A Vision for the Future of Center-Based Multidisciplinary Engineering Research: Proceedings of a Symposium

DETAILS

58 pages | 8.5 x 11 |
ISBN 978-0-309-44970-0 | DOI: 10.17226/23645

AUTHORS

Joe Alper, Rapporteur; National Materials and Manufacturing Board; Division on Engineering and Physical Sciences; National Academy of Engineering; National Academies of Sciences, Engineering, and Medicine

A Vision for the Future of Center-Based Multidisciplinary Engineering Research

Proceedings of a Symposium

Joe Alper, *Rapporteur*

National Materials and Manufacturing Board

Division on Engineering and Physical Sciences

National Academy of Engineering

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

THE NATIONAL ACADEMIES PRESS
Washington, DC
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

This activity was supported by Contract No. 10002530 and Award No. EFMA-1539798 with the National Science Foundation. Any opinions, findings, conclusions, or recommendations expressed in this publication and do not necessarily reflect the views of any organization or agency that provided support for the project.

Digital Object Identifier: 10.17226/23645

Printed in the United States of America

Suggested citation: National Academies of Sciences, Engineering, and Medicine. 2016. *A Vision for the Future of Center-Based Multidisciplinary Engineering Research: Proceedings of a Symposium*. Washington, DC: The National Academies Press. doi:10.17226/23645.

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. C. D. Mote, Jr., is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at **www.national-academies.org.**

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

Reports document the evidence-based consensus of an authoring committee of experts. Reports typically include findings, conclusions, and recommendations based on information gathered by the committee and committee deliberations. Reports are peer reviewed and are approved by the National Academies of Sciences, Engineering, and Medicine.

Proceedings chronicle the presentations and discussions at a workshop, symposium, or other convening event. The statements and opinions contained in proceedings are those of the participants and are not endorsed by other participants, the planning committee, or the National Academies of Sciences, Engineering, and Medicine.

For information about other products and activities of the National Academies, please visit nationalacademies.org/whatwedo.

COMMITTEE ON A VISION FOR THE FUTURE OF CENTER-BASED MULTIDISCIPLINARY ENGINEERING RESEARCH

MAXINE L. SAVITZ, NAE,[1] Honeywell, Inc. (retired), *Co-Chair*
DAVID R. WALT, NAE, Tufts University, *Co-Chair*
NADINE AUBRY, Northeastern University
CHERYL R. BLANCHARD, NAE, MicroCHIPS, Inc.
ROBERT D. BRAUN, NAE, Georgia Institute of Technology
CURTIS R. CARLSON, SRI International
JIM C.I. CHANG, National Cheng Kung University, Tainan, Taiwan
MARTHA N. CYR, Worecester Polytechnic Institute
MIKE GREGORY, University of Cambridge
WILLIAM C. HARRIS, Science Foundation Arizona
FRED C. LEE, NAE, Virginia Polytechnic Institute and State University
PHILIP M. NECHES, NAE, Teradata Corporation
MONICA OLVERA DE LA CRUZ, NAS,[2] Northwestern University
DARRYLL J. PINES, University of Maryland
RICHARD RASHID, NAE, Microsoft Research
S. SHANKAR SASTRY, NAE, University of California, Berkeley
EDWIN L. THOMAS, NAE, Rice University
KARAN L. WATSON, Texas A&M University
YANNIS YORTSOS, NAE, University of Southern California Viterbi School of Engineering

Staff

GREG EYRING, Senior Program Officer, National Materials and Manufacturing Board (NMMB)
NEERAJ GORKHALY, Associate Program Officer, NMMB
HENRY KO, Research Assistant, NMMB
JAMES LANCASTER, Acting Director, NMMB
JOSEPH PALMER, Senior Project Assistant, NMMB
MARIBETH KEITZ, Senior Program Associate, National Academy of Engineering
GREG PEARSON, Senior Program Officer, National Academy of Engineering
PROCTOR REID, Director, National Academy of Engineering Program Office
RICHARD ROWBERG, Deputy Executive Director, Division on Engineering and Physical Sciences

Consultant

JOE ALPER, Consulting Writer

---

[1] Member of the National Academy of Engineering.
[2] Member of the National Academy of Sciences.

NATIONAL MATERIALS AND MANUFACTURING BOARD

CELIA MERZBACHER, Semiconductor Research Corporation, *Chair*
RODNEY C. ADKINS, NAE,[1] IBM Corporate Strategy (retired)
MICHAEL I. BASKES, NAE, Bagley College of Engineering
JIM C. I. CHANG, National Cheng Kung University, Tainan, Taiwan
MALCOLM CHISHOLM, NAS,[2] Ohio State University
LEO CHRISTODOULOU, Boeing, Inc.
JACK HU, NAE, University of Michigan
SANDRA L. HYLAND, Consultant
MICHAEL F. MCGRATH, McGrath Analytics, LLC
ROBERT MILLER, IBM Almaden Research Center
EDWARD MORRIS, NCDMM, NAMII
NICHOLAS A. PEPPAS, NAE/NAM,[3] University of Texas, Austin
F. STAN SETTLES, University of Southern California
HAYDN WADLEY, University of Virginia
BEN WANG, Georgia Institute of Technology
STEVE ZINKLE, NAE, University of Tennessee, Knoxville

Staff

JAMES LANCASTER, Acting Director
ERIK B. SVEDBERG, Senior Program Officer
NEERAJ GORKHALY, Associate Program Officer
HENRY KO, Research Assistant
JOSEPH PALMER, Senior Project Assistant

[1] Member of the National Academy of Engineering.
[2] Member of the National Academy of Sciences.
[3] Member of the National Academy of Medicine.

Acknowledgments

This proceedings has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published proceedings as sound as possible and to ensure that it 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 process. We wish to thank the following individuals for their review of this proceedings:

Ann L. Lee, Genentech,
Thomas Litzinger, Pennsylvania State University,
Vilas Mujumdar, Consulting Engineer, Vienna, Virginia,
Robert M. Nerem, Georgia Institute of Technology, and
Julia M. Phillips, Sandia National Laboratories.

Although the reviewers listed above have provided many constructive comments and suggestions, they did not see the final draft of the proceedings before its release. The review of this proceedings was overseen by Arden L. Bement, Jr., Purdue University, who was responsible for making certain that an independent examination of this proceedings was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this proceedings rests entirely with the author and the institution.

The symposium presentations were both interesting and stimulating, and thanks go to each of the speakers for their time and effort. Speakers, in alphabetical order, were Katherine Banks, Andreas Cangellaris, Jean-Lou Chameau, Dean Chang, France Córdova, Frederic Farina, Orin Herskowitz, John Holdren, Arvind Krishna, Richard Miller, Eoin O'Sullivan, David Parekh, Thomas Siebel, and Kelly O. Sullivan.

Contents

APPENDIXES

Acronyms and Abbreviations

AUTM	Association of University Technology Managers
DOE	Department of Energy
ERC	Engineering Research Center
ERIC	Engineering Research and I-Corps Center
FY	fiscal year
I-Corps	Innovation Corps
MID	multi-interdisciplinary center
MRI	magnetic resonance imaging
NAE	National Academy of Engineering
NSF	National Science Foundation
OSTP	White House Office of Science and Technology Policy
PCAST	President's Council of Advisors on Science and Technology
PNNL	Pacific Northwest National Laboratory
R&D	research and development
STEM	science, technology, engineering, and mathematics

1

Introduction

As stated on the website of the Engineering Research Center Association, “The National Science Foundation’s (NSF) Engineering Research Centers (ERCs) are interdisciplinary, multi-institutional centers that join academia, industry, and government in partnership to produce transformational engineered systems and engineering graduates who are adept at innovation and primed for leadership in the global economy.”[1] Since the ERC program’s inception in 1985, NSF has funded 67 ERCs across the United States. NSF funds each ERC for up to 10 years, during which time the centers build robust partnerships with industry, universities, and other government entities that can ideally sustain them upon graduation from NSF support. As of 2015, the ERCs have disclosed 2,215 inventions, been awarded 739 patents, issued 1,339 licenses, spun off 193 companies employing 1,452 people, and graduated 4,057 students with bachelor’s degrees, 3,918 students with master’s degrees, and 4,432 students with doctorates. Currently, NSF supports 19 ERCs, and in 2015, NSF established three new centers with a total initial investment of $55.5 million for breakthrough solutions in compact mobile power, off-grid water treatment, and nature-inspired soil engineering.

To ensure that the ERCs, which NSF considers one of its flagship investments, continue to be a source of innovation, economic development, and educational excellence, NSF commissioned the National Academy of Engineering (NAE) and the National Materials and Manufacturing Board of the National Academies of Sciences, Engineering, and Medicine to undertake a study to articulate a vision for the future of NSF–supported center-scale, multidisciplinary engineering research. This 21-month study, conducted by the ad hoc Committee on the Future of Center-Based, Multidisciplinary Engineering Research, will be forward-looking and will focus on the forces that are likely to shape engineering research, education, and technological innovation in the future. The committee will also assess the associated challenges and opportunities in the center concept for the engineering community and will consider and evaluate the most promising models and approaches for multidisciplinary engineering research that can successfully address these challenges and opportunities. NSF’s ERCs will be used as prominent examples or cases in the study, but the study’s intent is not to evaluate them. The study will also be informed by other models of large-scale, multidisciplinary engineering research in the United States and other parts of the world. The statement of task for the overall study is provided in Appendix C.

As part of this project, the committee organized and convened a 1-day symposium intended to engage the broader engineering community in the study.[2] The Symposium on Exploring a New Vision for Center-Based, Multidisciplinary Engineering Research, held April 6, 2016, in Washington, D.C., featured four plenary panel presentations on the following topics, which are consistent with the themes of the statement of task:

[1] See the National Science Foundation’s Engineering Research Center website at http://erc-assoc.org/, accessed July 27, 2016.

