 cooperative research centers known for their innovative research capabilities. The program provides an opportunity for research universities to partner with other institutions to conduct industrially relevant research.
- **NSF, I-Corps** (budget request, FY 2013: $18.8 million): I-Corps fosters entrepreneurship to promote the commercialization of technology that has previously been supported by NSF-funded research. The program matches an entrepreneur and an NSF awardee to develop a business plan for commercializing a technology, and provides financial support to the team for the development of a prototype or proof of concept.
- **NSF, Engineering Research Centers (ERCs)** (budget request, FY 2013: $69 million): In 1985, NSF began sponsoring ERCs at universities across

prise, encompassing all fields of science, over the long term. International benchmarking has the potential to reveal scientific areas pursued elsewhere that may not be adequately supported in the United States (National Academy of Sciences, 2000).

The shift in funding over the past 25 years toward biomedical research is shown in Figure 2-3 in Chapter 2. A recent article in *Issues in Science and Technology* (Merrill, 2013) analyzes federal funding by field of science from 2001 to 2011 using data from NSF's federal funds survey. The article shows that since 2001, despite the push to double funding in the physical sciences and engineering under the America COMPETES Act, funding the United States, each in close partnership with industry, to foster technological breakthroughs for new products and services and to prepare U.S. engineering graduates for successful participation in the global economy. The ERCs provide a forum for industry to collaborate with faculty and graduate and undergraduate students on the commercial advancement of technologies in the focus areas of manufacturing, biotechnology and health care, energy/sustainability/infrastructure, and microelectronics/sensing/information technology.

- **Federal Small Business Innovation Research Program** (budget request, FY 2013: 2.8 percent of agency's extramural R&D budget): The SBIR Program is a set-aside program to enable domestic small business concerns to engage in research/R&D with the potential for commercialization. Federal agencies with extramural R&D budgets of more than $100 million are required to allocate 2.8 percent of their R&D budget to this program. Twelve federal departments and agencies participated in 2013: U.S. Department of Agriculture (USDA), National Institute of Standards and Technology (NIST), National Oceanic and Atmospheric Administration, U.S. Department of Defense (DoD), U.S. Department of Education, U.S. Department of Energy (DoE), U.S. Department of Health and Human Services (HHS), U.S. Department of Homeland Security, U.S. Department of Transportation, Environmental Protection Agency, National Aeronautics and Space Administration (NASA), and NSF.
- **Small Business Technology Transfer Program**, modeled after the SBIR Program (budget request, FY 2013: 0.3 percent of agency's extramural R&D budget): STTR is a highly competitive program that reserves a specific percentage of federal R&D funding for award to small business and nonprofit research institution partners. Federal agencies with extramural R&D budgets of more than $1 billion are required to allocate 0.3 percent of their R&D budget to this program. Five departments and agencies participated in 2013: DoD, DoE, HHS, NASA, and NSF.

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*Available: http://www.nsf.gov/eng/iip/iucrc/program.jsp [June 2014].

for the physical sciences has remained flat, and that for engineering has declined. In an attempt to reverse this trend, Congress boosted the budgets of NSF, National Institute of Standards and Technology (NIST), and the U.S. Department of Energy's Office of Science, under the presumption that this money would flow to the physical sciences and engineering. However, U.S. Department of Defense-funded engineering research, which accounts for one-third of all federal investments in engineering, declined steeply, down 26 percent from 2001 to 2010. Meanwhile, almost 75 percent of the $13.1 billion (in 2005 dollars) in research funding under

BOX 6-3
Instability in National Institutes of Health (NIH) Funding

This report emphasizes the important role of federal research funding in supporting the training of future scientists and engineers. But the importance of this funding in supporting the human capital component of the U.S. research enterprise extends well beyond research grants and stipends provided to graduate students. In many scientific fields, federal research funding supports the postdoctoral fellowships that are the first positions for new degree holders. In addition, federal funds are crucially important sources of support for junior faculty seeking to launch their laboratories and research careers. In other words, federal funds support a complex multiyear training regime for virtually all scientists in U.S. universities, a pipeline that extends from graduate school through postdoctoral training and the establishment of a scientific laboratory and research agenda.

This extended training process is vulnerable to disruption from fluctuations in research funding. When research grants for senior faculty are not renewed, support for graduate students and postdoctoral fellows is likely to be reduced, and when these funding reductions occur suddenly, the disruptive effects are all the greater. But the human capital pipeline also may be destabilized by unexpected surges in research funding, which attract more students to pursue graduate studies in a given field, lead senior faculty to open up more postdoctoral fellowships, and in some cases lead university administrators to support hiring of additional junior faculty. Funding upswings that are followed by cuts or even extended periods of flat growth in inflation-adjusted funding are especially disruptive in this context, and have the potential to degrade the efficiency of both the training and research supported by federal funds.

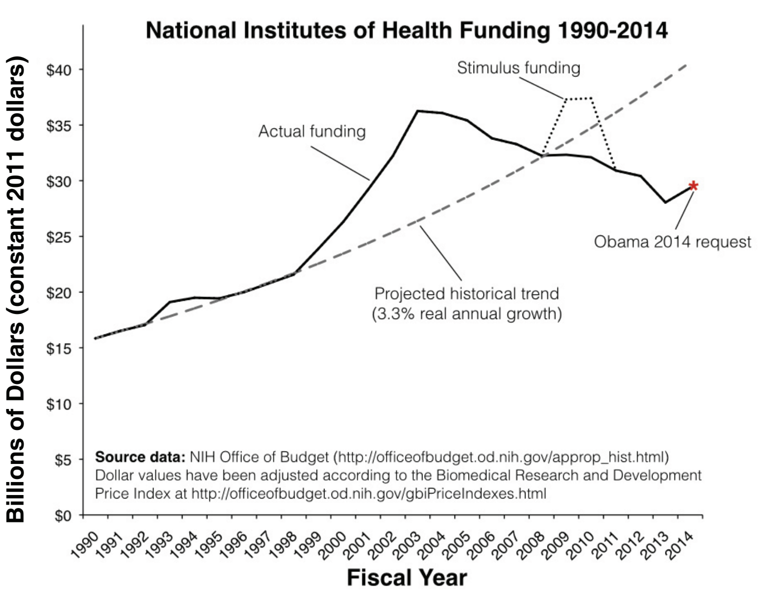
With this background in mind, it is sobering to observe the wide swings in federal funding for NIH, by far the largest single federal supporter of academic research in the United States, during fiscal years (FY) 1998-2014 (see the figure below). During the first 5 years of this period, a bipartisan coalition succeeded in doubling NIH funding, producing an average annual growth rate of 12 percent in constant-dollar NIH funding during FY 1998-2003 (see Freeman and van Reenen [2008], who use the Biomedical Research and Development Price Index to convert nominal to constant dollars). This period of rapid funding growth was followed by flat budgets that translated into declines in constant-dollar funding: Freeman and van Reenen estimate that by FY 2007, the real NIH budget was nearly 11 percent lower than in FY 2004, and by FY 2009, funding had dropped by roughly 13-14 percent. These reductions in funding were disruptive to the training pipeline described above. In the words of Freeman and van Reenen (2008, p. 28):

> The deceleration caused a career crisis for the young researchers who obtained their independent research grants during the doubling and for the principal investigators whose probability of continuing a grant or making a successful new application fell. Research labs were pressured to cut staff. NIH, the single largest employer of biomedical researchers in the country, with more than 1,000 principal investigators and 6,000 to 7,000 researchers, cut the number of principal investigators by 9 percent.

NIH's budgetary fluctuations continued. In early 2009, passage of the American Recovery and Reinvestment Act (ARRA) provided a 2-year increase in temporary funding for NIH of more than $10 billion, or nearly one-third of the agency's 2008 budget, triggering another sudden funding upswing. NIH and university administrators strove to minimize the destabilizing effects of this temporary funding surge on training, research, and education by allocating much of the increase to construction or one-time equipment purchases. The 2-year funding increase spanned FY 2009-2010 and was followed by a decline in constant-dollar NIH funding of more than $4 billion—from roughly $32 billion in FY 2010 to approximately $27 billion in FY 2011 (National Science Foundation, 2013).

The FY 2010-2011 funding reduction was followed by the sequestration budget cuts in FY 2012, which imposed an additional $1.5 billion in reductions on the agency's FY 2013 budget. As a result, the budget's real-dollar total was reduced to roughly $26 billion.

The figure below depicts NIH's budgetary fluctuations for the FY 1990-2014 period, using the Biomedical Research and Development Price Index to convert nominal to constant dollars. The wide swings in funding depicted in the figure indicate the magnitude of funding instability experienced by this key federal supporter of U.S. academic research during the past 20 years. Comparison of the long-term



How the National Institutes of Health is being unintentionally defunded.
SOURCE: White (2013). Reprinted with permission.

continued

BOX 6-3 Continued

trend line with the lower growth indicated by the actual funding for FY 1998 versus FY 2014 reveals the reduction in long-term growth in NIH's real budget. The effects of this reduction were greatly exacerbated by the wide swings in funding, which destabilized the training pipeline that produces future generations of biomedical researchers.

Although the NIH experience is unusual among federal research funding agencies—the initial doubling of the NIH budget during 1998-2003 and the large temporary increases under the ARRA reflect the political popularity of biomedical research within Congress—similar trends are apparent in the budgets of other important federal research funding agencies. The costs of these unstable funding trends are large and lasting, and undermine the performance of the overall U.S. research system.

the ARRA in fiscal years 2009 and 2010 supported NIH-funded research in the biological and medical sciences.

Performance Measures for Portfolio Management

Science must be managed not only through particular programs but also through portfolios of programs, some of which may entail research directed toward a particular national goal. Performance measures, whether based on research outputs, such as publications or patents, or on progress toward a particular goal, can be useful for managing programs within a portfolio. Some of the measures developed for evaluations of research funding programs (see Chapter 5) may be useful for performance measures.

Research projects often have predictable outcomes, in that most funded projects are designed to test a well-reasoned hypothesis and have a high likelihood of accomplishing their originally stated goals. Nonetheless, the ultimate utility of much research is unpredictable because research findings may eventually be used in unforeseen ways. Investing in research without a clear understanding of its utility is taking a risk. Just as with a financial investment, one cannot predict the winners and losers. But a broad financial investment portfolio can be relied upon to do well over the long term. Measures of risk, even if only qualitative, can be used to spread the risk of investments across the programs in a portfolio. The same is true for investments in research. A well-managed portfolio—by which we mean one that spreads risks, explores a diversity of approaches and topics within a field, invites unconventional thinking, and rewards long-term vision—can manage risks and lead to discoveries from some research projects that more than justify investment in the entire portfolio.

The U.S. government currently invests a large sum in a very broad research portfolio spanning many scientific and engineering disciplines. As we have noted, however, no agency, office, or committee within the Executive Branch or Congress systematically monitors the breadth of federal research investments across disciplines and scientific fields in ways that can support the goal of balance and sustainability of the overall scientific research enterprise.

Some recent policy experiments in developing portfolio analyses of federal research investments in specific fields have recently been launched. In 2011, NIH established an Office of Portfolio Analysis to enable NIH research administrators and decision makers to evaluate and prioritize current, as well as emerging, areas of research. In 2012, the National Science and Technology Council delivered a mandated report to Congress that provides a "national strategic plan for advanced manufacturing" (National Science and Technology Council, 2012). Partly because of this report, the White House directed the NIST to establish an Advanced Manufacturing National Program Office to coordinate management of government-wide research portfolios in manufacturing. In 2013, that office produced a concept paper describing both a conceptual model for management of research portfolios and specific metrics (Advanced Manufacturing National Program Office, 2013).

World-Class Basic Research in All Major Areas of Science

A successful research system is one in which the performance of basic research is characterized by excellence and high intellectual merit. World-class basic research in all major areas of science is important for at least three reasons.

First, research discoveries often rely upon insights in many scientific areas. For example, mathematics, statistics, and computer sciences advance discoveries in other sciences, while the social sciences contribute to effective uses of other sciences, including the adoption of innovations. Research in different areas of science interrelates in the systems through which discoveries and resulting technologies and innovations benefit society. Truly transformative scientific discoveries often depend on research in a variety of fields, from which connections can be made that lead to new ideas.

Second, in today's rapidly connected world, a discovery made somewhere is soon known everywhere. The competitive advantage may go not to the nation in which the discovery was made but to a nation that can leverage the productivity of follow-up research more effectively to produce commercially viable technologies, which ultimately drive domestic economic growth. Reaping these benefits from research discoveries throughout the world requires a highly sophisticated domestic research enterprise built on people, infrastructure, and funding. In particular, awareness of scientific discoveries may travel quickly, but sufficient understanding to extend them or to apply them for the development of new technologies or other innovations often requires that the nation's researchers possess considerable fundamental knowledge derived from diverse basic research.

Third, cultivating a system of world-class basic research attracts students and scholars from around the world to the United States. Their contributions to the U.S. research enterprise enhance its world-class stature, thus creating a self-reinforcing cycle.

Moreover, as discussed earlier, an additional benefit of research—particularly basic research—is its contribution to scientific infrastructure. Basic research generates—and benefits from—new methods of observation, measurement, data collection, analysis, and experimentation, enabling the quality of research to improve continually and the extent of research to expand (see Box 6-4). These new methods are most likely to have beneficial effects on both basic and applied research when they are widely adopted (Darby and Zucker, 2003). One example is basic statistical research in experimental design, which has enabled well-designed experiments in agriculture, medicine, and engineering. Another example is the Sloan Digital Sky Survey, as described in Box 6-5.

The Importance of Partnerships

Partnerships can help the research system produce world-class basic research. Discoveries often arise from collaborations and partnerships among individuals with different training, experience, and perspectives, such as researchers in academia and in industry. University-industry partnerships often are the means by which industry invests in university research, and they provide opportunities for the commercialization of research discoveries. Effective partnerships strengthen scientific and technological research in both universities and industry; inventions and even manufacturing feed back into research, and vice versa. NSF's Industry-University Cooperative Research Centers Program (discussed in Chapter 5) offers many successful examples, although evaluations of this program are at best incomplete. It should be noted that, while public-private partnerships are known to play a central role in the success of the American

BOX 6-4
Examples of How Scientific Infrastructure Enables Research Progress

Instrumentation: Electron Microscopy

Developed in 1931 by German researchers who received the Nobel Prize in Physics more than half a century later, in 1986 (Bellis, 2013), the modern electron microscope can magnify objects millions of times and allow researchers to view atomic-scale detail. This instrumentation is now used in materials research, biological research, semiconductor research, and industrial research for applications as diverse as mineral analysis in mining, forensics, and three-dimensional tissue imaging for medical analysis.

Technologies: Nuclear Magnetic Resonance (NMR) Spectroscopy, Magnetic Resonance Imaging (MRI)

NMR helps determine a liquid or solid material's molecular structure and identifies the various compounds that make up the material. The technology was discovered in the 1940s, in part as the result of a Massachusetts Institute of Technology (MIT) researcher's experiences during World War II with the detection of radio frequency power and the absorption of that power by matter to produce radar. The technology is now used in a variety of applications, ranging from chemistry quality control, to molecular physics, to the study of crystals and noncrystalline materials, to natural gas exploration and recovery. The technology was a critical step in the discovery of MRI, which allows for the early detection of countless health conditions, including cancer, Alzheimer's disease, multiple sclerosis, and stroke.

Observational Studies: General Social Survey

Initiated in 1972 by NORC at the University of Chicago, the General Social Survey (GSS) collects data on attitudes and behaviors in contemporary American society. These data allow scholars, students, and policy makers to draw comparisons between the United States and other societies. According to the NORC Website,* the GSS is the second most frequently analyzed source of data in the social sciences, after U.S. census data. The data are reported by journalists, considered by legislators and policy makers, and used as a major teaching tool in universities. According to the NORC Website, "More than 20,000 journal articles, books and Ph.D. dissertations are based on the GSS; and about 400,000 students use the GSS in their classes each year."

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[*] Available: http://www.norc.org/Research/Projects/Pages/general-social-survey.aspx [June 2014].

BOX 6-5
Big Data in Astronomy: The Sloan Digital Sky Survey

The Sloan Digital Sky Survey (SDSS)—named after the Alfred P. Sloan Foundation, which provided significant funding—is an ambitious astronomical survey that has been in progress since 2000 and will continue through 2014 (SDSS-I, 2000-2005; SDSS-II, 2005-2008, and SDSS III, 2008-2014). The systematic release of open-access data from the SDSS has accelerated the rate of findings and innovations in the field of astronomy. These datasets include spectra of 930,000 galaxies, 120,000 quasars, and 460,000 stars. The data are calibrated, checked for quality, and made available on an annual basis to researchers through online databases.

The various SDSS releases include a range of tutorials appropriate for audiences ranging from elementary school children to professional astronomers. The raw data also are available through other platforms, such as the National Aeronautics and Space Administration's (NASA) World Wind Program. The availability of SDSS data has supported a vast range of scientific investigations by astronomers and other researchers around the world. "Half of these achievements were among the original 'design goals' of the SDSS, but the other half were either entirely unanticipated or not expected to be nearly as exciting or powerful as they turned out to be" (Sloan Digital Sky Survey, 2008). In hindsight, the release of these data appears to be an obvious approach; in 2000, however, this approach was questioned by many who thought that the public release of these data was neither important nor relevant.

research enterprise,[2] additional studies are needed to fully characterize their role.