[2] The committee’s role was limited to planning the symposium, and this proceedings has been prepared by the rapporteur as a factual summary of what occurred at the symposium. Statements, recommendations, and opinions expressed are those of individual presenters and participants, and are not necessarily endorsed or verified by the National Academies of Sciences, Engineering, and Medicine, and they should not be construed as reflecting any group consensus.

- The evolving global context for center-based engineering research,
- Trends in undergraduate and graduate engineering education,
- New directions in university-industry interaction, and
- Emerging best practices in translating university research into innovation.

The symposium also featured smaller breakout working groups designed to elicit a broad range of ideas from the attendees.

In addition to planning the symposium, the committee will issue a final consensus report containing findings and recommendations. The consensus report may propose visions for center-scale research in engineering over the next 10 to 20 years and address issues such as new models for innovation that connect center research to real-world impacts; the appropriate role and emerging models for such centers in education and broadening participation; and how to continuously enable breakthrough engineering research by attracting the most innovative and diverse talent in the field. The committee aims to deliver a prepublication version of the report in January 2017 and a final version in April 2017.

HISTORY OF THE ERC PROGRAM

The ERC program was born out of concern about the state of engineering in the United States. In the early 1980s, industry, academic, and government leaders saw that academic engineering programs often lacked prestige and advanced technical capabilities. In addition, the somewhat narrow, theoretical focus of university engineering research programs was often out of step with industry's applications needs, particularly at a time when U.S. manufacturing faced new challenges from global competitors in key areas such as the automotive industry. At the same time, computer industry sectors such as data processing were on the brink of, or already making, revolutionary advances. The belief among many in the engineering community was that the role of the engineer needed to change to accommodate these challenges and opportunities.

NSF sought advice on the purpose and goals of ERCs from engineering leaders through the NAE, and the resulting 1983 NAE symposium report[3] recommended guidelines for an Engineering Research Center program. This document laid out two primary goals: ERCs should improve engineering research and education, and they should help the United States be competitive in global markets. In essence, these goals amounted to an attempt to revolutionize engineering education and research in the United States. The main means to accomplish these goals were academia-industry partnerships that would, among other things, facilitate knowledge and technology transfer, create interdisciplinary cultures on campus, and engage students in advancing technology with industry. "The Engineering Research Center should accustom students to the idea that the engineer does research in order to do, not merely in order to know,"[4] wrote Roland W. Schmitt, a General Electric vice president who served as National Science Board chair from 1984 to 1988.

With a budget of $10 million, the inaugural ERC competition attracted 142 proposals from more than 100 institutions. In April 1985, NSF made awards to fund the first six centers. George Keyworth, who was then-director of the White House Office of Science and Technology Policy, said the funding round "may have been the toughest grant competition in NSF's history."[5] The first-generation ERCs focused on manufacturing and commercial design. Subsequent generations featured an open competition of proposals on various research topics and began to explore information technology, microelectronics, biotechnology, and health care delivery systems. The third generation of ERCs, started in 2008, is now

[3] National Academy of Engineering, *Guidelines for Engineering Research Centers*, National Academy Press, Washington, D.C., 1983.

[4] National Research Council, *The New Engineering Research Centers: Purposes, Goals, and Expectations*, National Academy Press, Washington, D.C., 1986, p. 26.

[5] Ibid, p. 11.

investigating new opportunities in nanotechnology, sensing, and energy systems. At the same time, today's ERCs are nurturing pre-college students' interest in engineering, providing educational opportunities with international partners, and fostering a greater role for small business in ERC innovation.

In introductory remarks to this symposium, NSF Director France Córdova said that by any measure, the ERCs have delivered on the goals of bringing industry, academia, and government together to produce advances in engineering, innovative technologies, and effective solutions that translate into valuable industry-ready products and services. She noted that NSF reports estimate the economic value of ERC-originated products and processes to be in the tens of billions of dollars. That figure, she added, does not include the enormous benefits of those products that have improved health and safety, boosted industrial productivity, and enhanced environmental protection for the United States and the world at large.

While applauding the many successes of the ERCs is appropriate, said Córdova, NSF is deeply aware that the world has changed over the past 30 years, and she cited the Internet and three-dimensional, additive printing as but two examples of advances that are changing engineering and manufacturing. For NSF to remain the place where discoverers are developed and discoveries begin, it is important, she said, to not be satisfied with the status quo and consider if there are new ways to organize multidisciplinary engineering research and education that now only take advantage of today's technologies, but stand to benefit from those yet to come. Hence, this study, which Córdova envisions will be forward-looking and focused on the forces likely to shape engineering research and education.

Addressing the symposium attendees, she asked them to look 20 to 30 years into the future to help NSF develop an inspiring vision for center-scale research in engineering over that timeframe. "We want to hear your thoughts on the most promising models and approaches for multidisciplinary engineering research that can successfully address those challenges and opportunities," said Córdova. In particular, she asked the attendees to keep the concept of convergence in mind during their discussions, for as she put it, convergence represents such an important way of thinking about how engineering, physics, and biology work together with the social, behavioral, and economic sciences, as well as with computing and the information sciences, to drive toward new solutions, new ways of thinking, and new kinds of innovation. She also hoped the discussions would consider ways of organizing center-based research to balance the tension of breaking out of intellectual silos and falling back into them.

To help guide the day's discussions, Córdova posed the following four key questions for the symposium to address:

1. What models might most effectively enable breakthrough multidisciplinary engineering research and discoveries that require center-scale investment, considering the convergence of physical sciences, engineering, the life sciences, and social sciences?
2. What educational models of center-based engineering research programs are best suited to create a more diverse, internationally aware, and flexible talent pool capable of addressing complex real-world problems?
3. What academic-industry-practitioner partnership models might most effectively promote advances in user-inspired basic and translational research?
4. What metrics can be used to define successes and risks of such centered programs?

In considering these four questions, Córdova said NSF is interested in making sure that the ERCs are focusing on the research opportunities that have great potential for impact. "That is a big concern for us, especially as disciplinary boundaries are collapsing," she said. NSF is also concerned, she noted, that the ERCs going forward will keep pace with the way the innovation process has changed over the past 30 years while continuing to have a major impact on engineering education.

In concluding her remarks, Córdova shared an observation that Microsoft co-founder Bill Gates made about forecasting the future in an era of accelerating scientific and technological change. He said that forecasts will always overestimate the change that will happen in 2 years and underestimate the change that will occur over 10 years, with the point being that visions of what can be accomplished in a decade tend to fall far short of what can actually be done. With that in mind, she asked the participants to "think broadly, think big picture, and think way out of the box. Help us create a bold new paradigm for the ERC program, and NSF will do its very best to fulfill your vision."

ORGANIZATION OF THIS PROCEEDINGS

The symposium (see Appendix A for a copy of the symposium agenda) was organized by the committee in accordance with the procedures of the National Academies. The committee's role was limited to planning the symposium, and this proceedings has been prepared by the rapporteur as a factual summary of what occurred at the symposium. Statements, recommendations, and opinions expressed are those of individual presenters and participants and are not necessarily endorsed or verified by the National Academies, and they should not be construed as reflecting any group consensus. This proceedings summarizes the presentations and discussions that occurred throughout the symposium that will serve as input for the committee's subsequent deliberations to meet the goals of the study outlined above.

Chapter 2 provides an overview of the evolving global context for center-based engineering research, and Chapter 3 discusses new directions in university-industry interactions. Chapter 4 describes some of the trends in undergraduate and graduate engineering education, and Chapter 5 presents some emerging best practices in translating university research into innovation. Chapter 6 recounts the closing remarks made by John Holdren, director of the White House Office of Science and Technology Policy, and Chapter 7 presents some of the common themes and additional thoughts from two breakout sessions. Opinions expressed in these chapters are those of the speakers and do not necessarily reflect the views of the study committee. A full set of slides presented by the speakers as well as videos of their talks is available online.[6]

[6] National Academy of Engineering, "Exploring a New Vision for Center-Based, Multidisciplinary Engineering Research: Meeting Presentations and Video," April 6, 2016, https://www.nae.edu/Projects/147474/147561.aspx.

2

The Evolving Global Context for Center-Based Engineering Research

The symposium's first panel session featured three presentations designed to stimulate discussion about engineering research in the broader international context. The three panelists were Arvind Krishna, senior vice president for global research at IBM; Eoin O'Sullivan, director of the Centre for Science, Technology, and Innovation Policy at the University of Cambridge; and Jean-Lou Chameau, president of the King Abdullah University of Science and Technology. An open discussion moderated by David Walt, university professor at Tufts University, followed the presentations.

DATA AND ANALYTICS TO DRIVE INNOVATION

A common thread connecting some of the world's most pressing problems, such as how to help people age well, maximize water efficiency, assure food safety, reduce pollution, and manage energy production, is data, vast amounts of data, said Arvind Krishna. High-quality data are a critical resource, he said, and there is a need for new science to extract value from data to create a radically more efficient infrastructure that will enable the United States to continue to be a global leader technologically and economically. As an example, he said a small electrical grid can produce 150 petabytes of data that is just waiting to be analyzed in a way that would almost certainly lead to more efficient operations. Similarly, a single oil well can produce terabytes of data per day. Currently, the vast majority of those data are discarded, simply because the data producers do not know how to use it. Yet by some estimates, said Krishna, the output of existing wells could be improved by as much as 30 percent if operated more efficiently.

Enabling the analytical processes that would produce the type of productivity improvements Krishna envisions requires high-resolution, real-time, open data sets and new methods of getting shared value out of closed data sets, such as anonymized consolidated electronic health records, seismic exploration data, and the results of drug development efforts. One role for the next-generation ERCs, said Krishna, should be to generate open data sets and methods for mining closed data sets in a way that protects intellectual property rights. Another focus should be on creating new information theory for making mission-critical decisions with data using high-performance computing. He noted that while NSF has played an important role in developing high-performance computing, the entire computer industry, including the processor and semiconductor segments, are having an impact in this area—and are in turn impacted by it—at a scale that is "vastly underestimated by the average individuals."

Cognitive computing is making important strides, with important contributions from industry and academia, said Krishna, but further advances will require the development of new science in both hardware and software development. Krishna believes, as an example, that more work is needed to measure the entropy of data sets to determine the quality, richness, and diversity of a data set and whether it is complete enough to enable cognitive computing applications, such as anomaly detection, with context and behavioral analysis that ensures privacy. New science could also enable applications in the areas of risk-based capacity planning for infrastructure development, control of viral propagation, and computational creativity.

While new processor technologies using field-programmable gate arrays, for example, and advanced graphical processing units are producing multiple-fold improvements over traditional computing with regard to machine learning, those kind of incremental advances will not change the game, said Krishna. Neuromorphic computing, inspired by the architecture and operations of the brain, has already improved processing time on selected video tasks by three orders of magnitude, he said, but highly speculative technology still being investigated could increase the speed for training neural networks by four to five orders of magnitude. The timeline for turning these proof-of-concept demonstrations into implemented technologies will be longer than most companies can support, however, so this is a place where NSF could play a role through its centers by bringing researchers from academia and industry together to shorten that timeline. "The nation stands to benefit on the order of trillions of dollars if we can do that," said Krishna.

GLOBAL TRENDS AND INNOVATION POLICY

A number of global megatrends are shaping national economies and their innovation systems, said Eoin O'Sullivan, and these include threats to global stability, digitalization, globalization, demographic changes, changing consumer habits, accelerating product life cycles, external industrial policy trends, urbanization, and a focus on sustainability. While the precise list of innovation policy responses and emphases will change depending on a country's industrial strengths and specific challenges, there is a consensus among those who think about such issues on how policy might respond. These responses will highlight a sense of urgency and draw more attention to challenge-led innovation. As a consequence, said O'Sullivan, there will be a greater emphasis on engaging a broader range of users who have something to say about these far-ranging societal problems. Innovation policy will focus on steps to increase the speed of translating innovation into the marketplace, not just with respect to promoting the development of new prototypes and establishment of test beds, but also addressing scaling and manufacturability. Policy is also expected to stress global connectedness of innovation centers, yet also reflect the tension between collaboration and the need to capture value in a way that ensures an appropriate net flow of knowledge and innovation to the home country.

One change for centers that Sullivan believes will be important will be an increasing emphasis for them to fit into a broader system context, to connect to other innovation actors, such as the national research laboratories, applied research and development (R&D) institutes, and national metrology laboratories. Innovation policy, he predicted, will more easily enable linkages between these different components of an innovation ecosystem, which in turn will attract R&D funds at a time when such funds are becoming globally mobile.[1] Today, he noted, U.S.-headquartered companies are spending almost as much on R&D outside the country as inside the United States.[2] Recently, he said, Asia has become the number one destination for investment in corporate R&D.

The sense of urgency from competition that nations are feeling is reflected in recent policy documents of many national governments around the world referring to center-based programs, said O'Sullivan. While this may always be the case for countries such as Ireland and Singapore that rely heavily on R&D as a core component of national economic policy, this trend is new for nations such as Germany and the United Kingdom. These policy documents are not only stressing the importance of research centers as sources of innovation, but also their role as honest brokers in helping to develop supply chains and arrange for interactions and collaborations among larger firms. Research center administrators and staff, said O'Sullivan, are now trying to understand how they need to create and

[1] B. Jaruzelski, K. Schwartz, and S. Volker, 2015, Innovation's new world order, *Strategy+Business*, Issue 81 (Winter), October 27.

[2] B. Jaruzelski, K. Schwartz, and V. Staack, "Where Companies Spend Their R&D Money," [interactive], *Strategy+Business*, Issue 81 (Winter), October 27, 2015

nurture an environment that creates a visible critical mass of expertise to draw in corporate investment in an increasingly competitive global environment.

At the same time that countries talk more about national value capture, their innovation policies are emphasizing the need for their centers to be connected globally to other centers. There is an interesting ongoing debate, said O'Sullivan, about net knowledge flow at a time when nations with mature innovation economies are partnering with countries whose innovation economies are less mature. This division of labor tends to have engineering and scientific research take place in the more mature nations while prototyping, scale-up, and manufacturing occur in what he called the "catch-up" economies.

Another trend O'Sullivan has noticed has been the increasing number of thematic calls for center proposals rather than more general research calls. As a result, there are an increasing number of national workshops and road-mapping strategies that aim to create new communities and identify networks among individual potential collaborators. These workshops and mapping exercises tend to highlight key barriers to address and prioritize innovation challenges in such a way that the resulting proposals are often better and more thoughtfully crafted. O'Sullivan said he has also seen an increasing emphasis on manufacturability, piloting, and scale-up in research center goals, which has translated into more funding for such activities at the center level and an increasing emphasis on being agile and responsive to market opportunity. In Germany, for example, research center programs are encouraged to transfer to another research institute or center if it offers the opportunity to take advantage of new commercial opportunities.

These trends, said O'Sullivan, have led to centers being more engaged with business schools, economics departments, and experts in operations management. They are also challenging applicants for center programs to state in their proposals how they might engage other partners and leverage the expertise and infrastructure at other innovation institutes to maximize the impact of their work on the high-level global megatrends affecting national economies. This change is occurring even in countries such as Germany, which has its well-established Fraunhofer Institutes that work with industry and universities to scale cutting-edge research into real working technologies on an industrial timetable. Germany's new Forschungscampus Initiative creates center-like endeavors on university campuses to bring together university, government, and industry researchers in partnerships to address challenges that no one organization can tackle.

STUDENT AND FACULTY PERSPECTIVES

Over the past 15 years, said Jean-Lou Chameau, faculty and students are become more mobile, more global, and more opportunistic. Successful senior faculty, he added, have become particularly global, often having their main laboratory on one campus and auxiliary laboratories spread across the country and the world. These laboratories are then networked, creating an interactive, multicultural ecosystem for innovation. The challenge that results from this type of arrangement is for university structure and policy to keep up with these new models that faculty are creating in order to nurture allegiance to the home university. "This is the type of situation that can test the skills of deans and provosts," said Chameau.

At the same time, nations in Asia, Europe, and the Middle East have recognized this trend in faculty mobility and are creating opportunities at research institutes to attract senior faculty and the brightest students. Korea, Singapore, and Switzerland have been particularly adept at developing this type of center, he noted. "The intent is to entice researchers and students with a strong focus and long-term sustained support," said Chameau. "This issue of long-term sustained support is something to think about with regard to the U.S. engineering research centers." In Chameau's opinion, there is an opportunity for U.S. agencies and research universities to consider joint leadership with foreign institutions that are currently driving the creation of such centers. "Universities could integrate their campuses into research networks by building upon the aspirations of faculty and students who are already doing this on their own," he explained.

He also reiterated Krishna's and O'Sullivan's statements that corporations, particularly in Asia, the Middle East, and Europe, have become active participants in, and even drivers of, the creation of these new research centers, even more than they may have been in the past with the ERCs. Today, companies are becoming involved not only in defining the research scope of these centers, said Chameau, but are also bringing new partners to the table and participating in the research mission from the very inception of these centers. One positive result of the private sector's increasing role in center formation, he added, is that there has been an improvement in resolving conflicts of interest and developing commercialization and disclosure policies. In addition, the centers have been given more of a mandate to play a strong role in knowledge transfer and economic development, so much so that the goal of driving innovations and technology transfer have become the vision of these centers and essential components of their design. This is much different from the way universities have been structured in the past. An important aspect of this mandate that Chameau sees playing out in the United States, as well as in his current location in Saudi Arabia, is that centers are actively nurturing and leveraging the entrepreneurial spirit and innovative mindset of students.

International partnerships, with funding from both industry and national research agencies, are becoming more prominent in the newest generation of centers, said Chameau. In Europe, this has created a more reassuring environment for faculty with regard to sustainable funding, which in turn is enabling these centers to acquire the best equipment and attract better-quality researchers. Yet even with the creation of these new centers and more sustainable funding streams, the United States, in his opinion, is still regarded as the place that researchers want to be because of the amazing track record of U.S. institutions and agencies, including NSF. As a result, the United States has a great opportunity to focus on the grand challenges that O'Sullivan listed, which transcend national boundaries, and to be the leader in promoting joint investment in research and human capital worldwide. "I think the NSF could take a strong leadership role and get the benefits, including financial support and resource sharing," said Chameau.

Going forward, Chameau believes that just as Facebook is described as social by design, an increasing number of centers will be global by design. He also predicts that universities will become organized increasingly around research centers rather than being driven by academic units, which is now the case, and become more mission-oriented toward solving the great issues facing society. At the same time, he cautioned, universities and research centers will have to recognize the need for a mix of mission- and goal-oriented research and curiosity-driven research. It is important, he said, to not lose the aspects of the U.S. research enterprise that have made it so successful at both producing the fundamental knowledge that serves as the foundation for innovation and harnessing the entrepreneurial drive that turns knowledge into economic activity. One area in which the United States could do better, however, is in preparing postdocs for life in industry.

In closing, Chameau said that he is a strong believer that the success of the United States in research and innovation comes from tapping into the creativity of the nation's talent and enabling its scientists and engineers to pursue research without a specific product immediately in mind. "Although I told you that I love very much the mission-oriented goal, I think it has to be done in a way that it enables curiosity-driven work," said Chameau. "At the same time, people should be encouraged to take the steps to translation and commercialization. It should be part of their expectation."