Measures for Assessing Basic Research

The ability to achieve world-class basic research can be tracked with international benchmarking of a nation's leadership status by field of science. This qualitative metric was suggested by the NRC in 1993 (National Academy of Sciences, 1993) and tested with experimental panels that examined institutional and human resource factors influencing world leadership status in three areas of research (National Academy of Sciences, 2000).

International benchmarking makes it possible to track research performance, recognize niche areas in which each nation excels, and identify strengths and weaknesses as a means of improving the quality and impact

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[2] See http://sites.nationalacademies.org/PGA/guirr/index.htm [August 2014].

of each nation's research program. In its 2000 report, the NRC's Committee on Science, Engineering, and Public Policy identifies eight factors predicted to have the greatest influence on the quality of future U.S. research performance relative to that of other nations: (1) the intellectual quality of researchers and the ability to attract talented researchers; (2) the ability to strengthen interdisciplinary research; (3) the ability to maintain strong, research-based graduate education; (4) the ability to maintain a strong technological infrastructure; (5) cooperation among the governmental, industrial, and academic sectors; (6) increased competition from Europe and other countries; (7) a shift in emphasis toward health maintenance organizations in clinical research; and (8) adequate funding and other resources (National Academy of Sciences, 2000). Measures focusing on these eight factors could help sustain the world-class quality of basic research as an essential pillar of the research system.

Research funding agencies strive to achieve world-class research by awarding competitive grants based on the caliber of the project personnel, the innovativeness of the research, and the strength of the research design, among other factors. Increasingly, however, agencies also consider the impact of the research.

Typical measures of world-class stature focus on outputs: publications, patents, citations, and other bibliometrics. Peer review also is used to judge research quality, as a supplement to quantitative measures. But there is nearly universal agreement that research excellence can be measured not only by outputs but also by inputs, such as the caliber of scientific talent, the quality of research facilities, a balanced national investment in research among fields and disciplines, the working environment, and how research is planned and managed. Measures of these inputs can be relatively easy to obtain (National Research Council, 2013b, 2013d).

Measures of research reproducibility could also help in assessing the world-class stature and long-term impacts of basic research. The use of independent laboratories and the implementation of journal or funding agency requirements that data be made available to other researchers have been suggested as ways to facilitate the reproducibility of research findings (Lehrer, 2010; Little, 2011; Siegfried, 2013; Wadman, 2013b).

Finally, measures of research performance could begin to capture the trends in international research performed by American companies, at least some of which may be directly tied to corporate research centers in the United States, as a means of facilitating the rapid translation of new knowledge into product or process innovations.

CONCLUDING OBSERVATIONS

Together, the three pillars described in this chapter interact to drive the performance of the research and innovation systems. But how best to support these pillars requires further research and the development of improved measures. Supporting these three pillars will lead to more cutting-edge research and stronger connections among world-class researchers, which in turn will allow the United States to attract even more talent and garner even more benefits for society and the economy.

7

Conclusion

Since the publication of Vannevar Bush's 1945 report *Science: The Endless Frontier* and the creation of the National Science Foundation in 1953, the federal government has supported scientific research for societal benefit far beyond the initial purposes of national defense (Bush, 1945). The benefits gained have manifested and today include computers, the Internet, wireless communication, the laser, the global positioning system, and modern medicine, among many others. These advances have enabled the United States to achieve unprecedented prosperity, security, and quality of life.

Now, however, the nation faces increased global competition for new technologies and other innovations, even as it confronts growing economic exigencies. In this context, Congress wants to enhance the benefits of science for the U.S. economy and the advancement of other national goals—in particular, keeping the nation at the forefront of the global competition for new technologies and other innovations—while maximizing the efficiency and effectiveness of federal research investments.

In seeking to increase the returns on federal investments in scientific research, Congress asked the National Academies to study measures of the impacts of research on society. Of particular interest were measures that could serve to increase the translation of research into commercial products and services.

The committee's investigation revealed that measures can usefully quantify research outputs, such as publications, and technology transfer, such as patents and licenses. They can be used to assess the outcomes of some research areas, particularly applied research focused on a specific goal, and the impact of a university's research on the regional economy. Measures of these important activities can serve to increase the societal benefits of research. At the same time, we agree with a common finding that metrics of research impacts must be viewed with considerable caution and that assessments, therefore, require both metrics and professional judgment. But current measures are inadequate to guide national-level decisions about what research investments will expand the benefits of science.

The American research enterprise is indeed capable of producing increased benefits for U.S. society, as well as the global community. To reap those benefits, however, requires new measures to guide federal research investments. To develop those measures, it is necessary to understand what drives the American research enterprise and what has made it so productive.

A SYSTEMS PERSPECTIVE

To understand how federal investments in scientific research result in societal benefits, it is necessary to understand the American research enterprise as a system that must be viewed in relation to the innovation system in which the discoveries produced by research are used to develop new technologies and other innovations. Without this system-level understanding, policies focused on relatively narrow objectives—such as increasing university patenting and licensing of research discoveries or reducing the funding for certain disciplines or types of research—could have undesired consequences.

Such an understanding, however, is not easily achieved. Discoveries often emerge from the highly complex and dynamic research enterprise as a result of the system as a whole. They are not due to any individual component of the system and thus cannot be predicted from the nature of the components. Nor can one predict how the knowledge from a research discovery might eventually be taken up and used, by whom, and in what ways that will lead to a transformative innovation. Indeed, research discoveries and the innovations to which they lead often arise serendipitously. The complexity of the research and innovation systems is why attempts to trace major innovations back to their original supporting research have rarely if ever revealed a direct flow of money in, value out.

This complexity means that a desired effect of the research system (for example, increased output of research discoveries of commercial value) is unlikely to be achieved by changing one or even a few components without regard to the critical drivers of the system and their interrelationships. Because of the complex and continually changing interactions among components of the research system, a change in one component will lead to changes in others, often in unpredictable ways, and may have untoward effects.

THREE PILLARS OF THE RESEARCH SYSTEM

Significant opportunities exist to increase the societal benefits of scientific research and to inform policies designed to keep the United States at the forefront of global competition for new technologies and innovations. Moreover, measures can be developed to guide the effective implementation of such policies.

To these ends, however, it is necessary to take a systems perspective on the research enterprise, identifying the critical drivers, or pillars, of the research system and understanding the relationships among them. The committee identified three pillars of the research system: a talented and interconnected workforce, adequate and dependable resources, and world-class basic research in all major areas of science. These pillars are supported by an active, nongovernmental entrepreneurial community that is willing to make significant investments in research. This community is one external factor that—along with antitrust, regulatory, and intellectual property policies; venture capital; and other factors—creates a unique environment for the U.S. research enterprise relative to those of other nations.

The committee concludes that societal benefits from federal research can be enhanced by focusing attention on the three crucial pillars of the research system: a talented and interconnected workforce, adequate and dependable resources, and world-class basic research in all major areas of science.

A systems perspective also reveals how these three pillars interact to produce research discoveries: how knowledge flows among networks of individuals and institutions; how research is influenced by the availability of scientific infrastructure, funds, and other resources; how world-class research and the usefulness of research discoveries are affected by management, research environments, institutions, and peer review; and how these and other aspects of the three pillars interrelate.

A strong interplay among talent, resources, and basic research is critical. Talent is at the center: people generate knowledge; distribute it through colleges, universities, publications, and other means; and transform it through networks of individuals with varying perspectives and creative ideas. Without such human capital, the products of research cannot be applied in ways that create value for society. Maintaining broad expertise among those who conduct research also sustains the innovation system, because technological problems often arise in the development of an innovation that requires research for their solutions. Research and innovation are symbiotic in this way. Similarly, many aspects of manufacturing contribute to and draw on research.

Adequate and dependable federal funding can ensure balance and vitality within the system of research, ensuring the continual, competitive flow of discoveries in the near and distant future. Critical resources for research also include scientific infrastructure, or the tools that allow for research excellence, and world-class research universities, national laboratories, and other research institutions. All of these resources provide essential support for the research process.

Basic research supports the critical pillar of talent by promoting national and international networks of researchers, through which ideas flow and scientific resources are shared. Basic research is performed primarily in universities, which nurture talent and launch future researchers. World-class basic research in all major areas of science is important for three major reasons.

First, truly transformative scientific discoveries often depend on research in variety of fields. Mathematics, statistics, and computer sciences, for example, helped advance magnetic resonance imaging and other medical technologies, while the social sciences contributed to an effective allocation of the spectrum for wireless communications.

Second, in today's rapidly connected world, a discovery made somewhere is soon known everywhere. The competitive advantage may go not to the nation in which the discovery was made but to the nation that can use it more effectively to develop new technologies and other innovations. Reaping the benefits from research discoveries throughout the world requires a highly sophisticated domestic research enterprise built on people, infrastructure, and funding. In particular, awareness of scientific discoveries may travel quickly, but sufficient understanding to extend them or to apply them for the development of new technologies or other innovations often requires that the nation's researchers possess considerable fundamental knowledge derived from diverse basic research.

Third, world-class basic research attracts researchers from around the world. These researchers further excellence in research, thus creating a self-reinforcing cycle.

Moreover, another benefit of research—particularly basic research—is its contribution to scientific infrastructure. Basic research generates—and benefits from—new methods of observation, measurement, data collection, analysis, and experimentation, enabling the quality of research to improve continually and the extent of research to expand.

HIGH-RISK RESEARCH

Not all research achieves its intended goals; high-risk research inevitably results in some failures. But even failures can lead to unanticipated discoveries and steer research in new directions. The transformative innovations that eventually result from some high-risk research can more than justify the investment in other such research that may fail. Only government has the broad social purpose and long horizon to invest in high-risk research so that society can reap its ultimate benefits. In some cases, government also is called upon to fund proof-of-concept research aimed at determining the commercial viability of an invention, at least to the extent of reducing the risk to the point where private industry would invest.

EVALUATION OF RESEARCH PROGRAMS

The standard review mechanism for prospective evaluation of research grant and contract proposals is some form of peer review and assessment. Some have criticized peer review for discouraging the funding of high-risk research or radically new research approaches. More recently, others have criticized it for the dilution of expertise in the National Institutes of Health review process. Yet despite the need for improvements in the peer review process, and especially in light of the decreasing success rate for research proposals, experience with the widespread use of alternative mechanisms by public agencies is limited, and little existing evidence suggests that there is generally a better mechanism. Nonetheless, peer review is designed to assess not overall program effectiveness but investigator qualifications and the innovativeness of individual projects within a given research program, and typically is most appropriate as a means of awarding funding rather than assessing performance.

Evaluation of research programs also faces challenges of attribution of observed outputs, outcomes, or performance. Randomized experiments could play a role here, but may be feasible only for comparing individuals or groups within a research area. Even so, very little evaluation has been conducted through randomized experimentation, and we believe there are opportunities to expand the use of this method. We encourage continuing to experiment with modifications of this approach to evaluation for both prospective and retrospective assessments.

Regardless of what approach to prospective evaluation of a research funding program is explored, it is preferable to build evaluation into the program from the very beginning. Doing so helps clarify goals and expectations and allows for the collection of important data that might otherwise be missed.

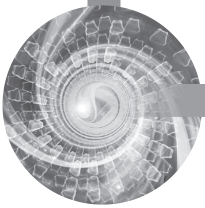
In today’s global economy, the United States is challenged to maintain a competitive position in the development of new technologies and other innovations to achieve national economic goals, especially for employment and income. The levels, composition, and efficiency of federally funded research need to be adjusted to meet today's circumstances. Measures can inform policy decisions to effect such adjustments. The United States, however, lacks an institutionalized capability for systematically evaluating the nation's research enterprise as a whole, assessing its performance, and developing policy options for federally funded research.

THE NEED FOR IMPROVED MEASURES

Measures of research activities, outputs, and technology transfer are important, and both the measures and the underlying data need to be improved. We see opportunities for improving ongoing data collection efforts. For example, Science and Technology for America's Reinvestment: Measuring the Effect of Research on Innovation, Competitiveness and Science would be more valuable if its data had more complete coverage, were linked to other data sources, and were made more accessible to researchers. We also see new areas in which measures can be developed, such as in the analysis of networks. But greater benefits can be realized by focusing attention on the three pillars of the research enterprise detailed above: talent, resources, and basic research. Measures designed around these pillars would promote a better understanding not only of these critical components and how they relate to each other, but also of the research enterprise as a system. These measures might include, for example, indicators of human and knowledge capital, indicators of the flow of knowledge in specific fields of science, indicators that can be used to track the flow of foreign research talent, portfolio analyses of federal research investments by field of science, international benchmarking of research performance, and measures of research reproducibility. Further research and data are needed, but a major contribution to that effort has been made by the National Research Council (2014) report *Capturing Change in Science, Technology, and Innovation: Improving Indicators to Inform Policy*.

CONCLUDING OBSERVATIONS

The U.S. research enterprise is a complex, dynamic system in part because it has evolved with many of the characteristics of free enterprise: it is decentralized, pluralistic, competitive, meritocratic, and entrepreneurial. In this complex system, it is impossible to predict what innovations may eventually result from research discoveries or which types of research would, in the absence of other types, lead to transformative innovations. Attention to the pillars of talent, resources, and basic research will ensure that discoveries and innovations continue to emerge from the scientific enterprise. Measures designed around these three pillars would promote a better understanding of the U.S. research enterprise as a system. These measures could be used to guide federal research investments that would enable the system to yield more of the societal benefits that have made it the world's premier scientific research enterprise.



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A

An Evaluation of STAR METRICS[1]

STAR METRICS (Science and Technology for America's Reinvestment: Measuring the Effect of Research on Innovation, Competitiveness and Science) is a joint effort involving the National Institutes of Health (NIH), the National Science Foundation (NSF) and the White House Office of Science and Technology Policy with the objective of documenting the outcomes and public benefits of national investments in science and engineering research. Data collection is planned in two phases. The first, Level 1, is drawing a limited number of data fields from existing university administrative databases and includes no personally identifiable information. The goal of Level 1 is to streamline and standardize data for reporting on the impact of federal research and development (R&D) spending on job creation. Although the initial focus is on spending supported by the American Recovery and Reinvestment Act (ARRA) both ARRA and non-ARRA spending are reported. Data collection for the second phase, Level II, has yet to begin.

While the program is relatively new, it takes two interesting steps by (1) automating and aggregating standardized reporting of grant payment information from university administrative records, and (2) creating a dataset that can plausibly reorient the analysis of federal R&D investments away from a focus on grants and toward a focus on investigators. Programs akin to STAR METRICs are beginning to gain traction in

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[1] The committee was assisted by Jason Owen-Smith and Alicia Carriquiry in drafting this appendix.

Australia, the European Union nations, and Japan, offering the eventual possibility of international comparisons.[2]

DATA STRUCTURE AND COMPONENTS

As of the committee's last communication with George Chacko, the official from NIH's Center for Scientific Review who oversaw the STAR METRICS Program at the time this report was drafted, 85 university campuses and one independent nonprofit laboratory had either begun to submit or committed to submitting data to the program.

Level I STAR METRICS data are divided into three files, each tracking a different flow of federal R&D expenditures by performing institutions. Each file is updated quarterly by each institution. The committee was unable to ascertain how timely and complete those updates are as access to the data remains difficult (see the discussion of access and user experience below). All three files share common information about the time period covered, the federal award ID (where appropriate), and the relevant performing institution account number for each record. The three files are as follows:

- **Individual file,** which tracks salary and wage payments to university employees (faculty, staff, students, and trainees). In its raw form, the individual file includes shared data fields, as well as a campus-specific, anonymized employee identifier, job classification information, an indication of whether the employee is full or part time, and a calculation of the fraction of total compensation charged to the grant account in a given time period. Information on the dollar value of individual wage payments is not included. Postprocessing by a federal subcontractor adds information on the agency where the grant originated, a standardized occupational classification, and information on whether each record derived from ARRA or non-ARRA sources. These files are used by the agencies to calculate or estimate the number of jobs created directly or indirectly by federal funding.[3]
- **Vendor file,** which tracks payments from universities to vendors for supplies and services. In addition to shared data fields, this file includes the Dun & Bradstreet (DUNS) number or zip code of each vendor and the amount charged to the account by the vendor. Postprocessing by DUNS and NIH supports the creation of

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[2] For more background information, see the STAR METRICS Website at https://www.starmetrics.nih.gov/ [August 2014].

[3] See https://www.starmetrics.nih.gov/Star/Participate#calculatingjobs [August 2014].

campus-specific "workforce" reports that estimate the number of jobs created by grant expenditures within the institution's home state and nationally.

- **Sub-award file,** which tracks subcontracts to other performers of R&D from a particular campus. In addition to the common data fields, this file includes a DUNS number for sub-award recipients and the amount of a relevant sub-award.

When combined and cleaned, these 3 files yield 14 data items for a wide variety of R&D performers. There is potential value in cross-campus comparisons of these data and in the estimates of job creation undertaken by NIH and other agencies. Nevertheless, the data are broad but relatively shallow. We thus believe that the greatest value STAR METRICs data could add to efforts to assess the value of research would come from (1) broadening coverage by enrolling additional institutions, (2) deepening coverage by expanding the data elements reported, and (3) linking STAR METRICS data to other national and international datasets. Below we address some of these possibilities. Despite the data's potential, much work remains to be done to establish their quality and to ensure broad, easy access for researchers.

POTENTIAL VALUE OF THE DATA

While we believe that the value of these data might be increased by the addition of new data fields, we focus our attention in this section on potential uses of the Level I data alone. We first address the descriptive and comparative possibilities we see in the STAR METRICS data and then summarize possibilities for linking these data to existing sources of information that might expand their reach.