DISCUSSION

Keith Roper, from NSF, asked the panelists for their ideas on how to balance global by design with the national boundaries associated with finance and intellectual property. Chameau replied that what he means by global by design is a structure that brings together a group of researchers from different parts of the world who want to pursue an idea and who believe strongly that they will be more successful as a group than as independent players or even working in independent centers. From his experience, he believes that if you have that kind of commitment among the group members, the issues of intellectual property can be resolved, although not always perfectly. O'Sullivan said that increased attention to the global grand challenges he listed is creating more openness to global collaboration because they are of a scale and complexity that no individual country can take them on by themselves. "There will be complementary expertise and capabilities that people will want to reach out to, and as a result there will be a greater scope for a win-win situation in taking on some of these challenges," said O'Sullivan. As a result, he believes it will become easier to align funding mechanisms between countries. He added that his experience in speaking with large R&D-intensive companies about their major partnerships with universities is that they want to better align and connect their investments at different universities and centers around the world. Krishna added that IBM's experience working in 195 countries shows that intellectual property issues are not that hard to solve from a global perspective. What is more difficult to address are data issues because data transfer is often controlled by national laws and regulations.

In response to a question about how funding agencies can help the research community develop ideas for new centers designed around specific goals, Chameau said that NSF has done a good job providing small amounts of seed money on an opportunistic basis for exploring certain ideas that could lead to something bigger. Krishna added that incentives and measurements are important, and that incentives are not necessarily about money, although he did not elaborate further.

Kelly Sullivan, from the Pacific Northwest National Laboratory (PNNL), asked the panelists for their ideas on how to deal with the different incentives, reward structures, and missions of various partners involved in a center. Krishna replied that the key is to acknowledge those differences upfront. Andreas Cangellaris, from the University of Illinois, Urbana-Champaign, noted that the challenge universities face today to retain faculty in "hot" areas of research while still sharing their expertise with industry in a way that is creative and sustainable. Krishna responded that Cangellaris had poached four members of his research team over the past 2 years as a way of illustrating the bidirectional nature of this challenge. "I think it is about creating shared and bidirectional systems and allowing people to move back and forth, albeit for limited amounts of time," said Krishna.

3

New Directions in University Interactions with Industry and National Laboratories

The second panel session aimed to address NSF Director France Córdova's question regarding academic-industry partnership models that might effectively promote advances in user-inspired basic and translational research, in addition to considering university-national laboratory partnerships. The three panelists in this session were David Parekh, corporate vice president for research at United Technologies and director of the United Technologies Research Center; Thomas Siebel, founder and chief executive officer of C3 IoT; and Kelly O. Sullivan, manager of institutional science and technology investments at PNNL. A discussion was moderated by Maxine Savitz, retired general manager for technology partnerships at Honeywell, Inc., and retired vice president of the NAE.

AN INDUSTRY VIEW OF UNIVERSITY PARTNERSHIPS

From his perspective of having spent time in academia and industry, and being a product of an ERC, David Parekh thinks of the relationship between industry and academia in terms of a three-dimensional space, with one axis representing how faculty organize themselves—from individuals to clusters across universities; the second axis representing industry, again ranging from the research an individual company engages in to consortium-based research; and the third axis representing funding sources, ranging from government to industry and combinations of the two. Things work well in each of the quadrants of that three-dimensional space, he said, although how the arrangements are structured will vary. Intellectual property, for example, is simpler to structure when one company is funding one investigator than when there are 10 different corporations and universities involved.

Parekh explained that his experience has taught him that there are five characteristics of successful and sustainable collaborations between industry and academia. The first is alignment and focus on a compelling idea. This does not mean that both parties need to have the same goals—an academic center might want to use a novel company-developed technology, and the company may be interested in cultivating and recruiting talented graduates—but they do need to be aligned on strategy, final outcomes, and metrics.

The second characteristic of a successful collaboration is having a compelling idea, something new that takes advantage of the skills and infrastructure that each collaborator can bring to a particular project. The third characteristic is critical mass—the idea that together the collaborators create a capacity that is more than the sum of what each partner alone can muster.

The fourth characteristic Parekh noted is talent and leadership. "We have seen many collaborations that have the right ingredients but a lack of the right leadership causes them to fall apart," he said. Relationships are the final piece of the puzzle, he added, and the one that sustains the best collaborations. In thinking about ERCs, Parekh said that whatever can be done to promote relationships, to promote engagement among the people involved in a project, is probably the most important factor for ensuring success and sustainability.

Looking ahead, Parekh sees three challenges for centers that can slow progress if not addressed. One is complexity involved in negotiating issues regarding intellectual property, given the multitude of models that companies and universities have. In his mind, the reinvention of intellectual property agreements that occurs every time a new center is formed is a waste of time and energy that causes unnecessary consternation among the partners. Related to this is the fact that industry and academia move at different clock speeds. Industry, he said, operates with a certain sense of urgency, while academia is more deliberative, and both approaches are valuable. The key is to have in place a mechanism that addresses the inevitable conflicts that occur when patience and impatience clash during the discussions that take place when establishing a center involving academic and industrial partners.

Parekh's second challenge involves cybersecurity and protecting the information flowing between collaborators while also creating an environment for the free flow of information among partners. The third related challenge is export control. He noted that if research is conducted in Europe, for example, and the data are sent to a collaborator in the United States, the collaborator may then, depending on the project, not be allowed to send the data back to Europe. "The complexity of managing the flow of information is a fundamental barrier to collaboration," said Parekh.

When thinking about the grand global challenges that previous speakers listed and the technologies being developed today, Parekh sees two overlays that he believes are changing how centers might need to have a different emphasis in the future. One overlay is the need to think in a systems context in a way that integrates that way of thinking into every aspect of how a center operates and approaches a problem. "This is not so much about establishing a multidisciplinary team as it is about the science of integration, about connecting the dots with new models of thought," said Parekh. The second overlay is the dimension of the person, he explained. "Much of our work is on technology, but the human really matters," said Parekh. People's experiences with technology in their lives affects their expectations from companies, which in turn changes how companies conduct business. That human dimension will need to be reflected in how centers are established and operate, he said.

In closing, Parekh called for greater engagement between industry and academia that goes beyond the twice-a-year meeting between researchers and an industry advisory panel. "Industry and academia need to work side by side, and taking away the barriers that prevent that kind of collaboration is important," said Parekh. He also suggested that future centers should focus on compiling and archiving data for the community at large and on developing tools to interrogate high-quality data. Centers could also serve, he said, as compelling models of how to promote engagement and as open sources of tools developed as part of the centers' research efforts.

PHILANTHROPY'S ROLE IN FOSTERING HIGH-IMPACT COLLABORATIONS

In his presentation, Thomas Siebel discussed three examples of multidisciplinary collaborative efforts that he thought could provide some useful insights when considering the future of NSF's ERCs. The first example was the Siebel Scholars, which since 2000 has provided a $35,000 award to the top graduate students selected by the deans from 25 graduate schools at 12 U.S. universities and 4 in Europe and Asia. As of the date of this symposium, the Siebel Scholars community, numbering more than 1,000, has authored 373 patents, founded more than 150 companies, launched more than 1,100 products, founded and operated 57 nonprofits, served on nearly 350 boards of directors, and managed more than $2.7 trillion in assets. In addition, said Siebel, these namesake scholars volunteer for more than 19,000 hours annually.

While these accomplishments are notable, he said the best part of this program is the collaborations that develop among the scholars. Each year, on the occasion of welcoming the new scholars, current and past scholars gather to discuss one topic in depth. For example, the inaugural conference, held in 2000 at the University of Chicago, discussed the threat of nuclear proliferation with guests Alexander Haig, John Major, and Roberts Gates. Other annual gatherings have focused on stem cell research, the U.S. criminal justice system, water supplies, and the economics of alternative energy. The next conference, he noted, will focus on grid cybersecurity.

Out of the gathering on stem cell research, the Siebel Foundation funded the Siebel Stem Cell Institute, a collaboration involving the University of California, Berkeley, the Howard Hughes Medical Institute, and the Stanford Institute for Stem Cell Biology and Regenerative Medicine. This institute now has 83 Siebel investigators from 11 countries and has provided seed grants to support 33 researchers working on 14 innovative collaborative projects, said Siebel.

Discussions among the scholars also led to the founding of the Siebel Energy Institute, an international consortium of universities focused on advancing data analytics research for energy systems, including the smart grid and the oil and gas industry, in an open, collaborative and publicly available manner. One goal of this institute, with initial funding of $10 million, is to use machine learning to dramatically increase the safety and reliability of the power generation grid while lowering costs and reducing its environmental impact. The Siebel Energy Institute has put out calls for papers to advance the science of machine learning in meaningful ways. Awardees are funded to write the papers and then conduct the research that will advance machine learning, with the papers and the research findings all put into the public domain.

COLLABORATING WITH A NATIONAL LABORATORY

The U.S. National Laboratory system comprises 17 institutions that are part of the Department of Energy (DOE) (Figure 3.1). Each laboratory, explained Kelly Sullivan, is owned by the U.S. government, and all but one are operated by contractors. PNNL, her home institution, is operated by Battelle Memorial Institute, and it has four locations in Washington and Oregon, including the only marine research facility in the DOE system. PNNL's $995 million fiscal year (FY) 2015 operating budget, she explained, was funded by a variety of sources, including DOE, the Department of Homeland Security, other U.S. government agencies, and industry.