Descriptive Comparisons across Campuses

STAR METRICS is the first data source that could enable micro-level comparisons of the organization and funding of academic R&D across a wide range of performing institutions. No comparable dataset exists. There is significant descriptive value in these data, but care must be taken to acknowledge difficulties with representativeness, as well as potential variations in data quality and reporting standards across performing institutions (see the next section on data quality). STAR METRICS Level I data have the potential to provide new and useful information on the flows of federal R&D money from performing institutions into the larger economy, on the types of jobs supported by federal R&D at performing institutions, and on the collaborative organization of academic research.

Data from the vendor file for a single quarter of purchases for a midwestern public university with a medical school indicate that this institution made 14,708 purchases from 2,221 vendors totaling some $49.72 million. The largest single purchase (~$335,000) was made from a chemical supply company in San Diego, California. The vendor from which the greatest number of purchases were made (1,830 purchases totaling nearly $3.35 million) was a scientific supply company in Hampton, New Hampshire. While we had access to raw vendor file data from only a single campus, such information might provide new and useful insight into the direct local and national economic impacts of federal R&D spending on campus. With appropriate linkages to other data sources, such data might also allow fine-grained estimation of the indirect and labor market impacts of such spending.

Table A-1 reports the number of wage payments by STAR METRICS standardized occupational classification for two very different universities in a single quarter. These data indicate the dramatic difference in scale between a large public university with a medical school and a smaller private university focused more heavily on physical science and engineering research. They also suggest interesting differences in how research is conducted. Consider just one comparison. Nearly 35.7 percent of all wage payments at the public university were to faculty. In contrast, at the private university, just 18.9 percent of wage payments went to faculty. This difference is highly significant in a two-sample test of proportions. While one should not make much of this ad hoc comparison of two campuses, establishing differences in the allocation of effort to R&D across campuses holds substantial possibilities for (1) understanding the direct employ-

TABLE A-1 Comparison of Wage Payments by Job Classification in a Single Quarter*

Standardized Job Classification	Public University (with medical school)	Private University (no medical school)
Faculty	5,130	486
Graduate Student	2,342	668
Postgraduate Researcher	1,471	344
Research Analyst/Coordinator	1,559	60
Technical/Staff Scientist	2,609	492
Clinician	84	0
Research Support	1,158	504
Undergraduate Student	1	19
Total	14,354	2,573

*Unit of measure: employees paid any part of a full-time equivalent (FTE) in a given job category.

ment effects of federal R&D, and (2) identifying the effects of different organizational arrangements for R&D on the outcomes of science.

A recent report published in *Science* suggests some of the potential uses of aggregated and comparative data of this sort (Weinberg et al., 2014). That research makes use of Level 1 STAR METRICS data from nine campuses to analyze the short-term economic effects of federal R&D spending. While the findings are descriptive and represent a downpayment on the kinds of analyses that could be developed with extended and linked STAR METRICS data, this paper demonstrates that (1) most people employed by federal grants are students and staff, (2) the composition of the academic workforce varies dramatically across funding agencies and fields of research, and (3) significant spending to purchase goods and services necessary to research is dispersed across more than 1,700 U.S. counties.

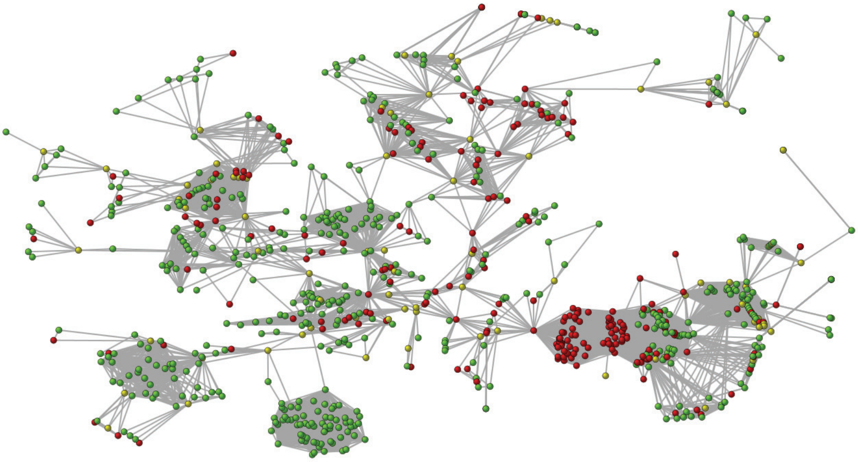
The structure of the individual data file—which associates payments to employees with particular grants and tracks cases in which individuals are paid by multiple sources—also offers new possibilities for studying the performance of R&D on campus. It is a fairly simple matter to take data in this format and render them as a social network in which nodes are individuals who receive payments, and ties indicate that two linked individuals were paid under the same grant. Figure A-1 presents graphic representations of the data for the two campuses highlighted in Table A-1. Differences in the extent and structure of collaborative networks across campuses may account for variations in levels and types of scientific productivity and thus in eventual economic, social, and public health outcomes.

Such comparative and descriptive data are potentially valuable, but both their scientific utility and usefulness for public policy are limited if they cannot be linked to other data sources to enable more rigorous analyses.

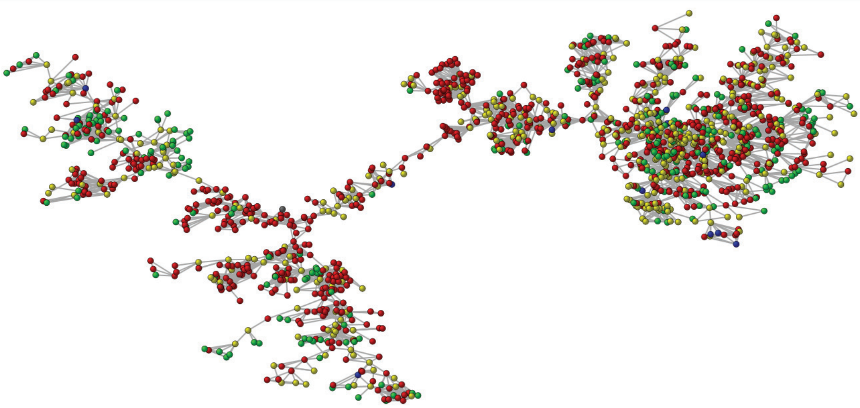
Linkages to Other Relevant Sources of Information

We briefly consider three possible means of linking STAR METRICS data to other sources of information that could prove useful in assessing the value of research for achieving national goals. Because few data fields are included in STAR METRICS Level 1 data, the possibilities for data linkages are relatively limited. The three most obvious linking strategies focus on DUNS numbers, federal grant numbers, and university/campus names.

At the organizational level, the DUNS numbers provided in the STAR METRICS vendor and sub-award files could be used to link these data to commonly used sources for the analysis of economic and labor force



a. Private university (without a medical school)



b. Public university (with a medical school)

FIGURE A-1 STAR METRICS collaborative network for two universities in a single quarter.
NOTE: Red = research staff (research scientists, technicians, coordinators, etc), Yellow = faculty, Green = trainees (grad students, post-docs), Blue = clinicians.

dynamics. Data maintained by the U.S. Census Bureau, including the Longitudinal Business Database and the Longitudinal Employee Household Dynamics dataset, could potentially be matched to STAR METRICS using DUNS numbers. Such linkages might enable new and more accurate estimates of the direct and indirect economic impacts of federal R&D spending on university campuses, but substantial work would be required to match the data, and a quick examination of vendor and subcontractor files for a single university suggests that data quality issues may pose substantial obstacles to this linkage (see the next section on data quality).

At the level of federal awards, unique grant numbers included in each file could be used to connect payments to general scientific topics. A government subcontractor's postprocessing of STAR METRICS data associated topic models derived from NSF grant abstracts with STAR METRICS records for NSF-funded research. Research.gov maintains an award-level database for all NSF awards by fiscal year that includes the institutional DUNS number and the unique NSF grant identifier. Other information included in this database is the congressional district of the awardee, the specific unit within NSF that funded the award, and the complete abstract at the time of submission. We were unable to determine how complete or effective such a linkage would be. Assuming that linkages to databases such as those found in Research.gov are sufficiently complete and accurate, postprocessing using, say, text analysis might enable understanding of the subdisciplines in science, technology, engineering and mathematics (STEM) that attract the most funding in a given year. For NIH grants, Owen-Smith undertook a pilot effort to link STAR METRICs grant numbers from a single university to publicly available data for NIH (unpublished data). This linkage allows NIH Research Condition and Disease Categorization codes to be associated with STAR METRICS records. Data quality issues discussed below may raise concerns for larger-scale matching efforts. However, Figure A-2 demonstrates some of the possibilities inherent in linking topic areas to STAR METRICS information by emphasizing the type of research being conducted for a small subset of the public university collaborative network presented in Figure A-1.

Associating topics and disease areas with STAR METRICS data could allow more fine-grained analyses of the productivity of particular areas of research, the portfolios of universities or federal agencies, and the organization of interdisciplinary R&D. In Figure A-2, red nodes represent research staff, and yellow nodes represent faculty. The research group highlighted by the blue oval at the top of the inset is pursuing work related to behavioral correlates of disease and death, while the group highlighted by the blue oval at the bottom works on HIV/AIDS vaccines. They are bridged by a team (highlighted by the red square) with grants for studies of liver cancer and organ transplants. The connection

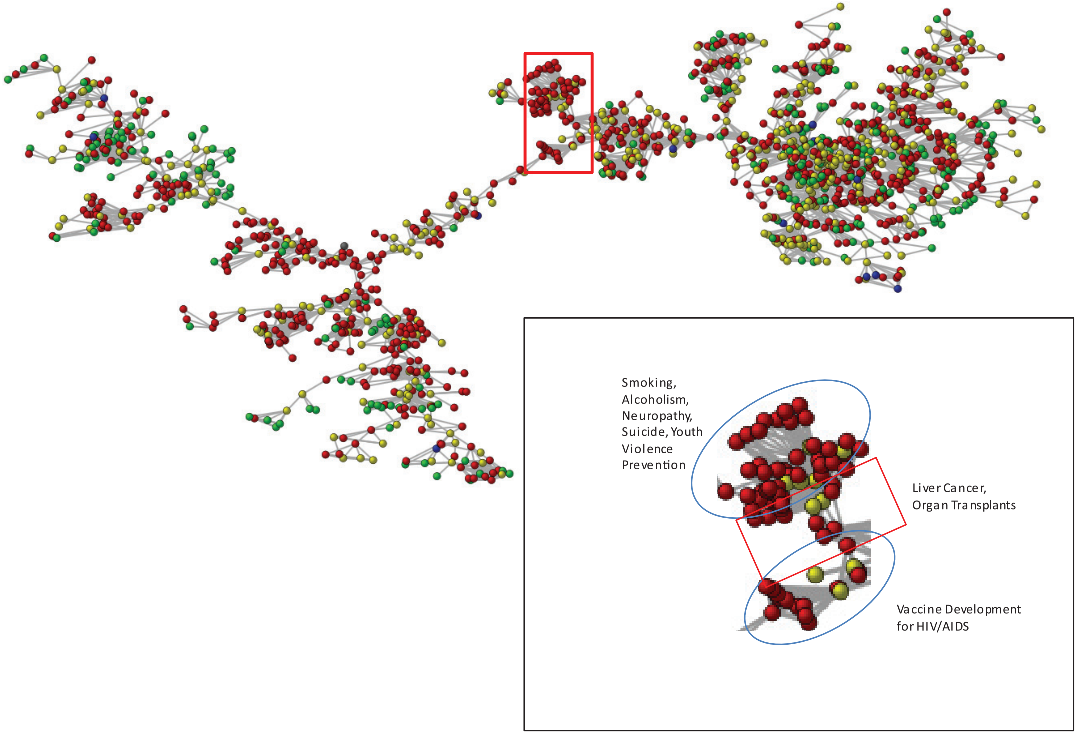


FIGURE A-2 Public university STAR METRICS network with National Institutes of Health Research Condition and Disease Categorization topic inset.

NOTE: Red = research staff (research scientists, technicians, coordinators, etc); Yellow = faculty; Green = trainees (grad students, post-docs); Blue = clinicians.

makes scientific sense as both alcoholism and hepatitis (common among at-risk youth) and HIV/AIDs are associated with liver cancers. Mapping the collaborative space of universities in such a fashion might provide new insights into different interdisciplinary research arrangements and thus offer improved possibilities for evaluating or seeding research projects with particular goals and targets. Cleaned grant numbers could in principle be linked (through for instance, acknowledgments of funding in publications or declarations of government interest in patents) to downstream scientific outputs and potentially to products or treatments. However, the process of that linkage would not be straightforward and could raise confidentiality issues.

Finally, university names could be used to link to existing federal R&D databases such as the NSF surveys of research expenditures or information on STEM degree completions. These linkages could, in principle, make it possible to ask and answer interesting questions about the effects of differently structured collaboration networks on the broad education and research functions of universities. A pilot effort to accomplish these very linkages supports discussion below of the extent to which current STAR METRICs data cover federal R&D expenditures and STEM degree completions.

While there are other sources of funding information, including, for example, *National Patterns of R&D Resources,* maintained and collected by NSF's National Center for Science and Engineering Statistics (NCSES), we do not discuss these in any detail. *National Patterns* has the advantage of relying on nationally representative samples and even censuses of institutions that receive funding from federal sources. Because this and other databases are designed with different goals in mind, however, R&D expenditure information is reported in formats that may not be compatible with STAR METRICS formats. For example, *National Patterns* focuses on institutions rather than disciplines, and funding information is aggregated accordingly. The timeliness of the reports is another challenge for these large national databases.

QUALITY OF THE DATA

Data Coverage of R&D Expenditures and STEM Workforce

To provide a preliminary assessment of the coverage of the STAR METRICS Level 1 data, we have attempted to determine roughly how representative STAR METRICS universities are of federal R&D performed by universities and of all (2-year, 4-year, and graduate-level) STEM degrees. We take the former to be suggestive of the extent to which STAR METRICS as it currently stands provides good coverage of R&D efforts on campus, while the latter offers some insights into the extent to which these data might be useful for addressing broad questions related to the scientific workforce and its training.

The NSF Survey of Research and Development at Universities and Colleges reports data on 893 campuses that spent federal R&D money in 2011. Of those campuses, 65 (7.27 percent) are currently enrolled in STAR METRICS. In total, NSF data report that $40.764 billion was spent. Of that amount, $15.712 billion (38.54 percent) was spent on campuses that are enrolled in STAR METRICS. Expenditure data are highly skewed. Table A-2 shows the top 25 campuses by federal R&D expenditures in 2011. These institutions accounted for 38.7 percent of all federal R&D expenditures. Fourteen of the institutions in Table A-2 are enrolled in

TABLE A-2 Top Twenty-Five Universities by Federal R&D Expenditures, 2011

University (NSF Standardized)	Federal Expenditures
Johns Hopkins University	*1,884,025*
University of Washington, Seattle	*950,293*
University of Michigan All Campuses	*824,752*
University of Pennsylvania	*707,051*
University of Pittsburgh All Campuses	*662,471*
Stanford University	*656,114*
Columbia University in the City of New York	645,233
University of California, San Diego	*636,879*
University of Colorado All Campuses	636,278
University of Wisconsin–Madison	*593,633*
Duke University	*585,262*
University of California, San Francisco	*570,116*
University of California, Los Angeles	563,560
University of North Carolina at Chapel Hill	561,708
Harvard University	*543,097*
Yale University	519,844
University of Minnesota All Campuses	*498,488*
Ohio State University All Campuses	*493,130*
Massachusetts Institute of Technology	489,080
Cornell University All Campuses	476,583
Pennsylvania State University All Campuses	472,693
Washington University	469,490
Vanderbilt University	458,173
University of Southern California	453,283
Georgia Institute of Technology All Campuses	*427,867*
Total	15,779,103

NOTES: Expenditure data in thousands of constant 2000 dollars; STAR METRICS campuses in italics; R&D = Research and Development
SOURCE: National Science Foundation (2009).

TABLE A-3 Top Twenty-Five Campuses by Total (2-year, 4-year, and graduate) STEM Graduates

University (NSF Standardized)	Number of Graduates
University of Phoenix	21,050
Community College of the Air Force	7,223
University of Florida	*6,348*
Ivy Tech State College Central Office	5,801
Pennsylvania State University Main Campus	5,728
Ohio State University Main Campus	*5,370*
University of Michigan, Ann Arbor	*5,310*
Purdue University Main Campus	*5,241*
Texas A&M University Main Campus	5,053
University of Washington-Seattle	*4,965*
University of Minnesota-Twin Cities	*4,956*
University of Illinois at Urbana–Champaign	4,594
University of Wisconsin–Madison	*4,412*
ECPI College of Technology	4,403
University of California, Berkeley	4,329
University of Southern California	4,262
University of California, Los Angeles	4,209
University of California, San Diego	*4,195*
University of Texas at Austin	*4,165*
University of Central Florida	4,091
Michigan State University	*3,974*
North Carolina State University at Raleigh	3,918
Georgia Institute of Technology Main Campus	*3,888*
Arizona State University Main Campus	*3,747*
University of California, Davis	3,696
Total	134,928

NOTES: STAR METRICS campuses in italics; STEM = Science, Technology, Engineering, and Mathematics.
Source: National Center for Education Statistics (2014).

STAR METRICS. Those 14 account for 61.1 percent of all federal expenditures by STAR METRICS campuses. They are highlighted in italics.