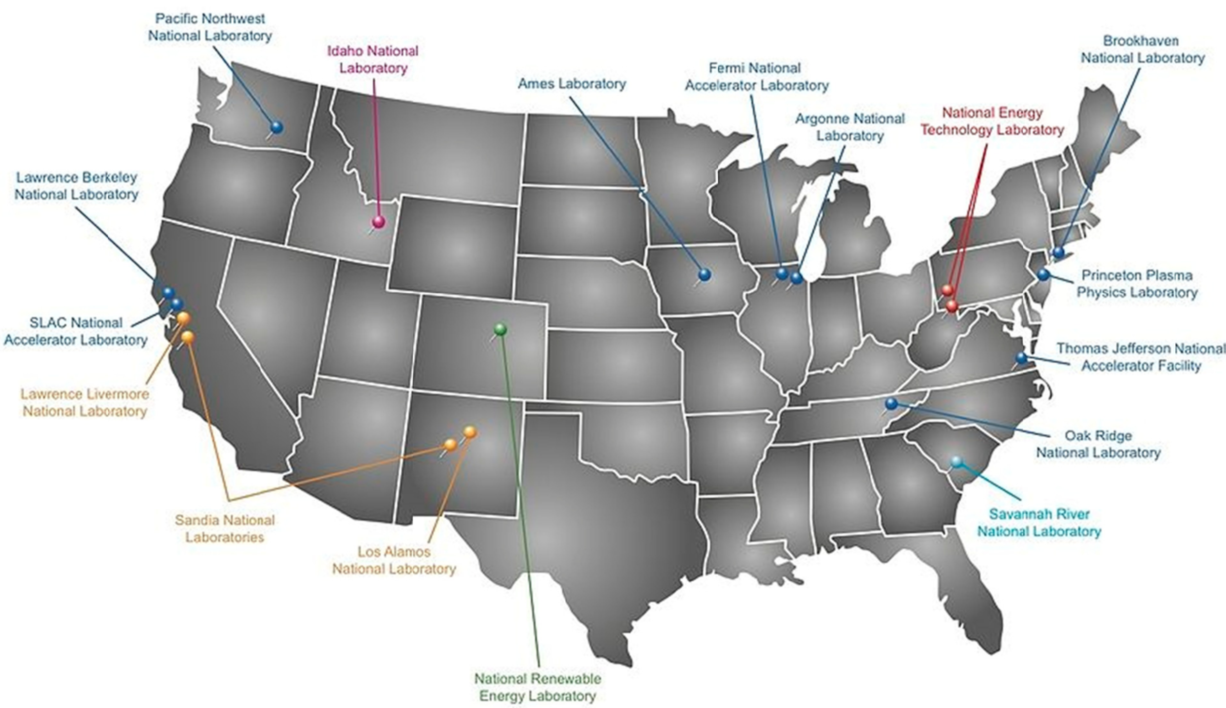

FIGURE 3.1 Locations of the 17 U.S. National Laboratories funded by the Department of Energy. SOURCE: U.S. Department of Energy.

As an example of the type of project PNNL scientists and engineers tackle, Sullivan pointed to the laboratory's work developing algorithms that enable all of the data coming in from a national network of radiation sensors installed at the nation's ports of entry. At one time, the data from this network took 10 days to analyze, but PNNL's team developed software that analyzes the data in 10 seconds. "The Department of Homeland Security now has real-time analysis of data from the nation's ports of entry," said Sullivan. U.S. allies have also deployed this software, she added.

Sullivan noted that PNNL's mission is to "transform the world through courageous discovery and innovation." To fulfill that mission, PNNL operates on a timescale that is somewhat faster than that of a university, creating a challenge for PNNL staff who are interested in working with graduate students on a thesis or dissertation project. "It is doable, but our university partner has to be willing to think about different models," said Sullivan. Such institutions do exist, and PNNL has developed joint appointment programs with Brown University, University of Washington, Washington State University, University of Utah, and others to share, rather than poach, talent. In some cases, PNNL staff work at the partner university; in other cases, faculty or staff work at PNNL. "Everything they do belongs to both institutions, which made the lawyers very uncomfortable," said Sullivan, referring to intellectual property and licensing issues.

PNNL, said Sullivan, has funded a number of joint research institutes, some of which succeeded while others failed. One challenge has been that institute researchers consider themselves to be affiliated with the research institute rather than PNNL, which leaves the broader research community wondering what PNNL brings to the table. "We need to figure out ways where the organizations involved in these research centers, including PNNL, all get credit for the work being done." Sullivan also noted the perverse situation regarding PNNL and the other five national laboratories that Battelle operates for DOE that makes it difficult for her to spend time at one of these other national laboratories. "I would have to change employers, which seems silly but is the truth," said Sullivan, who added that she is trying to develop some mechanism that supports, rather than inhibits, collaborations and staff exchanges between the national laboratories.

In thinking about the next 10 years, Sullivan suggested that the committee that organized this symposium might consider how employment issues can be addressed to enable the most fruitful collaborations. She also thought that universities should think about how to leverage the expertise and infrastructure at the national laboratories that the nation is already supporting. "We want your students to be working with us," said Sullivan. "They energize our staff and they help us be more creative, so think about how we can be a part of your campus. We do not give degrees, but certainly have a great deal to teach."

Referring to the Siebel Energy Institute and its focus on the grid, Sullivan said that PNNL and the National Renewable Energy Laboratory are co-leaders of the Smart Grid Lab Consortium, which she said is working on modernizing the grid and enabling the 3,600 utility operators to work together better. As an example, she noted that although each of the utilities generate data they do not share with one another, they do share data with the consortium under a proprietary agreement to enable research to develop better ways of managing the grid at its maximum capacity. One of the tools the consortium has developed, she said, has enabled PJM, a regional transmission organization that coordinates the movement of wholesale electricity in all or parts of 13 states and the District of Columbia, to save $100 million annually in operating costs.

In closing, Sullivan said, "I just want to make sure people understand that the national laboratories are your asset. They are your resource, so let us figure out how you can take advantage of that system."

DISCUSSION

Maxine Savitz started the discussion by asking Parekh to comment on how other countries are looking at research centers that might be different from the way the United States approaches them.

Parekh replied that he sees differences in terms of focus—for example, Germany's focus on advanced manufacturing technologies such as additive manufacturing. He also said that some countries take a more integrated approach that goes from discovery to commercialization, which he said can foster powerful collaborations. He observed that the rest of the world is trying to copy the United States with regard to establishing technology transfer offices; although he also noted that some of these countries are getting ahead of themselves because they are not yet generating a body of intellectual property that needs protecting and licensing.

Andreas Cangellaris asked Siebel to comment on the role that philanthropic organizations can play in energizing innovation as entrepreneurs try to find ways in which their interests can capitalize on the academic ecosystem and federal funding agencies. Siebel replied that the proliferation of multidisciplinary centers for design, which not only include engineers and scientists but experts in the fine arts, performing arts, liberal arts, and humanities, is leading to "amazingly creative work" in product design and ideation. He believes the proliferation of these centers, with funding from the nonprofit world, bodes well for the future of American product design and innovation.

Cangellaris voiced his opinion that the national laboratories need to start talking openly about the impact they have on the nation's technological development. He called on those organizations that partner with the national laboratories to help get the word out about the enormous value the nation gets from the national laboratories. Sullivan agreed wholeheartedly and added that the Cold War origins of the national laboratories is partly to blame for the low-key approach they have taken to publicity, but that is changing now to some extent, given that the national laboratories now engage in a great deal of unclassified work. Sullivan liked the idea of getting the partners to be more vocal about the role of the national laboratories, noting that it is better when someone else does the bragging.

Responding to a question about funding the riskiest research, and whether that is a place where nonprofit organizations could help, Parekh noted that industry does fund early-stage research through collaborations that address specific fundamental problems that need to be addressed as part of bigger projects. For example, United Technologies is doing cutting-edge research on modeling two-phase flows, but when it needs theoretical work to move the project forward, it turns to partners in academia who are best equipped to do theory development. Siebel then commented that philanthropy is primarily an American phenomenon and that in his opinion, philanthropic organizations that want to make a big impact on important problems should be making big bets on smart people rather than spreading their money around among many projects. Jean-Lou Chameau added that in his experience it is getting harder to fund high-risk projects, and that small, forward-thinking foundations could become ideal partners for such projects.

An unidentified participant asked the panelist for any ideas on how to improve academia's access to research data compiled by the private sector. Parekh said the key is collaboration, although there are barriers to overcome when it comes to providing access to closely held data and intellectual property. In his experience, although answering important questions might require giving up intellectual property, the payback is usually bigger than the cost. The one place where data exchange faces the fewest barriers is when industry participates in a government-funded program. "What is nice about those programs is that there is no debate about the terms and conditions, which makes it easy to get started. Then you can build the joint interests and commonality that makes things easier later," said Parekh.

The final question, from another unidentified participant, asked the panelists for their ideas on how the NSF centers can help students develop good integrative skills, given the growing importance of multidisciplinary research. Sullivan responded that systems integration is something PNNL does a great deal of and her experience has been that students do not have a good understanding of how to work in large teams and communicate across disciplines. Those two skills, and safety training, are areas in which she believes the ERCs should put more emphasis. Parekh said he would emphasize the importance of model-based approaches and platform-based design to reduce the number of iterations it takes to refine technologies and improve the transferability of research into practice and products.

4

Trends in Undergraduate and Graduate Engineering Education

The symposium's third panel session featured presentations from three speakers. Richard Miller, president of the Olin College of Engineering, discussed the innovations in engineering education that his institution has been developing. Katherine Banks, vice president and dean of engineering at Texas A&M University, discussed a new approach to doctoral education. Andreas Cangellaris, dean of engineering at the University of Illinois, Urbana-Champaign, identified some of the trends that are shaping undergraduate education. An open discussion moderated by David Walt followed the three presentations.