A similar examination of STEM degree completions suggests that STAR METRICS may be less effective for the analysis of broad scientific workforce questions. This, however, is to be expected given the dataset's overt focus on federally funded R&D expenditures. NCSES reports that 2,747 U.S. institutions issued at least one 2-year, 4-year, or graduate degree in a STEM field in 2011; in total, 1,156,521 such degrees were issued. Fifty six STAR METRICS campuses were among those that issued STEM degrees, producing some 80,501 STEM graduates, or 6.96 percent of the total. Table A-3 presents a list of the top 25 campuses by STEM completions in 2011. Once again, STAR METRICS campuses are italicized. Eleven of the top 25 campuses are enrolled in STAR METRICS. However, our choice to focus on the broadest possible definition of the STEM workforce makes this a conservative test as the list includes both community colleges and large for-profit universities. The 11 STAR METRICS campuses that were among the top 25 in 2011 produced 56,561 STEM graduates.

Data Quality

In a conversation with George Chacko, we learned that validating the quality of STAR METRICS data is a key concern for NIH and other federal agencies. Data quality concerns include not only evaluation of the data's completeness and accuracy, but also assessment of the methodology used to construct some of the variables in the database. One important goal of STAR METRICS is to estimate the impact on employment that can be attributed to federal spending on the sciences. To calculate employment, NIH makes choices about inputs and assumptions. Are those choices the most appropriate, or can they be improved? While a lack of access to STAR METRICS data and a lack of resources precluded our conducting a thorough analysis of data quality, our preliminary work provides some useful hints. We focus here on key variables for data linkage in the files of a single public university. As of this writing, we were unable to determine how representative these patterns are of other campuses.

Some potentially serious challenges posed by the STAR METRICS data include the following:

- Individual identifiers are university specific and constructed using local rules, so it is impossible to track faculty or students as they move across campuses or from universities to other research institutions. Also impossible is linking individuals to external sources of information on, for example, business initiations (unless they can be linked to university-based incubators using institutional DUNS numbers). This limitation in following individual professional paths is also noted below in the section on user experience.
- The STAR METRICS data provided by universities do not indicate disciplines, departments, or schools associated with the awards. It might be possible to address this limitation in postprocessing if DUNS numbers and unique grant identifiers could be used to link the data to more detailed award information, such as that available in Research.gov for NSF funding and in NIH's RePORTER for NIH and other funding agencies. If these linkages could be carried out effectively and accurately, detailed discipline and subdiscipline information associated with awards could be used to complement the STAR METRICS data.

Data quality problems in files for a single university campus suggest that such linkages could prove challenging, however. For instance, of the 14,907 transactions listed in one quarter's vendor file for a public university, 146 records lack any identifiers, and 10,021 replace DUNS numbers with U.S. or foreign zip codes. Thus only 4,740 records (31.8 percent) have potentially viable DUNS numbers. While there is no way to establish how much error occurs in reporting these numbers, better-quality data are necessary to support systematic matching using DUNS numbers at the organizational level.

Similarly, Owen-Smith's pilot effort to link STAR METRICS data for a single campus to NIH RePORTER information using NIH grant numbers suggests that accomplishing similar linkages at scale would be challenging but possible. Of 2,270 records of NIH grants that paid wages, 383 (16.8 percent) report NIH grant numbers that are unusable. Because of duplicate entries, the remaining 1,887 records resolve to 1,832 unique and potentially usable grant numbers. Of those, 1,172 (63.9 percent) match grant numbers listed in the NIH RePORTER system. If the university whose data we were able to access is characteristic, systematic linkages through grant numbers is likely to be an easier task than organization-level matching using DUNS numbers.

- Quarterly panels may be inappropriate for many types of analyses, so an important question is what kind of protocol might be used to aggregate quarterly information into annual panels. Transitioning from quarterly to annual panels might appear to be straightforward, but there are different approaches to doing so that have different advantages and limitations. The selected protocol would have to consider such issues as adjustment for missing quarterly data (or even imputation of missing information) and attenuate the potential impact of such factors as different starting and ending dates for fiscal years both for research institutions and funding agencies.

ACCESS AND USER EXPERIENCE

We had a productive conversation with Jim Onken from NIH's Office of Extramural Research and George Chacko. While STAR METRICS is up and running, and more institutions are being recruited all the time, the two main concerns at present are (1) the development of protocols for data access and (2) the data quality issue discussed above.

The STAR METRICS team is committed to developing data access protocols that allow as much access as possible while not violating data privacy or the confidentiality of information provided by reporting institutions. This is currently the subject of much discussion at NIH and NSF (and other participating agencies), but a policy is not expected to be in place any time soon. Thus at the moment, data access is limited, and the shape of an eventual data sharing policy is not clear. It may be that access to information that can be linked to specific institutions will require individual memorandums of understanding between data users and data providers. The use of deidentifiers and other masking techniques is probably not a viable alternative in that many data users would need to know enough institutional characteristics as to render almost all such techniques useless. Requiring researchers to negotiate access to data on a university-by-university basis would create significant, perhaps insurmountable barriers to the sorts of systematic comparative research that we propose above.

Data quality and validation of the methods used to calculate new variables are another critical concern. The STAR METRICS team would welcome ideas on how to establish an independent steering committee that would operate externally to STAR METRICS and would offer critical guidance on how to address the issue of the quality of data and methods. At present, no such body exists. This fact, coupled with a lack of access to data by almost everyone, has seriously impacted any efforts to evaluate the quality of the data contained in STAR METRICS.

A committee member spoke with potential users of STAR METRICS at a large federally funded research and development center (FFRDC) to understand the user perspective with regard to the utility and usability of the data. At present, this particular set of users believes that the first phase of STAR METRICS is focused too narrowly on the impact of grant funding on direct employment. They suggest that difficulties with data access and the need to reach agreements with individual reporting units, together with the narrow impact focus, greatly limit the usefulness of the database. More generally, FFRDC users often need to think of the impact of research funding from different perspectives, something that is difficult to do with the STAR METRICS database at this time. Improvements these users would like to see in STAR METRICS are the capability to link to other data sources (e.g., award-level information) and to carry out text analyses on the “broader impact” sections of funded proposals.

To better understand the point of view of the FFRDC users, it may be useful to think about the ways in which STAR METRICS might help answer such questions as those listed below, which are given as examples of the types of investigation that are often carried out at nonuniversity, not-for-profit institutions such as an FFRDC:

- **Innovation-centered analysis—**How has federal funding contributed to innovation? Consider an area such as cardiology, and identify the most important innovations in that area over the past 20 years. How were those innovations funded? What was the role of the federal funding agencies? What were critical steps in the development of the innovation, and would some of those intermediate products/ideas not have occurred except for the funding that was available at the right time? These are difficult questions because none of the existing databases (including STAR METRICS) are organized in a way that permits product- or innovation-centered focus.
- **Researcher-centered analysis—**How and in what form have federal investments in research impacted the professional path of researchers and their students? As discussed earlier, this type of analysis is currently impossible, mainly because researchers do not have unique identifiers that can be used to trace them during their professional lifetime. For example, it is impossible to gather information about a person's history of awards and other accomplishments (except by hand) or to understand that person's downstream impact in the form of his or her students' own accomplishments.
- **Agency-centered analysis—**What is NSF's contribution to the development of the 3D printer? To attempt to answer this type of question, one can look at patents and publications that are related to the 3D printer. Even if this information were easily accessible, however, it would not enable linking specific grants or even specific agencies *causally* to a discovery. Yet these questions of causal involvement arise often.

The FFRDC users we consulted are not naïve and fully understand that the questions they ask are complex and perhaps even ill posed. But some of the points they raised—such as the lack of unique identifiers for researchers—appear to be broadly applicable. The other issue that arose repeatedly is the need for STAR METRICS to be readily linkable to other databases so users can carry out analyses that may not have been contemplated by the STAR METRICS developers.

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B

U.S. Universities and Industrial Innovation: An Interactive Relationship Producing Economic Value from Research[1]

HOW ACADEMIC RESEARCH INFLUENCES INDUSTRIAL INNOVATION

The relationship between academic research and industrial innovation is a topic of great interest to policy makers and has received considerable attention from researchers in recent years. Although this relationship often is (mis)conceptualized as one in which "academia invents and industry invests" in commercialization, in fact the relationship may be better understood as an interactive one that is supported by flows of ideas and people from universities to industry and vice versa. Indeed, industrial research may lead and influence the agenda of academic research in some fields, as was the case in the early stages of research on light-emitting diodes (LEDs) and semiconductors (Mowery, 2011). According to Lécuyer (2005), Provost Frederick Terman of Stanford University encouraged William Shockley to locate his new firm near the university in 1955 to expose Stanford's engineering faculty to new research in solid-state physics and electronics, and a future dean of Stanford's Engineering School served an apprenticeship of sorts at Shockley Semiconductor to better understand semiconductor fabrication and design.[2] As noted by Mowery (2009b, p. 6):

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[1] The committee was assisted by David C. Mowery in drafting this appendix.

[2] "[James] Gibbons [future dean of engineering at Stanford], a junior faculty in the electrical engineering department [*sic*] at Stanford, worked at Shockley Semiconductor on a part-time basis. Frederick Terman, Stanford's provost, and John Linvill, the head of the

> The movement of researchers between industry and academia facilitates this interactive relationship (e.g., the move by Dr. Shuji Nakamura, a pioneering researcher in gallium-arsenide LEDs, from Nichia Chemicals in Japan to the University of California, Santa Barbara [UCSB] in 2000; see Chapter 7 of Mowery et al. [2004], for further discussion).[3]

Although the movement of researchers between industry and academia in the United States hardly could be described as frictionless, the boundaries between these different institutional venues for research and innovation are relatively porous in the U.S. research system. This represents a source of strength that may well distinguish the U.S. system from that of other industrial economies (although indicators on this point are difficult to develop).

As further described by Mowery (2009b), other studies have examined the influence of university research on industrial innovation. All of these studies (Cohen et al., 2002; Government-University-Industry Research Roundtable, 1991; Levin et al., 1987; Mansfield, 1991) emphasize differences among industries in the relationship between university and industrial innovation. The studies by Levin and colleagues (1987) and Cohen and colleagues (2002) summarize industrial research and development (R&D) managers' views on the relevance to industrial innovation of various fields of university research. Virtually all of the fields of university research rated by industrial respondents in both surveys as "important" or "very important" for their innovative activities were related to engineering or applied sciences, fields of U.S. university research with a long history of university-industry collaboration. Industry respondents consider few fields of university basic science research, aside from chemistry, as relevant to their innovative activities.[4]

Solid-State Laboratory, had recently apprenticed Gibbons to William Shockley. They had asked Gibbons to learn the techniques required for the fabrication of silicon devices from Shockley and then transfer these techniques back to the university. This was not the first time that Terman had sought to appropriate process technologies from local firms." (Lécuyer and Brock, 2006, p. 138).

[3] The academic research agenda in semiconductors and software at both the University of California, Berkeley, and the University of California, Santa Barbera, for example, benefited from the recruitment by academic departments of faculty from industry in both the United States and Japan. Equally important contributions to academic research flowed from faculty sabbaticals in industry and industry researchers' sabbaticals at universities (see Kenney and Mowery, forthcoming, for further examples). The OECD study *Benchmarking Science-Industry Relationships*, which emphasizes the importance of researcher mobility in strengthening such relationships, focuses primarily on flows of researchers from universities to industry in its benchmark measures (OECD, 2002).

[4] As noted by Mowery and Sampat (2005), however, the absence of such fields as physics, biology, and mathematics in these survey responses should not be interpreted to mean that academic research in these fields makes no contribution to technical advances in industry.

Cohen and colleagues (2002) also examined the relative importance for industrial innovation of different channels of communication linking intrafirm R&D to R&D in government or university laboratories. They found that pharmaceutical executives assigned greater importance to patents and licensing agreements involving universities and public laboratories than did other research managers in other industries. In these other industries, patents and licenses for inventions from university or public laboratories were reported to be less important than publications, conferences, informal interaction with university researchers, and consulting (similar findings are reported by Agrawal and Henderson [2002], Mowery and Sampat [2005], and Nelson [2012]). Pharmaceutical executives assigned greater importance than R&D managers from other industries to patents and license agreements involving universities and public laboratories, but pharmaceutical industry respondents, like those from other industries, rated research publications and conferences as a more important source of information than patents and licenses.

The consistency in the findings of the study by Levin and colleagues and the more recent survey conducted by Cohen and colleagues is striking. These studies also indicate that the relationship between academic research and industrial innovation in the biomedical field differs from that in other knowledge-intensive sectors (Mowery and Sampat, 2005). Academic research rarely produces "prototypes" of inventions for development and commercialization by industry, but academic research does inform the methods and disciplines employed by firms in their R&D facilities. Industrial R&D managers rely on a variety of channels for learning about and exploiting the results of academic research, and the channels rated by industrial R&D managers as most important in this complex interaction between academic and industrial innovation rarely include patents and licenses (Mowery and Sampat, 2005).

The work of Cohen and colleagues (2002) and other scholars singles out six channels through which industrial innovation is influenced by university research:

(1) faculty publishing;
(2) university patenting and licensing;
(3) faculty consulting;
(4) faculty entrepreneurship, including the establishment by faculty

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Instead, these results reflect the fact that the effects on industrial innovation of basic research findings in such areas as physics, mathematics, and the physical sciences are realized only after a considerable lag. Moreover, application of academic research results often requires that these advances be incorporated into the applied sciences, such as chemical engineering, electrical engineering and material sciences.

or other university researchers of new firms to commercialize their inventions;

(5) informal interactions between university and industry researchers, including conference presentations and related interactions; and

(6) training and placement of students in industrial positions.

The recognition by scholars of the array of channels through which universities interact with industry has only begun to inform understanding of the relationships among these seemingly parallel channels. A better understanding of these relationships, as well as the links among these different channels of interaction, is essential to the design of policies intended to enhance the contributions of university research to industrial innovation. For example, if an emphasis on patenting and licensing has a chilling effect on faculty's open disclosure of research results, the overall contributions of university research to industrial innovation could be reduced in the face of expanded patenting and licensing of university research advances. Understanding the relationships among these different channels of interaction is further complicated by the fact that their relative importance differs among fields of technology. The following sections summarize some of the recent scholarly research on several of these different channels of interaction between academic research and industrial innovation.

FACULTY CONSULTING AND ACADEMIC RESEARCH

A number of studies have examined the role of faculty consulting in patenting and technology transfer to industry. A series of papers by Zucker, Darby, and collaborators (Zucker et al., 1998, 2002) focuses on the collaboration with industry of "star scientists" in biomedical fields at universities. The studies examine the effects of such collaboration (such as serving on a scientific advisory board and collaborating with scientists in the firm) on the performance of biotechnology firms, arguing that, because of the "noncodified" nature of essential knowhow in biotechnology, collaboration that is mediated by the labor market for star scientist consultants is far more important than formal channels of technology transfer such as licensing. For Zucker and Darby, faculty consulting and entrepreneurship are more important than patenting and licensing in university-industry technology transfer. But these studies do not directly compare the effects of links between star scientists and firms with the effects on firms of licensing university intellectual property. In many cases, the faculty consultant and the licensed technology are likely to be complements, since the star scientist may be the developer of the technology being licensed. But this complementary relationship raises the possibility that at least some of the effects of the consultant relationships highlighted by Zucker and Darby reflect the presence of a technology license.

A study of faculty consulting and patenting by Thursby and Thursby (2007) develops a different perspective on the relationship between faculty consulting and university technology licensing, focusing on the substantial fraction (nearly 38 percent) of a sample of patents that have faculty members at 87 U.S. universities listed as inventors but are not assigned to the faculty's university employers. The large share of faculty patents that are not assigned to universities reflects in part the considerable variation among U.S. universities in the regulations governing the assignment of patented intellectual property.[5] This study also found that the biomedical sciences exhibit the lowest share of nonuniversity-assigned patents, while engineering fields show the highest such share.

Thursby and colleagues conclude from their econometric analysis that the patents not assigned to faculty inventors' universities are associated with faculty consulting, although their evidence on this point is indirect, based as it is largely on what they describe as the "more incremental" character of the patents not assigned to universities. The results of this study suggest a relationship between faculty consulting and patenting that differs from that emphasized by Zucker and Darby. For Zucker and Darby, faculty patenting and faculty consulting (as well as other forms of paid interaction with firms) are substitutes. The analysis by Thursby and Thursby, however, suggests that consulting and some forms of patenting (more incremental patents that are assigned to firms) may be complements, although these authors did not examine the relationship in this study between different assignment patterns for individual faculty—that is, whether faculty who are listed as inventors on numerous firm-assigned patents also were contributors for large numbers of university-assigned patents.

FACULTY PATENTING AND SCHOLARLY PUBLISHING

A related body of empirical work examines the relationship between patenting and another important channel for university-industry interaction—publishing. Agrawal and Henderson (2002) and Cesaroni and colleagues (2005) examine the relationship between publishing and patenting for individual faculty members at U.S. research universities.

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[5] Some institutions do not require such assignment for intellectual property developed without the use of academic facilities, while others, such as the University of California, assert a right of ownership over all intellectual property developed by faculty, staff, or students, regardless of the extent of use of university facilities in its development.

Agrawal and Henderson examined this relationship for Massachusetts Institute of Technology (MIT) faculty in two engineering departments, while Cesaroni and colleagues looked at a larger sample of faculty from a number of U.S. universities. Both studies found that higher levels of patent productivity do not reduce publication productivity. Agrawal and Henderson found no relationship between the two spheres of productivity, although they concluded that faculty whose publications are more highly cited (i.e., whose research had a greater impact) appear to patent more extensively, and Cesaroni and colleagues found that higher levels of patenting were associated with higher levels of publication productivity.

Of interest, Cesaroni and colleagues found that only university-assigned patents issued to faculty were associated with higher levels of publication productivity, providing additional evidence in support of the contention of Thursby and Thursby (2007) that faculty patents not assigned to universities are associated with consulting. The positive relationship between publication and patent productivity also appears to taper off at higher levels of patent productivity, suggesting that very intensive faculty patenters may indeed be slightly less productive in publishing; however, these diminishing returns are seen at fairly high levels of patenting (the peak occurred at nine patents per researcher).

Overall, this and other evidence (see Azoulay et al., 2009) indicate that faculty patenting and faculty contributions to the open scientific literature are if anything complementary. There is no evidence in this empirical work that faculty patenting below extremely high levels is associated with a diminution in scholarly publishing. The evidence on the impact of faculty patenters' research (as measured by citations of their work in subsequent papers), however, is more complex: there are at least some indications that patenting may slightly reduce citations of publications describing research advances that are subsequently patented.

FACULTY ENTREPRENEURSHIP AND SCHOLARLY PRODUCTIVITY

Although the above findings on patenting and productivity shed considerable light on the relationship between two important channels for university-industry interaction, an equally important issue, and one on which little research has yet been published, concerns the relationship between faculty entrepreneurial activity (including but by no means restricted to consulting) and scholarly productivity. If anything, the efforts of faculty to assist in the foundation and early-stage growth of firms are likely to impose greater demands on their time and distractions from academic research than is true of patenting, which arguably draws on many of the same skills as publishing.

One of the few attempts to examine the relationship between faculty entrepreneurship and research activity is that of Ding and Choi (2011), who looked at the participation of faculty as founders or members of scientific advisory boards (SABs) for firms in the U.S. biotechnology industry that had successful initial public offerings during 1972-2002. Although Zucker and Darby include faculty participation in SABs as one of their measures of linkage between star scientists and firms, the Ding and Choi analysis includes a much broader sample of firms, faculty, and universities; compares the participation of faculty in SABs with their involvement as firm founders; and examines the relationship between both types of entrepreneurial activity (which in fact differ substantially in content and time demands) and faculty research productivity. The results of this study suggest that SAB participation and faculty involvement as firm founders are if anything inversely related, both in frequency and in terms of the point during faculty career trajectories at which they occur (older faculty at more prestigious universities are more likely to be SAB members).[6] Another important and interesting finding is the lack of any strong negative relationship between publication activity and participation by faculty in either form of entrepreneurial activity. Contemporaneous research productivity appears to be more strongly correlated with faculty involvement in the founding of a firm, perhaps as a vehicle for commercial exploitation of an important research advance, but neither type of involvement with firms appears to significantly depress research activity. Indeed, faculty involved as SAB members are more likely to have larger cumulative publication stocks. Like the work of Zucker and Darby discussed above, the Ding and Choi analysis suggests that research and faculty entrepreneurship are complementary.

The links between faculty-founded firms and university licensing are surprisingly unclear in most available data, including data compiled by the Association of University Technology Managers (AUTM) (2001, 2002). The AUTM data suggest that firms founded specifically to commercialize licensed technology account for a minority of university licensees. The AUTM annual reports for 2001 and 2002 indicate that 14-16 percent of university patent licensees in these years were start-up firms founded to exploit the licensed inventions. More than one-half (50-54 percent) of academic licensees during this period were small firms (fewer than 500

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[6] One reason for this observed relationship between seniority and SAB activities among faculty is the likelihood that junior faculty may pursue consulting or other entrepreneurial activities with industry (e.g., participating in the establishment of a new firm or scientific collaboration with a start-up firm).

employees) already in existence, while roughly one-third of licensees (32-33 percent) were large firms.[7]

The emphasis in recent academic research (DiGregorio and Shane, 2003) on the role of university "spin-offs" in the licensing activities of U.S. universities thus needs to be qualified by recognition that such start-ups are less significant as licensees than large firms in absolute numbers. Surprisingly, in view of the large amount of research in this broad field that has examined academic spin-off firms (Nerkar and Shane, 2003; Shane and Stuart, 2002), little is known about the relationship between technology licensing and the formation, growth, or survival of such firms. Little information exists, for example, on the share of academic spin-offs that are also technology licensees, and the AUTM data suggest that such spin-offs account for a small share of all licensees of university patents.

Indeed, the role of faculty entrepreneurs who establish new firms to commercialize university inventions and the role of university spin-offs in regional economic development both merit critical scrutiny (Mowery, 2011). The analysis of faculty patents not assigned to universities by Thursby and Thursby (2007) suggests that a significant share of the patents of those faculty who are financially involved with these firms are not licensed from their university but assigned directly to spin-off firms. This characteristic of patents not assigned by faculty to their university does not of course preclude the possibility that a foundational patent or patents may have been licensed by the spin-off to which other patents have been directly assigned by the faculty inventor, but it assuredly points to a more complex relationship. Because of the lack of comprehensive data, surprisingly little is known about the origins of the technological innovations that are central to the university spin-offs founded by faculty or about the role of licensed inventions in these firms' foundation and success or failure, and even less is known about the role of university faculty in the management of these firms (Mowery, 2011).

U.S. UNIVERSITY-INDUSTRY RESEARCH COLLABORATION AND TECHNOLOGY TRANSFER BEFORE THE BAYH-DOLE ACT[8]

Starting in the earliest decades of the 20th century, university-industry collaboration in the United States was facilitated by the unusual structure

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[7] The AUTM survey data report only the characteristics of licensee firms for all licenses, both exclusive and nonexclusive. These data do not enable examination of the relative importance of exclusive vs. nonexclusive licenses among different types of firms (e.g., start-up, small company, large company).

[8] This discussion draws on Mowery et al. (2004).

of the nation's higher education system, which contrasted with those of other industrial economies. As Mowery (2007, p. 165) notes:

> The U.S. higher education system was significantly larger, included a highly heterogeneous collection of institutions (e.g., religious and secular, public and private, large and small, and so on); lacked any centralized, national administrative control; and encouraged considerable interinstitutional competition for students, faculty, resources, and prestige (see Geiger, 1986, 1993; Trow, 1979, 1991, among other discussions). In addition, the reliance of many public universities on local (state-level) sources for political and financial support further enhanced their incentives to develop collaborative relationships with regional industrial and agricultural establishments. The structure of the U.S. higher education system thus strengthened incentives for faculty and academic administrators to collaborate in research and other activities with industry—and to do so through channels that included much more than patenting and licensing.

Although a growing number of U.S. universities had adopted formal patent policies by the 1950s (Mowery, 2007), many of these policies, especially those at medical schools, prohibited patenting of inventions, and university patenting was less widespread than was of the case in the post-1980 period. According to Mowery and Sampat (2005, p. 119):

> The decade of the 1970s, as much as or more so than the 1980s, represented a watershed in the evolution of U.S. university patenting and licensing. U.S. universities expanded their patenting, especially in biomedical fields, and assumed a more prominent direct role in managing their patenting and licensing activities, supplanting the Research Corporation. Agreements between individual federal agencies and universities [institutional patent agreements (IPAs)] also contributed to the expansion of patenting during the 1970s. Private universities in particular also began to expand their patenting and licensing rapidly during this decade.

Several factors appear to have contributed to the new approach taken by many U.S. universities to managing their intellectual property. Among the most important of these factors during the 1970s was slower growth in federal funding for university research, reflecting reductions in defense-related funding for university research, which particularly affected both MIT and Stanford. For financially pressed universities, reduced growth in federal research funding increased the attractiveness of the potential revenues associated with licensing these research advances. Interest in patent licensing revenues among faculty and administrators grew in parallel with their dissatisfaction with the performance of the leading institutional "agent" charged with responsibility for handling many universities' patenting and licensing transactions—the Research Corporation.

A second important factor in U.S. universities' increased interest in patenting and licensing faculty research advances during the 1970s was new scientific discoveries that appeared to hold considerable promise for licensing to industry. Federally funded academic research in the life sciences was an important catalyst for these discoveries. Much of the academic research that generated fundamental scientific advances in the field of molecular biology, laying the foundations for the biotechnology industry, was funded by the National Institutes of Health (NIH) as part of the Nixon Administration's "war on cancer," which led to increased funding for biomedical research during the 1970s. Several of the private research universities that were experiencing reductions in federal defense-related research funding (e.g., Stanford) housed academic medical centers that were the locus of significant basic research advances in the field of molecular biology. In contrast to many basic research advances, these discoveries appeared to leading pharmaceutical firms and other enterprises to hold enormous commercial promise, creating a potentially strong and lucrative market for licenses to biomedical intellectual property.

The influence of these factors is revealed in the decision by Stanford University to patent and license the Cohen-Boyer rDNA technique, which was based on research conducted at Stanford and the University of California, San Francisco.[9] Stanford had established a technology licensing office in 1970 under the direction of Neils Reimers, who learned of the Cohen-Boyer invention from a *New York Times* article published in 1978 (Hughes, 2001). Stanley Cohen was initially opposed to patenting the technology, but Reimers convinced him that patenting the discovery would spur industrial application.[10] Reimers also argued that "the patent, if granted, might become the impressive royalty generator that the university had thus far never had" (Hughes, 2001, p. 561). Such a "royalty generator" was particularly important in the face of flat growth in overall federal research funding and significant cutbacks in defense-related support for academic research. As another Stanford administrator noted in a letter to Donald Frederickson, then director of NIH: "It is a fact that the financing of private universities is more difficult now than at any time in recent memory…we cannot lightly discard the possibility of significant income [from the invention]" (quoted in Hughes, 2001, p. 564).

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[9] Although the technique was developed jointly by researchers at Stanford and the University of California, Stanford managed the patenting and licensing process because it had an IPA with NIH, which funded the research (see below).

[10] Nonetheless, in a discussion of the Cohen-Boyer licensing strategy, Reimers argued that "whether we licensed it or not, commercialization of recombinant DNA was going forward. As I mentioned, a nonexclusive licensing program, at its heart, is really a tax. . . . But it's always nice to say "technology transfer" (Reimers, 1998).

THE BAYH-DOLE ACT OF 1980

As reported by Mowery and Sampat (2005, p. 119),

> The Bayh-Dole Patent and Trademark Amendments Act of 1980 provided blanket permission for performers of federally funded research to file for patents on the results of such research and to grant licenses for these patents, including exclusive licenses, to other parties. The Act facilitated university patenting and licensing in at least two ways. First, it replaced a web of IPAs that had been negotiated between individual universities and federal agencies with a uniform policy. Second, the Act's provisions expressed congressional support for the negotiation of exclusive licenses between universities and industrial firms for the results of federally funded research.

In addition, the act reduced the power of federal funding agencies to oversee the terms of licensing agreements between research performers and licensees.

Lobbying by U.S. research universities was one of several factors behind the passage of the Bayh-Dole Act in 1980. The act is as much an effect as a cause of expanded patenting and licensing by U.S. universities during the post-1960 period (Mowery and Sampat, 2005). The IPA regime, along with similar programs at the Department of Defense, had facilitated growth in university patenting and licensing during the 1970s. Nevertheless, by the late 1970s, many of the U.S. universities active in licensing were concerned about potential restrictions on their licensing policies imposed by federal agencies. In August 1977, the Office of the General Counsel of the U.S. Department of Health, Education, and Welfare (HEW) expressed concern that university patents and licenses, particularly exclusive licenses, could contribute to higher health care costs (Eskridge, 1978). HEW ordered a review of its patent policy, including a reconsideration of whether universities' rights to negotiate exclusive licenses should be curtailed.[11] During the ensuing 12-month review, the agency deferred decisions on 30 petitions for patent rights and three requests for IPAs.

According to Broad (1979, p. 476), in response to HEW's review of its patent policies, "universities got upset and complained to Congress." A former Purdue University patent attorney, Norman Latker, who had been an architect of the changes in HEW's patent policies in 1968 that led to the creation of IPAs, was fired from HEW after denouncing the agency's

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[11] According to the testimony of Comptroller General Elmer Staats during the Bayh-Dole hearings, the purpose of the HEW review was "to make sure that assignment of patent rights to universities and research institutes did not stifle competition in the private sector in those cases where competition could bring the fruits of research to the public faster and more economically" (U.S. Senate Committee on the Judiciary, 1979, p. 37).

subsequent review of these policies. Latker asked Senator Birch Bayh of Indiana to develop legislation liberalizing and rationalizing federal policy toward university patents on federally funded research.[12] At the same time, technology transfer officials at Purdue complained to Bayh about difficulties in obtaining rights to patents funded by the U.S. Department of Energy (Stevens, 2004). Latker, together with these other university licensing officials, aided in drafting portions of what became the Bayh-Dole Act. As described by Mowery (2009b, p. 9),

> The passage of the Bayh-Dole Act was one part of a broader shift in U.S. policy toward stronger intellectual property rights.[13] Among the most important of these policy initiatives was the establishment of the Court of Appeals for the Federal Circuit (CAFC) in 1982. Established to serve as the court of final appeal for patent cases throughout the federal judiciary, the CAFC soon emerged as a strong champion of patentholder rights. But even before the establishment of the CAFC, the 1980 U.S. Supreme Court decision in *Diamond v. Chakrabarty* upheld the validity of a broad patent in the new industry of biotechnology, facilitating the patenting and licensing of inventions in this sector.

Any assessment of the effects of Bayh-Dole thus must take into account the effects of the (nearly simultaneous) shift in U.S. policy toward intellectual property rights, as well as the effects of growth in NIH funding in molecular biology and related fields before and after 1980.

THE EFFECTS OF BAYH-DOLE

Noting that it is impossible to separate the effects of Bayh-Dole from those of other developments in policy during the early 1980s, it is interesting to consider how U.S. university patenting has changed since 1980.[14]

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[12] Latker returned to HEW's patent office in 1978, after his dismissal was overturned by a civil service review board on procedural grounds. Reporting on these events in *Science*, Broad (1979, p. 476) noted: "The reinstatement is timely. Support is now building for the Bayh-Dole patent bill, and Latker's return to the HEW is seen by many university researchers and patent transfer fans, to whom Latker is something of a hero, as a shot in the arm for their cause."

[13] According to Katz and Ordover (1990), at least 14 congressional bills passed during the 1980s focused on strengthening domestic and international protection for intellectual property rights, and the Court of Appeals for the Federal Circuit created in 1982 has upheld patent rights in roughly 80 percent of the cases argued before it, a considerable increase from the pre-1982 rate of 30 percent for the federal bench.

[14] The Bayh-Dole Act sought to accelerate the commercialization of federally funded research across all institutional performers, including federal laboratories. Surprisingly, in light of the flood of empirical studies of university technology transfer since 1980, studies have attempted to examine the response of the U.S. federal laboratories to the act.

Universities increased their share of patenting from less than 0.3 percent in 1963 to nearly 4 percent by 1999, but the rate of growth in this share appears to have accelerated before rather than after 1980 (Mowery, 2007). Also noteworthy is the distribution of university patents among technology fields during the pre- and post-Bayh-Dole periods. While nonbiomedical university patents increased by 90 percent from 1968-1970 to 1978-1980, biomedical university patents increased by 295 percent (Mowery, 2007). The increased share of the biomedical disciplines within overall federal academic R&D funding, the advances in biomedical science that occurred during the 1960s and 1970s, and industry's interest in the results of this biomedical research all affected the growth of university patenting during this period (Mowery, 2007).

Following passage of the Bayh-Dole Act, universities become increasingly involved in the management of patenting and licensing. As described by Mowery (2007, p. 168),

> The share of U.S. research university patenting accounted for by institutions with at least 10 patents issued before 1980 declined from more than 85 percent during 1975-1980 to less than 65 percent by 1992. By contrast, low-intensity pre-1980 patenters (institutions with fewer than 10 patents) increased their share of all academic patents from 15 percent in 1981 to almost 30 percent in 1992. And institutions with no patenting activity during 1975-1980 increased their share of overall academic patenting from zero in 1980 to more than 6 percent by 1992.

The less experienced "entrant" universities received less significant patents in the immediate aftermath of the act's passage (based on citations to these patents in subsequent granted patent applications), although the gap between the quality of their patents and those of experienced institutional patenters had narrowed by the end of the 1980s (Mowery, 2007). This narrowing of the gap in the quality of patents among different university cohorts after 1980 suggests that the patenting strategies of less experienced academic patenters changed during the 1980s toward a more selective approach. Entrant universities in particular appear to have learned to patent, but the sources and mechanisms of such learning are not well understood. Mowery (2007, pp. 168-169) notes:

> This evidence concerning the relatively low quality of the early patents obtained by many entrant institutions also underscores the need for caution in using counts of patents (on their own or relative to R&D spending) as a measure of the productivity of research universities. Patents vary widely in quality: as with academic papers, a great many patents are never cited or actively worked by anyone, and the value of any portfolio of patents typically is dominated by a very small number of patents. Comparisons of patent activity across universities, or (even more questionable) between universities and industry, must incorporate

some adjustment for the quality of patents, for example, through citation-weighting of patents.[15]

MANAGEMENT OF UNIVERSITY PATENTING AND LICENSING

According to Mowery (2009a, p. 39):

> By 2002, according to the Association of University Technology Managers (2003), gross licensing revenues for all U.S. universities exceeded $1.2 billion. Licensing data from the University of California nine-campus system [a tenth campus was opened in 2007], Stanford University, and Columbia University, all of which have ranked among the institutions reaping the highest gross licensing income, show that biomedical patents accounted for more than 66-85 percent of the gross licensing revenues of these academic institutions for much of the 1980s and 1990s (Mowery et al., 2004). Even for these relatively successful academic licensors, however, licensing revenues (especially net licensing revenues that flow to the institution) represent a remarkably small share of overall academic operating budgets.