A NOVEL APPROACH TO ENGINEERING EDUCATION

For more than 500 years, said Richard Miller, an unquestioned assumption has been that the more a person knows, the better that person's life will be. Today, this assumption plays itself out in getting students prepared to participate fully in the knowledge economy, and in practice this means that educators have been intent with filling students with content. However, there is a problem with this approach. "It is called Google," said Miller, which means that the value of knowing things is decreasing, while the value of using knowledge is increasing. As a result, the knowledge economy is transitioning to a maker economy, one that places value on what someone can do rather than on what they know. Engineering education is adapting to this new world, said Miller, by creating classes that are collaborative, focus on experiential learning, and have students making something. At the same time, teachers are becoming coaches rather than instructors. At his institution, for example, students will have completed some 25 projects by the time they graduate and can present prospective employers with portfolios with photographs and videos of things they have built. Employers report that Olin graduates appear to have the equivalent of a couple of years of experience, which for all intents and purposes they do, because of the emphasis on experiential learning.

Miller predicted, however, that there will soon be another workplace transition that will create what he called the innovation economy. In the innovation economy, the key attribute students will need is the ability to conceive of original ideas and generate insights. He admitted that he has no clear idea how this innovation economy will be organized or even how to best prepare students to thrive in an innovation economy. The best approach at the moment, he said, is to create an environment in which peers and mentors will have a big influence on students—on the assumption that creativity has less to do with an individual's innate skills and talents and more to do with the environment in which they can use those capabilities. "Our best shot is to nurture a student's intrinsic motivation and cultivate design thinking," said Miller.

Design thinking, he explained, is currently embodied by programs such as the Jacobs Institute for Design Innovation, but he offered that design should be the domain of the engineering field. "Applied science is about answering questions about why something happened, but engineering is about envisioning what has never been and doing whatever it takes to make it happen," said Miller. "That is design." Design, he explained, is different than project-based learning, which he likened to learning to paint by numbers, whereas design is painting on a blank canvas. Design is first identifying the problem, conceiving of a solution, and determining what it should look like. "That creativity exercises a different part of the brain," said Miller. Quoting the poet William Butler Yeats, Miller said, "Education is not the filling of a pail, but the lighting of a fire." According to the placement officers he has spoken to, companies are still hiring students who know things, just as they have since the 1950s. However, the highest salaries are going to students who can do things with that knowledge and who can generate new ideas.

Education must change, said Miller, not only for the practical reason of meeting the demands of employers in a maker or innovation economy, but for the bigger reason of addressing the 14 grand challenges the NAE has identified. These are not merely engineering and scientific challenges, these are human challenges, said Miller. Tackling these problems—some of which he blamed on engineering and scientific solutions to problems of the 20th century that were implemented without much societal input—will require more than just engineers and scientists contributing to the new solutions. What is needed, said Miller, is a new kind of engineering innovator, one who can conceive of new ideas that so profoundly change the way people live that they cannot remember the way life was before innovation occurred.

Miller's fear is that the traditional approach to education—one that puts engineering in one place, business and economics in another, and psychology, the arts, and humanities in a third place—may be inhibiting innovation. Each of these areas asks different questions that all must be answered to produce something that is truly innovative. Engineering and science worry about feasibility, business and economics tackle viability, and the arts and humanities ask questions about desirability—all key aspects of true innovation. From that perspective, said Miller, "no amount of doubling down on hard science courses will produce the innovators we need."

Going forward, education needs to cultivate attitudes, behaviors, and motivations among students to enable them to become innovators. These attributes, which Miller said are being embraced by a growing number of companies, includes an entrepreneurial mindset, ethical behavior, teamwork and leadership, a global perspective, interdisciplinary thinking, creativity and design, empathy and social responsibility, and employability skills. He recommended the book *Creating Innovators* by Tony Wagner, which talks about helping students learn to improvise. Miller also suggested that the nation should create a national laboratory for science, technology, engineering, and mathematics (STEM) education innovation.

As a final comment, Miller said that the science and engineering communities talk about research as if it was the highest calling. "Research is important, but creating new prototypes, new models, is also important so that we will have something to research," said Miller. As an example, he referred to the Wright brothers, who invented aviation. "It was later that we discovered the field of aeronautics," said Miller. He closed with his favorite quotation, from Charles Vest, former president of the NAE, who said, "Making universities and engineering schools exciting, creative, adventurous, rigorous, demanding, and empowering milieus is more important than specifying curricular details."

A NEW APPROACH TO DOCTORAL EDUCATION

To begin her presentation, Katherine Banks said that everything Miller spoke about with regard to undergraduate education should also occur at the graduate level. She also noted that in her opinion, the ERCs have been tremendous examples of use-inspired and curiosity-inspired research centers that have benefited the entire nation. In fact, she said, ERC-developed research and educational models that stimulate out-of-the-box and multidisciplinary thinking have often initiated change at the nation's universities, particularly in undergraduate education.

However, she continued, the general model for doctoral education has stayed the same for decades, if not centuries. In this model, an individual student works independently in the laboratory, writes a traditional dissertation, and then presents it to a committee for approval. "Certainly, this model works extremely well, so the challenge is to enhance that model to allow students to experience different types of programs outside of traditional dissertation-focused research," said Banks.

Noting that there are discussions ongoing among faculty at institutions across the nation about the role of the graduate student, Banks said there are a number of questions that these discussions are trying to answer. “How do we define the work environment for these students? How do we define the tasks they must complete for research projects that fund these students? Are they employees or students?” she asked. “What is the workforce driver for these students? Is it the marketplace or is it our own laboratories?” In her opinion, the difficult conversations needed to answer these questions should occur before transformational change can occur in graduate education, adding that faculty become quite concerned by any type of model that would decrease its responsibilities as major professors for graduate students. As an example, her institution recently held discussions about developing new programs for graduate students, an idea strongly supported by faculty members. However, when asked if they would release their students so they could participate in a summer program outside of their laboratories, there was “quite a bit of reluctance to take that step,” said Banks.

One question that her institution has been asking lately is why doctoral education focuses on turning out academicians when the majority of its Ph.D. students get jobs in industry or at the national laboratories. “We know that 92 to 93 percent of our Ph.D. students move into industry or the national laboratories, yet they have received no training or opportunity for training in business, in communication, or in working in large teams,” said Banks. An approach her institution has implemented to address this problem has been to allow engineering Ph.D. students to compile a portfolio of projects, papers, and disclosures as proof they have mastered their subject rather than writing the traditional dissertation.

Another problem with graduate education, said Banks, is that students, by and large, have no opportunity to make connections with the national laboratories or industry. Her institution is trying to include industry internships as part of the Ph.D. program. Texas A&M has also developed a strong professor of practice program in which individuals with significant levels of industry experience come to the university as full-time employees, not adjunct professors. The university currently has some 60 professors of practice and is aiming to have 100 in the engineering college. One benefit of this program has been an increased appreciation among faculty for the high-caliber fundamental research taking place in industry. Another benefit has been to bring an industry perspective to both the classroom and the laboratory. There is currently ongoing debate about whether these professors of practice should serve as major professors for doctoral students and whether there should be a co-advisor from among the tenure-track faculty.

As a final thought, Banks reiterated Miller’s call to increase the focus on entrepreneurship in graduate engineering education, to allow students to focus on creation rather than just directed research on a specific topic. This idea is quite popular with graduate students at Texas A&M, she said, with the extra unintended benefit of increasing interactions between graduate students and engineering undergraduates. She did note that one challenge will be changing the perspective of international graduate students, who come into Ph.D. programs with a certain expectation of following the traditional model.

TRENDS IN UNDERGRADUATE EDUCATION

One topic discussed in depth at the most recent World Economic Forum, held January 20-23, 2016, in Davos-Klosters, Switzerland, said Andreas Cangellaris, was the coming of the fourth industrial revolution. This revolution, which builds on the digitally based third industrial revolution and is being driven by emerging advances in nanotechnology, materials science, energy storage, additive manufacturing, robotics, artificial intelligence, biology, and the Internet of Things, will disrupt every industry and has the potential to improve quality of life at a global scale. At the same time the forum was being held, a book titled *The Rise and Fall of American Growth* was published, and its author, Robert Gordon from Northwestern University, argued that the great days of American innovation are past, and unless the nation can begin innovating at a much faster pace than ever before, the nation’s future will be difficult. While these two messages may seem contradictory, said Cangellaris, they are both saying that innovation will be key if the nation is serious about taking advantage of new opportunities.

In his opinion, a foundation of the American research university can be summarized in one sentence: "We prosper through discovery and innovation; and through education we put prosperity to good use." Cangellaris also believes that the grand challenges laid out by the NAE will not only produce important breakthroughs, but also inspire students, faculty, and parents. "This is something that we cannot forget as we think about the future of education," said Cangellaris. "These challenges are so inspirational, and it is not only the United States that is thinking about them, the rest of the world is, too." His institution, as is true for many other leading U.S. universities, is partnering with institutions around the world to provide solutions will need to reflect the local economic and geopolitical situations.

Referring to the Google effect that Miller noted, Cangellaris said it is real and has had a powerful effect on how faculty interacts with students by creating time for faculty to engage with students rather than merely providing them with information. Knowledge is accessible in ways it never was before that go beyond just looking up facts using Google. As an example, he cited a NASA website where students can play with the Mars lander *Curiosity* and learn what it is like to operate a robot remotely.

Today, said Cangellaris, there has never been a better opportunity for higher education to capitalize on the fact that education, training, and research have to come together to prepare students for the maker and innovator economy. He noted how faculty are finding creative ways of ensuring that undergraduates have the opportunity to be exposed to research, both for the benefit of the student and faculty. "Who does not want more creative, curious minds contributing to finding answers to difficult problems?" asked Cangellaris. In addition, research and internship experiences make students feel comfortable with the truth that science and engineering do not have all of the answers.