Very few U.S. universities publish sufficient data to enable estimation of the net revenues that their licensing operations contribute to institutional income. One institution that did publish such data through the early 2000s is the University of California system-wide technology licensing office, whose data cover the entire University of California system. As noted by Mowery (2009a), that system's annual net licensing revenues after deduction of operating expenses and payments to inventors averaged roughly $30 million during fiscal years 1999-2004—roughly 1 percent of the system's annual research expenditures of nearly $3 billion and well below the $235 million in industry-sponsored research conducted in the system in fiscal year 2003. Given that the system reported relatively high gross annual licensing revenues (averaging nearly $100 million) during this period, it appears likely that the financial contributions of patent licensing to most university operating budgets are modest at best, and negative for a great many institutions. Moreover, these financial inflows appear to be dwarfed by those associated with industry sponsorship of academic research (Mowery, 2009a).

Revenues are of course not the only motive for university licensing

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[15] An especially misguided use of patent counts for evaluation involves use of such counts for individual university faculty as a measure of professional performance. Among other effects, the creation of incentives for faculty to patent is likely to increase significantly the operating expenses of university technology licensing offices that must bear the costs of prosecuting an expanded flow of patent applications, many of which may cover inventions of limited technological significance and commercial potential.

activities.[16] Other important motives include recruiting and/or retention of faculty who wish to see their inventions patented and licensed, the transfer of university inventions to commercialization, regional or state-level economic development, and preservation of the freedom of academic scientists to conduct research. This array of potential goals for patenting and licensing activities, however, creates some challenges for management. These goals are not entirely compatible—for example, support for regional economic development may entail acceptance of lower royalty rates on licenses for firms active in the vicinity of the university. Technology licensing thus will involve some trade-offs among these goals, trade-offs that must be embodied in a coherent institutional policy and clearly communicated to the staff charged with responsibility for these activities. The goals of institutional technology licensing programs also must be consistent with the metrics used by the institution to evaluate and reward licensing office staff. Yet despite these trade-offs, as well as the relatively modest scale of net revenues at many university technology licensing offices, a recent survey revealed that technology licensing officers regard licensing revenues as the most important goal of their activities (Jensen and Thursby, 2001).

INDUSTRY-SPONSORED RESEARCH AND INDUSTRY CRITICISM OF UNIVERSITY LICENSING POLICIES

Despite significant growth in industry-supported research at U.S. universities as a share of total U.S. university R&D after 1980 (see Figure B-1), this share peaked in 1998-1999 at slightly more than 6 percent of total university research funding and has since declined. As of 2008, industry-sponsored research at U.S. universities accounted for a smaller share of university R&D than was the case in the early 1950s. Reasons for the decline in the industry-funded share of U.S. university R&D since 1999 are not well understood.

Industry criticism of U.S. universities' licensing policies and practices intensified during the early 2000s, particularly in the information technology (IT) sector. As recalled by Mowery (2009a), Dr. R. Stanley Williams of Hewlett Packard, a firm with a long history of close research collaboration with U.S. universities, stated in testimony before the U.S. Senate Commerce Committee's Subcommittee on Science, Technology and Space:

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[16] Indeed, the National Research Council's (2010) study of university technology licensing programs states that "patenting and licensing practices should not be predicated on the goal of raising significant revenue for the institution. The likelihood of success is small, the probability of disappointed expectations high, and the risk of distorting and narrowing dissemination efforts is great" (p. 5).

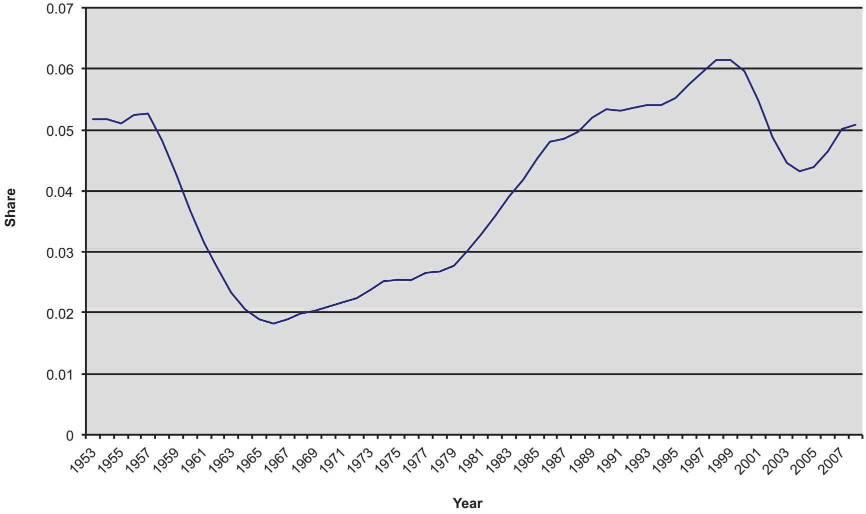

FIGURE B-1 Industry-funded share of total academic R&D, 1953-2008 (excluding federally funded research and development centers).
NOTE: R&D = Research and Development.
SOURCE: National Science Foundation (2010).

> Largely as a result of the lack of federal funding for research, American Universities have become extremely aggressive in their attempts to raise funding from large corporations. . . . Large U.S.-based corporations have become so disheartened and disgusted with the situation they are now working with foreign universities, especially the elite institutions in France, Russia and China, which are more than willing to offer extremely favorable intellectual property terms.[17]

A more sweeping critique was presented at a 2003 conference organized by the Government-University-Industry Research Roundtable at the National Academy of Sciences, as described by Mowery (2007):

> . . . the universities' approach of securing iron-clad protection for intellectual property seems to be yielding diminishing returns, even within the narrow confines of the licensing activity itself. . . . The requisite legal negotiations for IP-that-will-ultimately-prove-to-be-useless are laborious, individualized and negotiated between universities and companies on a case-by-case. The up-front legal negotiations can easily cost more than the total cost of the research project being conducted, and/

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[17] See http://www.memagazine.org/contents/current/webonly/webex319.html [August 2014].

> or extent past the time when the company has interest in the technology path being pursued. . . . In summary, the uncertainty of the true value of university-generated intellectual property, combined with a litigious culture, have combined to make the university-industry working relationship—one that has historically contributed greatly to graduate education—unaffordable and nearly unsustainable within the U.S. (Government-University-Industry Research Roundtable, 2003, p. 2).

These critical comments triggered considerable discussion between large industrial firms (many of which are in the IT sector) and U.S. research universities over intellectual property policies and licensing guidelines (Mowery, 2007). In December 2005, four large IT firms (Cisco, Hewlett Packard, IBM, and Intel) and seven universities (Carnegie Mellon University; Georgia Institute of Technology; Renssellaer Polytechnic; Stanford University; University of California, Berkeley; University of Illinois at Urbana–Champaign; and University of Texas at Austin) agreed on a "statement of principles" for collaborative research on open-source software that emphasizes liberal dissemination of the results of collaborative work funded by industrial firms (Mowery, 2009a).[18]

Relationships between established firms and universities were most often the targets of the critical statements that received press coverage and some attention from policy makers (Mowery, 2009a). Interestingly, the economic interests of established firms with large patent portfolios differ in some ways from those of small start-up firms that are owners or licensees of far fewer patents. Furthermore, a large number of conflicts

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[18] The "Open Collaboration Principles" cover "…just one type of formal collaboration that can be used when appropriate and will co-exist with other models, such as sponsored research, consortia and other types of university/industry collaborations, where the results are intended to be proprietary or publicly disseminated." According to the "Principles," "The intellectual property created in the collaboration [between industry and academic researchers] must be made available for commercial and academic use by every member of the public free of charge for use in open source software, software related industry standards, software interoperability and other publicly available programs as may be agreed to be the collaborating parties. . . " See http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CCkQFjAA&url=http%3A%2F%2Fsites.kauffman.org%2Fpdf%2Fopen_collaboration_principles_12_05.pdf&ei=lHNpU4ebJoqPyASi4YKYCw&usg=AFQjCNGTkBvau6MnVz9eEeazakuYxAJBHw&sig2=ywl6B3MeD7wy886l0bMQGA&bvm=bv.66111022,d.aWw&cad=rja [May 2014].

These principles originated in an August 2005 "University and Industry Innovation Summit" in Washington, DC, organized by the Kauffman Foundation of Kansas City and IBM. See http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&cad=rja&uact=8&ved=0CC8QFjAB&url=http%3A%2F%2Fpublic.dhe.ibm.com%2Fsoftware%2Fdw%2Funiversity%2Fcollaborativeresearch%2FUniversityIndustrySummit.pdf&ei=8HNpU8TQHMiZyATj_YLICg&usg=AFQjCNFQCmyFJ7q7FyYKqD2YBpN105McFA&sig2=w1E29mTk59rrsjE-cVobNw&bvm=bv.66111022,d.aWw [May 2014].

have involved nonbiomedical firms, as the value of individual patents in such industries as IT typically is lower than is true of biomedical research. Nevertheless, the current controversies and discussions between U.S. industrial firms (some of which, as was noted earlier, contrast U.S. university intellectual property right policies unfavorably with those of universities outside of the United States) and U.S. research universities appear to have led some U.S. universities to revise their institutional strategies for supporting collaborative research relationships with U.S. industry (Mowery, 2009a).

For example, some leading U.S. research universities have developed licensing strategies that assign greater weight to the goal of using licensing as a tool to increase industry sponsorship of academic research. The director of the Stanford Office of Technology Licensing now oversees the university's Industrial Contracts Office, which manages sponsored-research agreements with industry while also overseeing materials transfer agreements, which govern the transfer of research tools and materials among researchers. Industrial firms supporting campus research can receive licenses (in some cases, royalty-free) to the results of this research.

A similar trade-off between maximizing licensing revenues and obtaining industry research funding is apparent in the creation in 2003 of the Intellectual Property and Industry Research Alliances Office in the University of California, Berkeley licensing office, which absorbed the established Office of Technology Licensing and a new Industry Alliances Office, charged with overseeing the negotiation of sponsored-research agreements with industry. Moreover, the Berkeley licensing office, along with other University of California technology licensing offices, has implemented a new policy recognizing the differences among industries in the value (and likely licensing income) of patents in different fields of research. In 2000, the University of California President's Office authorized the negotiation of royalty-free licenses with industrial sponsors of campus research in electrical engineering and computer science.

These initiatives, along with the assignment of responsibility for a broader set of relationships with industry to campus directors of technology licensing offices at both Stanford and the University of California, Berkeley suggest that these leading academic licensors are developing a more nuanced approach to the management of trade-offs within their technology transfer strategies (Mowery, 2007). Two key features of this new approach appear to be an effort to manage patenting and licensing as part of a broader institutional strategy for supporting collaboration with industry, and some effort to tailor patenting and licensing policies to the contrasting economic and technological importance of formal intellectual property instruments among different fields of research. What is less well understood is why it has taken so long for U.S. universities to revise their approach to managing patenting and licensing. Indeed, the more than three decades since the passage of the Bayh-Dole Act have witnessed a surprising lack of experimentation with new licensing structures and policies among U.S. universities. As U.S. (and non-U.S.) universities expand their use of alternative policies and organizations for managing interactions with industry, better data on what is being done and how well it is accomplishing its goals are badly needed.

CONCLUSIONS

U.S. universities have a long tradition of engagement with industry in research and other collaborative activities. This pattern of engagement has benefited from a two-way flow of ideas and people between academic and industrial research settings. Both the historic structure of the national U.S. system of higher education and factors external to U.S. universities (e.g., labor markets that support relatively high levels of domestic inter-institutional mobility of researchers, new-venture financing from various private sources) have contributed to this tradition of collaboration, which has included extensive patenting and licensing of university inventions to industry. But interaction between U.S. universities and innovation in industry throughout the 20th and 21st centuries has relied on a number of different channels, ranging from the training of students to faculty consulting, publication of research advances, and industry-sponsored research, among others. These channels operate in parallel and are interdependent. Moreover, the relative importance of different channels of interaction and information flow between industrial and academic researchers appears to vary considerably among different research fields.

The so-called "Bayh-Dole era" that began in 1980 extended and expanded this engagement, which drew as well on extensive federal support for research, notably in the life sciences. That support produced important advances that sparked growth in university patenting and licensing, increasingly managed directly by U.S. universities, during the 1970s. There is little evidence during the post-1980 period that increased faculty engagement in entrepreneurial activities, including new-firm formation and patenting and licensing of inventions, negatively affected the scholarly productivity of leading researchers. Nonetheless, the intellectual property management policies of at least some U.S. universities sparked criticism from U.S. firms in the early 2000s, especially those in IT. In response to this criticism, some U.S. universities have experimented with new approaches to the management of patenting and licensing that take into account the differences among research fields in the importance of patents as vehicles for information exchange and technology transfer.

Reflecting their complex roles in regional and U.S. national economies, university technology transfer programs can be used to pursue an array of institutional goals. But these goals are not always mutually consistent or compatible, meaning that policy priorities must be established in technology transfer programs and clearly linked to policies in operation. Revenue-maximizing licensing strategies are shortsighted.

Effective metrics for evaluating the performance of universities in transferring technology and supporting industrial innovation should be aligned with the specific goals of a given university or research institute. They also should attempt to account for the full breadth of channels through which university research influences industrial innovation, including the training and placement of students, faculty research publications, faculty- or student-founded firms, patents, and licenses. Given the lack of data covering these various channels for most U.S. universities, as well as the need for metrics to be tailored to the goals and environment of individual universities, it would appear to be unrealistic and unwise for federal agencies or other government evaluators to impose a single, uniform set of metrics purporting to measure the technology transfer performance of all U.S. universities. The institutional heterogeneity that historically has been a strength of the U.S. system of higher education should be recognized and preserved in any evaluative framework.

This institutional heterogeneity also implies a need for flexibility and variety in the policies used by U.S. universities to support interactions with industry and the commercialization of academic research advances. Although the Bayh-Dole Act and other relevant federal policies do not dictate any single institutional structure for managing patenting, licensing, and related activities in university-industry collaboration, U.S. universities have been slow to experiment with different approaches to managing these activities during the more than three decades since the act's passage. Such experimentation, combined with efforts to assess the effectiveness of alternative approaches to university policies on collaboration, should be encouraged by federal agencies, industry, and other stakeholders. Nonetheless, no single approach is likely to prove feasible or effective across the numerous and diverse academic institutions and private firms engaged in federally funded research and industry collaboration.

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   This report explores avenues in which changes in U.S. policies and practice might have the greatest impact on research innovations. Because transdisciplinary and transsector research play particularly important roles in advancing scientific discovery, the report recommends pursuing a deep conceptual and functional connectedness across scientific disciplines (particularly the physical and life sciences) and fostering cooperative, synergistic interactions among academia, government, and the private sector.

2. Council of Canadian Academies Expert Panel on Science Performance and Research Funding. (2012). *Informing Research Choices: Indicators and Judgment*. Ottawa: Council of Canadian Academies. Available: http://www.scienceadvice.ca/uploads/eng/assessments%20and%20publications%20and%20news%20releases/science%20performance/scienceperformance_fullreport_en_web.pdf [August 2014].

This report reviews the development in other countries of performance indicators of scientific research and their use in allocating funds. The panel concludes that several performance metrics are available; however, no single indicator, set of indicators, or assessment strategy offers an ideal solution in research assessment contexts for natural sciences and engineering discovery research. In light of this observation, the panel recommends four guiding principles to support research funding agencies undertaking science assessments in support of budget allocation: context matters, do no harm, transparency is critical, and expert judgment remains invaluable.

3. Group of Eight. (2011). *Measuring the Impact of Research: The Context for Metric Development*. Go8 Backgrounder 23. L. Rymer, principal author. Turner, Australia: Author. Available: http://www.go8.edu.au/__documents/go8-policy-analysis/2011/go8backgrounder23_measimpactresearch.pdf [August 2014].

   This report presents a careful and critical review of the different approaches to measuring research impacts. Measuring return on investment can be tricky because the impact of research depends on a complex web of factors, such as how quickly the scientific community becomes aware of the findings, the success of follow-up research, how quickly the findings are put to practical use, the likelihood of success (high-impact research often entails greater risk), and how "positive impact" is defined. Having issued that warning, the report describes how the impacts of scientific research can be grouped into eight broad categories: effective teaching; advances in knowledge; encouraging additional investment by other parties; financial returns; and economic, social, environmental, and intangible (e.g., national reputation) outcomes. Impact in these categories can be assessed using the following methods, although the authors emphasize that none of the current measures can provide definitive results: input measures, output measures and benchmarking (e.g., bibliometric measures), peer review by expert panels, researchers' anecdotes about the benefits of their work, detailed case studies of research outcomes, cost-benefit analyses, hindsight studies, surveys (e.g., stakeholder surveys to assess the perceived significance of a project; commercialization surveys to quantify staff, spin-off companies, and patents), economic models, and econometric analyses.