Cangellaris also reiterated Banks's comment that education today might actually be suffocating creativity and stifling the ability to think about "weird things." What is needed, he said, is a system that encourages students to think about doing the impossible and to do the impossible in areas that matter to people who come from different backgrounds and geographic regions. As an example, he cited the Illinois Cancer Scholars program, which takes freshman engineering students who say they want to be engineers to cure cancer, assembles them into a cohort, and from the beginning of their time at the University of Illinois, gives them the opportunity to immerse themselves in oncology as well as their specific engineering disciplines. The students, he said, are passionate about this immersion experience, and the sense among faculty is that this program goes a long way toward turning some of these curious and passionate students into amazing and passionate innovators.

As is true at other universities, the University of Illinois has created a design school that aims to prepare innovators across disciplines. "These design centers can energize the campus, bringing the entire university community together in a way that has not happened before and that eliminates the silos that get in the way of innovation," said Cangellaris, who believes design centers are one of the most exciting opportunities for changing undergraduate education. He also noted that there is still much to learn about how to develop design centers.

Cangellaris concluded the panel presentations by saying that he is a firm believer that it is the role of U.S. universities to educate as many innovators as possible, regardless of where they come from or even where they live. "The United States has always been a driver of new ways of thinking about higher education," said Cangellaris.

DISCUSSION

A symposium participant agreed that practical experience was important, but so too is mastering fundamentals and subject matter. As an example, he said musicians need to master the fundamental of music before they can be truly innovative. Miller agreed but noted that if musicians were trained in the same way engineers are, they would first learn about the theory of vibration and sound and about note shapes and the natural frequencies of strings and columns of air. They then would learn music theory and orchestration, and finally, in their final year of school they would be given an instrument and taught to play scales. "Musicians learn music by playing it, every day, and building up a repertoire," said Miller. "I think engineering is also a performing art in which you build up a repertoire in the same way. Musicians do learn theory along the way but not at the expense of playing music." He also cited Harvard Medical School's New Pathways Program that merges learning and experience as one model for engineering education. Students in this program get 1 hour of lecture a day and then they work on real case studies. Banks agreed that it is not necessary for a student to have all of the fundamentals before they are allowed to explore applications.

Dean Chang, from the University of Maryland, asked how universities can afford these more resource-intensive programs that require teaching teams and how faculty can get their instructional credits when they are team teaching. Miller responded that the Massachusetts Institute of Technology has data showing that while there is an initial investment in teaching faculty to work in this mode, these programs are then cost-neutral. Banks added that the professor of practice program has been beneficial in contributing to the development of these programs.

Another participant asked if these new models of education will mean the end of tenure, to which Banks replied that the tenure process works well and is not being questioned at Texas A&M. What is important, however, is increasing the diversity of expertise at the institutions. Miller added that while his institution does not offer tenure, it does have renewable contracts with secure terms. In his mind, getting rid of disciplinary departments is more important to creating a collaborative, innovative culture than doing away with tenure. Cangellaris noted that NSF has been very supportive of efforts to rethink innovation in education and how to reward that in new ways. Miller added that the infusion of design into engineering will require new metrics for evaluating both faculty and student performance. At his institution, faculty voted unanimously to revamp the reward system by doing away with the three traditional distinct performance areas—teaching, research, and service—and creating new categories that better reflect the overlap between building student success, building the institution, and producing nationally visible achievement.

5

Emerging Best Practices in Translating University Research into Innovation

The symposium's final panel session focused on technology transfer and featured three speakers. Frederic Farina, chief innovation and corporate partnerships officer at the California Institute of Technology (Caltech), and Orin Herskowitz, director of Columbia University's Columbia Technology Ventures, together provided some context about university technology transfer and described some of the emerging trends and trade-offs in technology transfer that might be relevant to the ERCs. Dean Chang, associate vice president for innovation and entrepreneurship at the University of Maryland, discussed lessons learned from NSF's Innovation Corps (I-Corps) program. An open discussion moderated by Maxine Savitz followed the panel presentations.

TRENDS IN TECHNOLOGY TRANSFER

One unusual feature of Caltech's technology transfer office is that it combines all activities related to technology transfer, corporate partnerships, intellectual property, and entrepreneurship under one roof, said Frederic Farina. The reason for creating a one-stop shop was to make it easy for industry to work with the university and meet whatever a company's needs would be—whether it is licensing a patent or forming a research collaboration. In this arrangement, one person serves as the contact to manage a company's entire relationship with the university, similar to the way an account manager functions. In this way, a company does not have to navigate a path from the Office of the General Counsel to the Office of Sponsored Research and then to the various deans and department heads, explained Farina.

Caltech, he continued, has a very aggressive patenting strategy. Rather than evaluating inventions, his office errs on the side of caution and applies for patents. "We believe it is difficult to predict success, particularly for the type of fundamental and oftentimes early stage research we do at Caltech," said Farina. The university, with 300 faculty members and 2,000 students, created 228 invention disclosures in 2015, he noted, and creates an average of some 12 startup companies annually. From Farina's perspective, the role of his office is to service the faculty, an aspect that he believes many universities overlook. "I think a key aspect of what we do is engage the faculty in the process and support them in the activity," said Farina.

Orin Herskowitz said Columbia University has a similar mission and approach, which is to help faculty get their technologies from the laboratory to the marketplace and to do so in a way that generates funds to support research and education at the university. Two unusual missions that his office had taken on are to help procure funding to support specific research projects and to educate faculty and students on matters of entrepreneurship. He noted that while his office, too, serves as the single point of contact for industry, it works within what he characterized as a broad and loosely federated, anarchic system of entrepreneurship. "There are many initiatives around entrepreneurship, but not run from the same office," said Herskowitz.

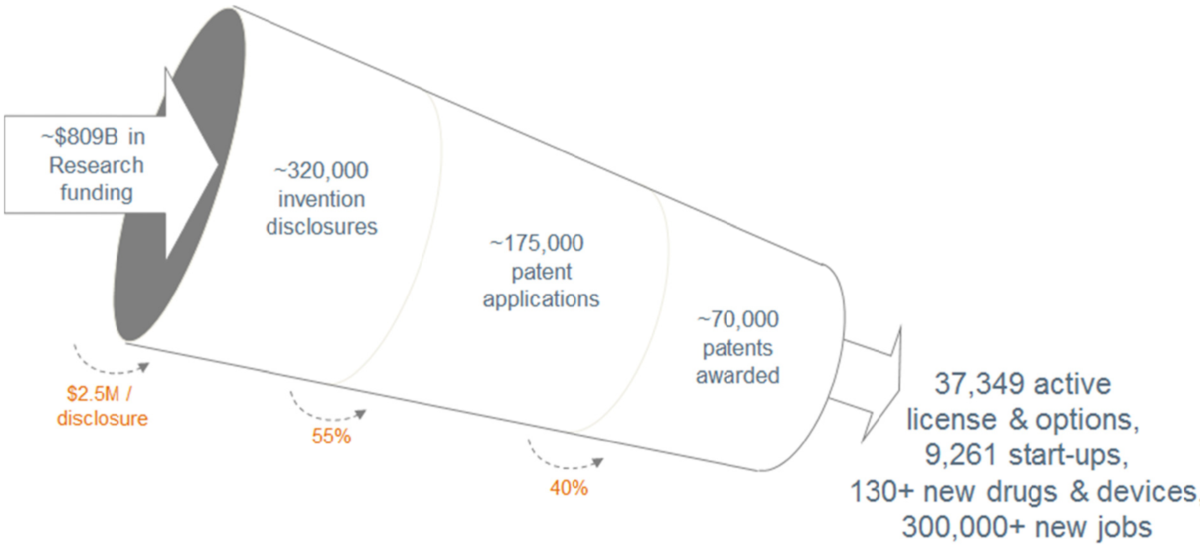

FIGURE 5.1 Cumulative inputs and outputs of U.S. universities, 1991-2014. SOURCE: Orin Herskowitz, Columbia University, presentation to the symposium, April 6, 2016, slide 9.

Columbia, he explained, has approximately 400 faculty members who produce some 400 invention disclosures a year. In 2015, his office issued 117 licenses and options, half of them exclusive and half of those were to startups. In 2015, the university realized $195 million in licensing revenues. He also noted that his office has 40 full-time staff members and 35 graduate student trainees, and that annual patent expenses average between $9 million and $10 million.

As far as how universities fit into the nation's innovation space, the approximately $800 billion in research funds that went to universities over the past 23 years generated some 320,000 invention disclosures that resulted in approximately 175,000 patent applications and 70,000 awarded patents. As of 2014, said Herskowitz, there are 37,349 active licenses and options for university-generated patents, and 9,261 startups, more than 130 drugs and devices, and more than 300, 000 new jobs have been created from this licensing activity (Figure 5.1). These data, he explained, come from 23 years of Association of University Technology Managers (AUTM) annual licensing surveys. He also noted that the end of the university technology funnel is the beginning of the industry and venture capital funnel, which sees roughly 1 of every 100 pharmaceutical compounds becoming approved drugs and roughly 1 of every 10 venture investments becoming a significant hit.

What this means for universities is that commercial success that generates significant licensing revenues is a rare outcome for most universities. In fact, said Herskowitz, 85 percent of U.S. universities' technology transfer activities lose money, with the bulk of licensing revenues accruing to a small subset of universities from a small number of "blockbuster" products. In fact, one AUTM Licensing Survey found that less than 40 percent of licenses generated any revenue, and less than 1 percent of licenses generate more than $1 million in annual licensing revenues. Columbia University, for example, has generated more than $3 billion in licensing revenues, but some 90 percent come from four patents, said Herskowitz. One factor that plays a critical role in determining if a licensed invention becomes a successful product, said Farina, is having the inventors involved in the commercialization process. "I don't know of a single success in which an invention was just handed over to a company without any additional interactions," he said.