4. Guthrie, S., Wamae, W., Diepeveen, S., Wooding, S., and Grant, J. (2013). *Measuring Research: A Guide to Research Evaluation Frameworks and Tools.* Santa Monica, CA: RAND Corporation. Available: http://www.rand.org/pubs/monographs/MG1217.html [August 2014].

   This study analyzes six research evaluation frameworks in various countries, also providing a brief overview of eight additional frameworks. It presents a guide to the key considerations entailed in developing approaches to research evaluation. The report also describes several tools used in research evaluation. The report emphasizes that perennial challenges to research evaluation (e.g., attribution, contribution, time lag between research and outcome, level of performance) need to be addressed in the development of evaluative methods. Furthermore, frameworks and tools should be tailored to the purpose of the evaluation and the type of material being evaluated. Research evaluation tools typically fall into one of two groups: formative tools, which are flexible and able to deal with cross-disciplinary and multidisciplinary assessment; and summative tools, which do not require judgment or interpretation and are quantitative, scalable, transparent, comparable, and suitable for high-frequency longitudinal use. These two types of evaluation tools serve different needs; multiple methods are required if researchers' needs span both groups. The report notes further that research evaluation approaches should suit their wider context. Different approaches may be acceptable and credible in different environments, and it is important to consider this when developing a framework.

5. Hughes, A., and Martin, B. (2012). *Enhancing Impact: The Value of Public Sector R&D*. Cambridge, UK: CIHE-UK~IRC Task Force on Enhancing Value: Getting the Most Out of UK research. Available: http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&ved=0CDEQFjAA&url=http%3A%2F%2Fukirc.ac.uk%2Fdocs%2FCIHE_enhancing_Impact_Report.pdf&ei=qg7KUJCWGPSG0QGwtYCgBg&usg=AFQjCNE4YWYfGKTwm93yuTO8XRBv2fSGtQ&bvm=bv.1355272958,d.dmQ [August 2014].

   This is the second in a series of reports exploring how the United Kingdom can gain the most value from publicly funded research. The report stresses the importance of moving from simple measures of impact, such as university spin-offs and patents, to a more nuanced understanding of the connections between the public and private sectors in a system of knowledge production and innovation. The report concludes that narratives, rather than economic values, may be the most effective way to assess the impacts of research and the pathways to these impacts. The narrative format would allow for a description of the various factors influencing impact and therefore avoid many of the challenges inherent in developing useful metrics.

6. Mazzucato, M. (2011). *The Entrepreneurial State.* Demos. London, UK: Magdalen House. Available: http://marianamazzucato.com/projects/entrepreneurial-state/ [August 2014].

   In this paper, Mazzucato argues that opportunities are being missed if recent developments in the innovation literature, economic theory in general, and experience from elsewhere in the world are not considered in setting UK policy. The paper aims to provoke a radical change in the understanding of the government's role in economic policy. The author hopes to spark a conversation about how the state can use its power to specify the problems it wishes to solve through technological advances and innovation, thereby ensuring that those advances are able to take place. The paper concludes that a more entrepreneurial economy would be beneficial to the United Kingdom, and that such an economy would not necessarily require the British government to withdraw but to lead. The paper provides 10 recommendations for increasing innovation through various efforts, including policy changes, tax incentives, and elimination of existing roadblocks.

7. Martin, B.R., and Puay, T. (2007). *The Benefits from Publicly Funded Research.* Brighton, UK: Science and Technology Policy Research Unit, University of Sussex. Available: http://www.erawatch-network.eu/reports/sewp161.pdf [August 2014].

   This paper concludes that there is no simple answer to the question, "What are the economic and social benefits of basic research?" The authors note that the benefits of publicly funded research come in a variety of forms, flowing through a variety of channels and over differing time scales. Seven relatively distinct mechanisms or "channels" are described through which benefits from research flow into the economy and society. The findings reported show that the benefits are substantial, certainly sufficient to justify considerable government investment in basic research. The findings reveal seven main mechanisms or "exploitation channels" through which the benefits of basic research may flow to the economy or to society at large: (1) increase in the stock of useful knowledge, (2) supply of skilled graduates and researchers, (3) creation of new scientific instrumentation and methodologies, (4) development of networks and stimulation of social interactions, (5) enhancement of problem-solving capacity, (6) creation of new firms, and (7) provision of social knowledge.

8. National Academy of Sciences, National Academy of Engineering, and Institute of Medicine. (1993). *Science, Technology, and the Federal Government: National Goals for a New Era.* Committee on Science, Engineering, and Public Policy. Washington, DC: National Academy Press. Available: http://www.nap.edu/catalog.php?record_id=9481 [August 2014].

   This report recommends that the United States be among the leaders in all major areas of science, and notes that the nation's ability to achieve world-class basic research could be tracked with the qualitative metric of international benchmarking. In particular, the report suggests that maintaining a world standard of excellence in all fields will help ensure that the United States can "apply and extend scientific advances quickly no matter when or where in the world they occur." To this end, the federal investment must be vigorous enough to support research across the full spectrum of scientific and technological investigation.

9. National Academy of Sciences, National Academy of Engineering, and Institute of Medicine. (2000). *Experiments in International Benchmarking of U.S. Research Fields.* Committee on Science, Engineering, and Public Policy. Washington, DC: National Academy Press. Available: http://www.nap.edu/catalog.php?record_id=9784 [August 2014].

   This is a follow-up to the 1993 National Research Council report *Science, Technology, and the Federal Government: National Goals for a New Era,* summarized above. In this report, international benchmarking is used to assess U.S. performance in the fields of immunology, materials science and engineering, and mathematics. The report identifies eight factors predicted to have the greatest influence on the quality of future U.S. research performance relative to other nations: (1) the intellectual quality of researchers and the ability to attract talented researchers; (2) the ability to strengthen interdisciplinary research; (3) the ability to maintain strong, research-based graduate education; (4) the ability to maintain a strong technological infrastructure; (5) cooperation among the governmental, industrial, and academic sectors; (6) increased competition from Europe and other countries; (7) a shift in emphasis toward health maintenance organizations in clinical research; and (8) adequate funding and other resources. Metrics focused on these eight factors could help sustain the world-class quality of basic research as an essential pillar of the research system.

10. National Institutes of Health. (2013). *Draft Report on Approaches to Assess the Value of Biomedical Research Supported by NIH.* Working Group on Approaches to Assess the Value of Biomedical Research Supported by NIH, Scientific Management Review Board. Bethesda, MD: Author.

    A draft of the working group's report notes that the tools, techniques, and data needed to develop comprehensive measures of value are still in the early phases of development, and therefore it is not possible to assess the value of NIH-funded biomedical research at this time. However, the draft report notes six strategies that could enhance assessment efforts: (1) a sustained investment in NIH's data infrastructure, and dedicated funds and a mechanism to support assessment projects; (2) a focus on clear connections between the generation and impact of scientific knowledge; (3) a movement toward "credible, interpretable, and useful assessments of the value of NIH" that "attribute outcomes to all contributors and adopt a timeframe that is broad enough to include sufficient time for discovery to be applied"; (4) partnerships with stakeholders to complete the assessments; (5) establishment of a trans-NIH Committee on Assessments that would develop a strategy and process for assessing the value of NIH-sponsored research; and (6) beginning assessment activities with a clear statement of purpose for the exercise and a strong strategy for communicating and disseminating the assessment results.

11. National Research Council. (2011). *Measuring the Impacts of Federal Investments in Research: A Workshop Summary.* S. Olson and S. Merrill, Rapporteurs, Committee on Measuring Economic and Other Returns on Federal Research Investments. Washington, DC: The National Academies Press. Available: http://www.nap.edu/catalog.php?record_id=13208 [August 2014].

The workshop participants noted the myriad challenges to developing a universal measure of research impact that spans all scientific fields (e.g., the returns of research occur on an unpredictable timeline and depend on further efforts by individuals, society, or other organizations; the definition of "positive impact" can be variable; intangible outcomes such as knowledge, national reputation, and failure are crucial to success but difficult to measure). With that caveat, the participants identified six target areas in which the short- and long-term economic and noneconomic impacts of federal research funding can be assessed: (1) economic growth, (2) productivity, (3) employment, (4) social values (e.g., environmental protection and food security), (5) public goods (e.g., national security), and (6) the behavior of decision makers and the public.

12. National Research Council. (2012a). *Continuing Innovation in Information Technology*. Computer Science and Telecommunications Board, Division on Engineering and Physical Sciences. Washington, DC: The National Academies Press. Available: http://www.nap.edu/catalog.php?record_id=13427 [August 2014].

    This report, referred to as the "tire-tracks" report for its famous diagram, shows how investments in academic and industry research are linked to the creation of new information technology (IT) industries with more than $1 billion in annual revenue. It describes how industry builds on government-funded university research and illustrates the interdependencies among subfields of computing and communications research. The report concludes that properly managed, publicly funded research in IT will continue to create important new technologies and industries, with an unpredictable timeline from the discovery of a new idea to the creation of a highly profitable industry. The complex partnerships among government, industry, and universities—and the federal government's support of basic research—are critical to the success of IT, and consequently to national security and economic and societal well-being.

13. National Research Council. (2012c). *Research Universities and the Future of America: Ten Breakthrough Actions Vital to Our Nation's Prosperity and Security*. Committee on Research Universities, Board on Higher Education and Workforce. Washington, DC:

The National Academies Press. Available: http://www.nap.edu/catalog.php?record_id=13396 [August 2014].

This report recommends the 10 most important actions that Congress, state governments, research universities, and others can take to maintain U.S. excellence in research that will help achieve national goals. For each recommendation, the report outlines an implementation strategy, budget considerations, and expected outcomes. Specifically, the report recommends that the federal government (1) adopt stable and effective policies, practices, and funding for university research and development (R&D) and graduate education; (2) provide greater autonomy for public research universities so they can leverage local and regional strengths to compete strategically and respond with agility to new opportunities; (3) strengthen the business role in the research partnership, facilitating the transfer of knowledge, ideas, and technology to society and accelerating "time to innovation" to achieve national goals; (4) increase university cost-effectiveness and productivity to provide a greater return on investment for taxpayers, philanthropists, corporations, foundations, and other research sponsors; (5) create a "Strategic Investment Program" that funds initiatives at research universities critical to advancing education and research in areas of key national priority; (6) the federal government and other research sponsors should strive to cover the full costs of research projects and other activities they procure from research universities in a consistent and transparent manner; (7) reduce or eliminate regulations that increase administrative costs, impede research productivity, and deflect creative energy without substantially improving the research environment; (8) improve the capacity of graduate programs to attract talented students by addressing issues such as attrition rates, time to degree, funding, and alignment with both student career opportunities and national interests; (9) secure for the United States the full benefits of education for all Americans, including women and underrepresented minorities, in science, mathematics, engineering, and technology (STEM); and (10) ensure that the United States will continue to benefit strongly from the participation of international students and scholars in the nation's research enterprise.

14. National Research Council. (2012d). *Rising to the Challenge: U.S. Innovation Policy for Global Economy.* C.W. Wessner and A.W. Wolff, (Eds.), Committee on Comparative National Innovation Policies:

Best Practice for the 21st Century, Board on Science, Technology, and Economic Policy. Washington, DC: The National Academies Press. Available: http://www.nap.edu/catalog.php?record_id=13386 [August 2014].

This report emphasizes the importance of sustaining global leadership in the commercialization of innovation, which is vital to America's security, its role as a world power, and the welfare of its people. Both advanced and emerging nations are pursuing policies and programs that appear to be less constrained than those in the United States. This report argues that more attention should be paid to achieving and benefiting from the outputs of innovation—the commercial products, the industries, and particularly high-quality jobs to restore full employment. America's economic and national security future depends on success in this endeavor.

15. National Research Council. (2013a). *Capturing Change in Science, Technology, and Innovation: Improving Indicators to Inform Policy*. R.E. Litan, A.W. Wyckoff, and K.H. Fealing (Eds.), Panel on Developing Science, Technology, and Innovation Indicators for the Future, Committee on National Statistics, Division of Behavioral and Social Sciences and Education, Board on Science, Technology, and Economic Policy, Division of Policy and Global Affairs. Washington, DC: The National Academies Press.

This report examines science and technology indicators from a number of nations in North America, Europe, Asia, and Australia and offers recommendations on improving the U.S. National Science Foundation's science and technology indicators to better enable the agency to respond to changing policy concerns. In particular, the report examines the use of specific metrics for measuring networks, as well as human and knowledge capital, and notes that indicators of human and knowledge capital could be created by linking existing longitudinal data from agencies and organizations such as the U.S. Census Bureau, the National Center for Science and Engineering Statistics (NCSES), and the Bureau of Labor Statistics. In addition, indicators could be generated to track the flow of knowledge in specific fields of science, which could potentially help answer questions about STEM labor mobility and provide the information needed to better match STEM training to the demand for particular skills. The report offers a number of recommendations for NCSES, including making data quality a top priority, and working with other government agencies and departments to make existing data available and linkable between agencies.

16. OECD. (1996). *The Knowledge-Based Economy*. Paris: Author. Available: http://www.oecd.org/dataoecd/51/8/1913021.pdf [August 2014].

    This OECD report describes the knowledge-based economy and explains why current understanding of this economy is constrained by the extent and quality of the available knowledge-related indicators. The report emphasizes the need to produce and disseminate the specific genres of knowledge that are needed at the time. It distinguishes the "know-what" (knowledge of facts and information) from the "know-why" (knowledge of the laws and principles of nature), the "know-how" (capabilities and practical skills), and the "know-who" (knowing who has each type of knowledge). A well-functioning system cannot simply rely on the knowledge of information and underlying principles gained in school and through basic research (i.e., the know-what and know-why). The system also depends on workers with practical skills (i.e., the know-how) and the invaluable awareness of other workers and their expertise, which is gained through networks, partnerships, and other professional relationships. The report notes four areas for indicator development (knowledge stocks and flows, knowledge rates of return, knowledge networks, and knowledge and learning) and makes recommendations on the development of indicators of the knowledge-based economy, noting that such indicators must start with improvements to more traditional input indicators of R&D expenditures and research personnel. Better indicators also are needed of knowledge stocks and flows, particularly relating to the diffusion of information technologies, in both the manufacturing and service sectors; social and private rates of return on knowledge investments to better gauge the impact of technology on productivity and growth; the functioning of knowledge networks and national innovation systems; and the development of human capital.

17. OECD. (1997). *National Innovation Systems.* Paris: Author. Available: http://www.oecd.org/dataoecd/35/56/2101733.pdf [August 2014].

This report explores the web of interactions among institutions, researchers, and private firms that make up national innovation systems and identifies best practices. It notes that an effective innovation system produces revolutionary advances both within the research system and beyond, relying on networks of institutions and researchers to integrate, transform, and disseminate discoveries in diverse fields. The report reflects the first phase of a two-phase OECD project to map knowledge flows and develop indicators for assessing national innovation systems.

18. OECD. (2000). *The Impact of Public R&D Expenditure on Business R&D.* D. Guellec and B. Van Pottelsberghe, Directorate for Science, Technology and Industry (Eds.). Paris: Author. Available: http://dx.doi.org/10.1787/670385851815 [August 2014].

    This report concludes that among the major instruments of government policy, both fiscal incentives and direct funding stimulate business-funded R&D, whereas government- and university-performed research appear to have a crowding-out effect. In short, when the purpose is to increase business-funded R&D, it is apparently better to give money than knowledge to business. However, it must be kept in mind that publicly produced knowledge may result in technology that is used by business while not inducing it to increase its research expenditure. Moreover, it is not the major purpose of government laboratories to produce knowledge for the business sector. For university research, barriers to the transfer of knowledge to business can be mitigated by government (targeted) funding of business R&D. And whereas the crowding-out effect is immediate (contemporaneous with the research spending), spillovers may take time to reach industry, beyond the horizon of the assessment.

19. OECD. (2002). *The Global Competition for Talent: Mobility of the Highly Skilled.* Paris: Author. Available: http://www.oecd.org/sti/stpolicy/talent [August 2014].

    This report analyzes international flows of human resources in science and technology, relying on the most recent data on policies and research performance assessments from OECD member and observer countries. The findings reported suggest that global innovation has increased as the international mobility of highly skilled workers has become more complex and frequent, and as more economies have come to participate in R&D and innovation activity. Consequently, competition for talent is now influencing innovation policy initiatives across the globe. The report recommends addressing shortcomings in national policies that may limit the domestic supply of skilled workers, and ensuring that the wider environment for innovation and scientific endeavor is sound.

20. President's Council of Advisors on Science and Technology. (2012). *Transformation and Opportunity: The Future of the U.S. Research Enterprise*. Washington, DC: Executive Office of the President. Available: http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_future_research_enterprise_20121130.pdf [August 2014].

    This report documents the importance of research and recommends a number of steps to strengthen the U.S. research enterprise. It explains why, according to the classic public good argument, the federal government must fund basic research.

21. U.S. Congress. (1986). *Research Funding as an Investment: Can We Measure the Returns? A Technical Memorandum.* Office of Technology Assessment. Washington, DC: U.S. Government Printing Office. Available: http://www.princeton.edu/~ota/disk2/1986/8622_n.html.

    This report, requested by the Task Force on Science Policy of the House Committee on Science and Technology, explores whether the use of quantitative mechanisms associated with the concept of "investment" might allow for the meaningful prediction and measurement of research returns. The report concludes that while some quantitative techniques might prove useful to Congress in evaluating specific areas of research, basic science is not amenable to the type of economic analysis that might prove useful for applied research or product development. Even in the business community, the report concludes, decisions about research are much more the result of open communication followed by judgment than of quantification. The American research system endures and succeeds because it is complex and pluralistic, depending on various players (e.g., scientists, citizens, administrators, Congress) to reach final decisions on funding. Expert analysis, openness, experience, and expert judgment are better tools than economic quantitative methods, according to the report.

22. U.S. Department of Commerce. (2012). *The Competitiveness and Innovative Capacity of the United States*. Washington, DC: Author. Available: http://www.commerce.gov/sites/default/files/documents/2012/january/competes_010511_0.pdf [August 2014].

    This report, prompted by the America COMPETES Act, finds that the competitiveness of the United States can be improved by focusing on three pillars that historically helped unleash the innovative potential of the private sector: federal support for basic research; education; and competitive, cutting-edge technological infrastructure (e.g., helping rural areas gain broadband Internet access). All three pillars are areas in which the federal government has made, and should continue to make, significant investments.

D

The Study Process

The committee conducted this study over a year and a half, meeting four times during 2013. In organizing and conducting the study, we had the benefit of collaboration with a number of other groups within the National Academies, in particular the Board on Science, Technology, and Economic Policy; the Committee on Science, Engineering, and Public Policy; the Government-University-Industry Research Roundtable; the University-Industry Demonstration Partnership; the Committee on Research Universities; and the Committee on National Statistics' Panel on Developing Science, Technology, and Innovation Indicators for the Future. All of these groups have conducted studies and conferences relevant to this study.

In addition to the work of these groups, myriad studies have been conducted on quantifying the impacts of research, in particular on the economic returns on investments in research. We began our work with a review of these studies, which were summarized by staff for our discussion. Some of the major studies, including those conducted in Australia, Canada, and the United Kingdom, are included in the annotated bibliography in Appendix C.

We also benefited from many contemporaneous conferences, workshops, and other meetings at which we were represented by committee members or staff. These meetings were organized by the American Academy of Arts and Sciences, the Association of Public and Land-Grant Universities, the Brookings Institution, the Committee on Institutional Cooperation, the Innovation Policy Forum, the Information Technology and

Innovation Foundation, the Massachusetts Institute of Technology, the National Bureau of Economic Research, the Quebec City Conference, the National Science Foundation, Thomson Reuters, and Time/Qualcomm, among others. Many other individuals and groups shared research with us, including The Battelle Memorial Institute; the OECD Directorate for Science, Technology and Industry; and the Working Group on the Value of Biomedical Research of the National Institutes of Health (NIH) Scientific Management Review Board.

With the benefit of these many studies and meetings, we were able to focus attention at our own meetings on other specific topics in greater depth. Committee members prepared presentations for us in their relevant areas of expertise and wrote or reviewed text based on those presentations for this report. Staff of National Academies committees conducting relevant studies met with us to discuss the implications of their work for our study.

In addition, we benefited from presentations by and discussions with a number of other experts, including Bruce B. Darling, executive officer, National Academy of Sciences and National Research Council, and former University of California vice president for laboratory management; Regina Dugan, senior vice president for advanced technology and projects, Motorola Mobility, and former director of the Defense Advanced Research Projects Agency; Lee Fleming, professor, Department of Industrial Engineering and Operations Research, University of California, Berkeley; Robert Fri, Resources for the Future, who chaired National Academies studies reviewing research and development programs of the Department of Energy; Ilan Gur, program director and technology to market senior advisor, Advanced Research Projects Agency-Energy; and Michael F. Molnar, director, National Institute of Standards and Technology (NIST) Advanced Manufacturing Office and director, NIST Advanced Manufacturing National Program Office.

With our guidance, staff incorporated our presentations and discussions, along with text prepared by our members, into preliminary drafts of this report. We reviewed these drafts at both our third and fourth meetings, and at many times between these meetings and thereafter, and reached consensus on our findings and overarching conclusion. This report benefited from our own careful review, as well as that of reviewers appointed by the National Academy of Sciences.

E

Biographical Sketches of Committee Members and Staff

Richard F. Celeste (*Chair*) was president of Colorado College, where he served until 2011. He was director of the Peace Corps from 1979 to 1981 and served as U.S. ambassador to India from 1997 to 2001. He was governor of Ohio from 1983 to 1991, following which he served as managing partner in the consulting firm of Celeste & Sabety, Ltd. Mr. Celeste graduated magna cum laude from Yale University, where he remained for one additional year as a Carnegie teaching fellow. In 1961, he went to Oxford University as a Rhodes scholar. He returned to Yale in 1963 for graduate study, working as curriculum advisor and part-time civics teacher.

Rodney A. Brooks is Panasonic professor of robotics emeritus, Massachusetts Institute of Technology (MIT). He is a robotics entrepreneur and founder, chairman, and chief technical officer (CTO) of Rethink Robotics (formerly Heartland Robotics). He is also a founder, former board member, and former CTO of iRobot Corporation. Dr. Brooks was the director (1997-2007) of the MIT Artificial Intelligence Laboratory and then of the MIT Computer Science & Artificial Intelligence Laboratory. He also held research positions at Carnegie Mellon University and MIT and a faculty position at Stanford University. He served as a member of the International Scientific Advisory Group of National Information and Communication Technology Australia and the Global Innovation and Technology Advisory Council of John Deere & Co. His research interests are in computer vision, artificial intelligence, robotics, and artificial life. Dr. Brooks received degrees in pure mathematics from the Flinders University of

South Australia and a Ph.D. in computer science from Stanford University in 1981.

Alicia Carriquiry is distinguished professor of statistics at Iowa State University. Her research interests are in Bayesian statistics and general methods. Her recent work focuses on nutrition and dietary assessment, as well as on problems in genomics, forensic sciences, and traffic safety. Dr. Carriquiry is an elected member of the International Statistical Institute, a fellow of the Institute of Mathematical Statistics, and a fellow of the American Statistical Association. She has served on the executive committee of the Institute of Mathematical Statistics, of the International Society for Bayesian Analysis, and of the American Statistical Association and was a member of the board of trustees of the National Institute of Statistical Sciences. She holds an M.Sc. in animal science from the University of Illinois, an M.Sc. in statistics, and a Ph.D. in statistics and animal genetics from Iowa State University.

Steven Ceulemans, National Academies Christine Mirzayan science and technology policy graduate fellow and consultant, is vice president of innovation and technology for the Birmingham Business Alliance, where he supports the growth of the Alabama knowledge economy through technology-based economic development in the Birmingham region. He previously served as director of technology commercialization for the New Orleans BioInnovation Center, growing technology start-ups in New Orleans, Louisiana. He worked in research and development roles for a number of organizations, including the PwC Health Research Institute, Software AG, the Louisiana Cancer Research Consortium, Tibotec (Johnson & Johnson), Procter & Gamble, and the Joint Research Centre (European Commission). In 2010, Mr. Ceulemans received the Louisiana Governor's Technology Award as Academic Technology Leader of the Year. He is a doctoral candidate in health systems management at Tulane University and holds master's degrees in international business from Vlekho Business School in Brussels and in biochemistry and molecular biology from Louisiana State University Health Sciences Center in New Orleans.

Christopher M. Coburn is vice president, research ventures and licensing, Partners HealthCare, where he is responsible for commercial application of health care innovations. Representing Brigham and Women's Hospital, Massachusetts General Hospital, and McLean Hospital, Partners HealthCare is the largest academic research enterprise in the United States, with nearly $1.5 billion in sponsored research. Prior to joining Partners, Mr. Coburn was founding executive director of Cleveland Clinic Innovations, Cleveland Clinic's corporate venturing arm. During his 13-year tenure, Cleveland Clinic spun off 57 companies that raised more than $700 million in equity financing. Mr. Coburn has served on many corporate and community boards, including those of Autonomic Technologies, Explorys, and the U.S. Enrichment Corporation. He is a former vice president and general manager of Battelle Memorial Institute. He served under Governor Richard Celeste as Ohio's chief technology officer. He has consulted, testified, and spoken on innovation and commercialization throughout North America and in nearly 30 countries. He holds a bachelor's degree in political science from John Carroll University and an M.P.A. from George Washington University.

Stephen E. Fienberg is Maurice Falk University professor of statistics and social science in the Department of Statistics, the Machine Learning Department, the Heinz College, and Cylab at Carnegie Mellon University. A leader in the development of statistical methods for the analysis of multivariate categorical data, he also has worked on the development of statistical methods for large-scale sample surveys and censuses, such as those carried out by the federal government, and on the interrelationships between sample surveys and randomized experiments. His current research includes technical and policy aspects of privacy and confidentiality and methods for the analysis of network data. Dr. Fienberg also has been active in the application of statistical methods to legal problems and in assessment of the appropriateness of statistical testimony in actual legal cases, and he has linked his interest in Bayesian decision making to the issues of legal decision making. Dr. Fienberg is cochair of the National Academies Report Review Committee. He is a fellow of the American Academy of Arts and Sciences and the Royal Society of Canada. He holds a Ph.D. in statistics from Harvard University.

Ann R. Griswold is a science and health writer and the owner of SciScripter Writing & Editing, through which she prepares content for universities, medical organizations, scientific academies, and other nonprofit organizations. She was previously media and communications manager for the *Proceedings of the National Academy of Sciences.* She holds a Ph.D. in biomedical sciences from the University of Florida, an M.A. in science writing from Johns Hopkins University, and a B.S. in microbiology from the University of Maryland. She is certified by the Board of Editors in the Life Sciences.

Bronwyn H. Hall is professor of economics (emerita), University of California, Berkeley, and professor of economics of technology and innovation, University of Maastricht, the Netherlands. Her research focuses on the economics and econometrics of technical change. She is coeditor of the *Handbook of the Economics of Innovation*. Her current research includes comparative analysis of the U.S. and European patent systems, the use of patent citation data for the valuation of intangible (knowledge) assets, comparative firm-level investment and innovation studies (the G-7 economies), measurement of the returns to research and development (R&D) and innovation at the firm level, and analysis of technology policies such as R&D subsidies and tax incentives and of recent changes in patenting behavior in the semiconductor and computer industries. Dr. Hall has made substantial contributions to applied economic research through the creation of software for econometric estimation and of firm-level data for the study of innovation, including a widely used database on U.S. patents. She is a research associate of the National Bureau of Economic Research and the Institute for Fiscal Studies, London. She is also founder and partner of TSP International, an econometric software firm. She holds a B.A. in physics from Wellesley College and a Ph.D. in economics from Stanford University.

John E. Kelly, III is senior vice president and director, research, International Business Machines Corporation (IBM). He directs the worldwide operations of IBM Research, with approximately 3,000 scientists and technical employees at 12 laboratories in 10 countries around the world, and helps guide IBM's overall technical strategy. His top priorities are to stimulate innovation in key areas of information technology and quickly bring those innovations to market, to sustain and grow IBM's existing business and create new businesses, and to apply these innovations to help IBM clients succeed. Dr. Kelly also leads IBM's worldwide intellectual property efforts. IBM has led the world in U.S. patents for 19 consecutive years, generating more than 6,000 patents in 2011 and delivering more than $1 billion per year in income from its intellectual property. Dr. Kelly was previously senior vice president of IBM technology and intellectual property and vice president of systems, technology, and science for IBM Research. He has served on the National Research Council's Computer Science and Telecommunications Board. He holds an M.S. in physics and a Ph.D. in materials engineering from Rensselaer Polytechnic Institute.

Josh Lerner is Jacob H. Schiff professor of investment banking at Harvard Business School and head of its entrepreneurial management unit. His research focuses on issues concerning technological innovation and public policy, in particular on the structure and role of venture capital and private equity organizations and on innovation policies and how they impact firm strategies. He codirects the National Bureau of Economic Research's Productivity, Innovation and Entrepreneurship Program. Dr.

Lerner founded and runs the Private Capital Research Institute, a nonprofit devoted to encouraging access to data and research on venture capital and private equity. He is a recipient of the Swedish government's 2010 Global Entrepreneurship Research Award. He holds a Ph.D. in economics from Harvard University.

David C. Mowery is professor of new enterprise development, Walter A. Haas School of Business, University of California, Berkeley. He holds the William A. & Betty H. Hasler chair in new enterprise development, Haas Business and Public Policy Group. He has served as an adviser to OECD and a number of government agencies and industrial firms. His research interests include the impact of technological change on economic growth and employment; management of technological change; and international trade policy and U.S. technology policy, especially high-technology joint ventures. Dr. Mowery has written on industrial leadership, the global computer software industry, competitiveness strategy for the global chemicals industry, and collaborative R&D, among other topics. He holds a B.A. and a Ph.D. in economics from Stanford University.

Jason Owen-Smith is Barger Leadership Institute professor and associate professor of sociology and organizational studies and director of the Barger Leadership Institute at the University of Michigan. Dr. Owen-Smith is a sociologist who examines how science, commerce, and the law cohere and conflict in contemporary societies and economies. His research examines the dynamics of high-technology industries, the commercialization of academic research, and the science and politics of human embryonic stem cell research. He seeks to understand how organizations, institutions, and networks can maintain the status quo while generating novelty through social transformations, scientific discoveries, and technological breakthroughs. Dr. Owen-Smith is the recipient of a National Science Foundation Faculty Early Career Development Award and an Alfred P. Sloan Foundation Industries Studies fellowship in biotechnology. He holds a Ph.D. in sociology from the University of Arizona.

John Edward Porter is a partner in the international law firm of Hogan Lovells US LLP. He served 21 years as U.S. Congressman from the 10th district in Illinois, serving on the Appropriations Committee and as chair of the Subcommittee on Labor, Health and Human Services, and Education. His subcommittee had jurisdiction over all of the federal government's health programs and agencies (including the National Institutes of Health [NIH] and the Centers for Disease Control and Prevention, but excepting the Food and Drug Administration) and education programs and agencies. During his chairmanship, he led efforts resulting in doubling of the funding for NIH. Mr. Porter was founder and cochairman of the Congressional Human Rights Caucus, a voluntary association of more than 250 members of Congress working to identify, monitor, and end human rights violations worldwide. He coauthored the legislation creating Radio Free Asia and served as chair of the Global Legislators Organized for a Balanced Environment. He currently chairs Research!America and is vice chair of the Foundation for the National Institutes of Health. He is a member of the boards of the PBS Foundation and the First Focus Campaign for Children. He is a member of the Bretton Woods Committee, the Inter-American Dialogue and the Council on Foreign Relations. Previously, he was chairman of PBS and a trustee of the Brookings Institution and served on boards of the RAND Corporation, the American Heart Association, and the John F. Kennedy Center for the Performing Arts. Among more than 275 awards for his service in Congress is the Mary Wood Lasker Award for Public Service. Before his election to Congress, Mr. Porter served in the Illinois House of Representatives and prior to that as an honor law graduate attorney with the U.S. Department of Justice in the Kennedy administration. He attended Massachusetts Institute of Technology, and is a graduate of Northwestern University and, with distinction, of the University of Michigan Law School. He holds 10 honorary degrees. The John Edward Porter Neuroscience Research Center on the NIH campus is named in his honor. Mr. Porter is a member of the Institute of Medicine and the 2014 recipient of the National Academy of Sciences Public Welfare Medal, the Academy's highest honor.

Stephanie S. Shipp is deputy director and research professor, Social and Decision Analytics Laboratory, Virginia Bioinformatics Institute, Virginia Tech, National Capital Region. Her research focuses on the intersection of the science of big data, resiliency, and metropolitan analytics. Previously, she was a senior research staff member, Institute for Defense Analysis Science and Technology Policy Institute (IDA STPI), and she is currently an adjunct staff at IDA STPI. Dr. Shipp specializes in the assessment of science and technology projects, programs, and portfolios. Her work spans topics related to innovation and competitiveness, with emphasis on advanced manufacturing, the role of federal laboratories, and funding of high-risk/high-reward research. She was previously director of the Economic Assessment Office in the Advanced Technology Program at the National Institute of Standards and Technology. Prior to that, she led economic and statistical programs at the Census Bureau, the Bureau of Labor Statistics, and the Federal Reserve Board. She was a member of the international advisory board for VINNOVA, Sweden's innovation agency, and led expert panels in 2012 and 2014 that evaluated the Swedish Research Council's Linnaeus Grants, which provide direct government funding to research fields to increase Sweden's competitiveness. Dr. Shipp holds a Ph.D. in economics from George Washington University.

Miron L. Straf (*Study Director*) is deputy director (special projects) of the Division of Behavioral and Social Sciences and Education at the National Research Council. Previously, he served as director of the division's Committee on National Statistics and was at the National Science Foundation, where he worked on developing the research priority area for the social, behavioral, and economic sciences. Dr. Straf served on the faculty of the University of California, Berkeley, and the London School of Economics and Political Science and was president of the American Statistical Association. He received the American Association of Public Opinion Research's Innovators Award for his work on cognitive aspects of survey methodology. His major research interests are government statistics and the use of statistics and research for public policy decision making. He holds a Ph.D. in statistics from the University of Chicago.

Gregory Tassey is a research fellow in the Economic Policy Research Center, University of Washington. His major fields of research are the economics of innovation, technology-based economic growth policies, and impact analysis of research and development programs. His research has been published in policy and economics journals, and he is the author of four books, the most recent of which is *The Technology Imperative*. He previously was a senior economist in the National Institute of Standards and Technology and served as cochair of the White House National Science and Technology Council's Interagency Working Group on Advanced Manufacturing. Dr. Tassey holds a B.A. in physics from McDaniel College and a Ph.D. in economics from George Washington University.

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