One reason why so few inventions become successful, revenue-generating products is the oft-mentioned "valley of death," the gap that exists between government and foundation grants that take an invention to the point of early feasibility studies and the latter stages of product development when

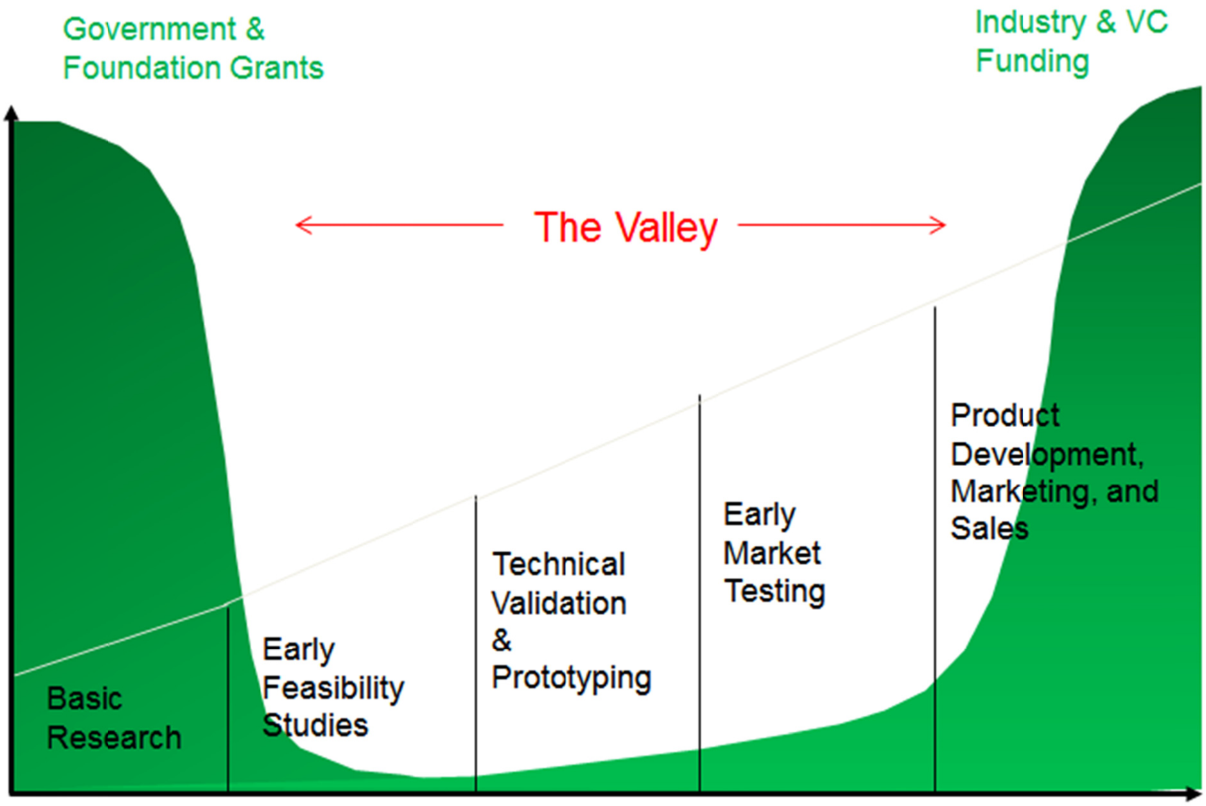

FIGURE 5.2 The "valley of death." SOURCE: Orin Herskowitz, Columbia University, presentation to the symposium, April 6, 2016, slide 13.

industry and venture capital feels comfortable with the risk of taking a product to the market (Figure 5.2). Herskowitz noted that many universities are increasingly focusing on how to fund early feasibility studies, technical validation and prototyping, and early market testing activities that would bridge the valley of death. Farina suggested that the ERCs should start devoting 10 percent of their budgets to these bridging activities.

Another challenge to the successful commercialization of inventions is that it often takes years to license an invention. Herskowitz, citing 32 years of data from Columbia University and similar data from the National Cancer Institute, the Universities of California, and Cornell University, said that only 55 percent of deals are completed within 3 years of first disclosure, and only 85 percent are finalized within 6 years, and even then it can take many more years for a license to generate significant revenues. Farina added that maintaining patents is expensive and that universities are having to make decisions about which inventions they will continue to support. Small universities may not even have the resources to patent inventions, he noted.

With regard to emerging trends in technology transfer, Herskowitz and Farina said that universities, cities, states, and the federal government are showing increased enthusiasm and support for technology commercialization, which is leading to better collaborations, benchmarking, and sharing of best practices. Campus entrepreneurship is showing explosive growth, and the number of discovery outcomes from multidisciplinary and multi-university collaborations are increasing, which increases the complexity of licensing activities. The changing patent landscape will have an undetermined impact on technology transfer, as will the increasing importance of, and experimentation with, so-called alternative licensing approaches such as patent pools and "click-licensing."

Looking at the future of the ERCs, Herskowitz and Farina listed several trade-offs that need to be considered. For example, should the ERCs focus on engaging established industry partners or on startups? Should they be developing new, strong innovation and commercialization ecosystems or leverage existing strong ecosystems? Should they focus on "blue-sky" research or applied research? Should the focus be on funding basic research or supporting commercialization activities? Should they employ simple metrics or complex metrics for success? Each ERC might chose different combinations of these, said Herskowitz, depending on the ERC's research focus.

AN EXPERIENCE WITH NSF'S INNOVATION CORPS

The purpose of NSF's I-Corps is to increase the economic impact of the more than $7 billion of research it funds annually, explained Dean Chang. I-Corps was developed by entrepreneurs and is taught by entrepreneurs, he said, noting that there are seven I-Corps lead universities—University of California, Berkeley; University of Southern California, University of Michigan; University of Texas, Austin; Georgia Tech; University of Maryland; and City University of New York—and a total of 17 I-Corps universities in the national innovation network. According to Chang, virtually every faculty member who has gone through the I-Corps program says afterwards that every university research program should have some level of familiarity with the concepts I-Corps teaches, which prompted him to suggest that every ERC should be an ERIC—an Engineering Research and I-Corps Center.

One of the fundamental parts of the I-Corps program requires participants to interview 100 potential customers for their technology to get a better sense of what customers want from a product. "The number one reason startups fail is that they build something nobody wants," said Chang. "Since 90 percent of startups fail, you have to wonder why so many of them can build something nobody wants." Too often, he said, a startup will deliver a product that does not meet 100 percent of potential customers' needs because the entrepreneur does not fully understand what customers truly need in a new product. In Chang's case, a company he helped start was within 2 months of going bankrupt because it built a product that met only 75 percent of what its customers wanted.

That does not have to be case, said Chang, because industry will happily reveal what it needs and whether or not a given technology has the potential to deliver a needed solution. "Go out there and talk to customers. Ask them what they want," said Chang. "The key is to not go out and sell. The goal is to learn." Herskowitz noted that most of the value that Columbia University gets from its similar Lean LanchPad program is that it gets its inventors out of their laboratories and into the offices of potential customers.

As an example of the power of talking to customers, Chang recounted the story of an experience that Doug Dietz, a GE engineer who was the principal designer of the magnetic resonance imaging (MRI) scanner, had when he went to a hospital to see how his machine was working. There, he witnessed a child screaming as she was being dragged into the MRI suite and realized how terrifying the typical MRI machine was to a child. He responded by meeting with children, parents, technicians, and receptionists and used the information he gained from those interviews to create a child-friendly MRI suite that completely changed the MRI experience for the better for children. However, to get GE managers to buy into the $40,000 in renovation costs associated with creating a child-friendly MRI suite, he also had to develop a compelling business case, which proved to be simple in the end, given that 80 percent of the children who had a traditional MRI experience ultimately had to be sedated by an anesthesiologist, an expensive and time-consuming process. In contrast, the child-friendly MRI suite increased throughput, dramatically shortening the payback period not only for the child-friendly design but the MRI itself.

Chang ended his presentation by posing several questions. "Should we and can we foster more empathetic and impactful engineers? Where does an engineer's job end—at the end of the technology or during the design-thinking phase of the experience? Does it delve into the business model side of things, where you get the buy-in?" he asked. In his opinion, every innovator on campus should get the training to answer all of those questions. At the University of Maryland, for example, I-Corps is now a campus-wide initiative with the Office of the President, the provost, his office, the technology transfer office, and the business school. He noted that while the ERCs bring in researchers from multiple scientific and engineering disciplines, they should also be engaging faculty from the social sciences, arts, and business schools.

DISCUSSION

In the ensuing discussion, a symposium participant commented that companies such as Google, Facebook, and Yahoo do not operate on a patent model, and so success should not be measured solely on the basis of patents and licensing activity. Instead, commercialization depends more on customer pull and networking. His hope was that if ERCs become ERICs that they work hard at developing a networking ecosystem that fosters technology transfer. This participant also said that in his opinion, universities are too often reluctant to let the market kill off startups and technology that will not succeed. Herskowitz agreed with both of these comments, adding that while Google actually did begin with a patent license from Stanford University, that license has not driven most of the company's success. He also noted that technology transfer offices are increasingly providing other services to support entrepreneurship and commercialization activities that go beyond patents. Farina also agreed as well, although he said that a startup's patent portfolio can serve as a "security blanket" for venture capitalists.

6

Closing Observations

The Symposium on Exploring a New Vision for Center-Based, Multidisciplinary Engineering Research concluded with a plenary talk by John Holdren, Science and Technology Advisor to the President and Director of the White House Office of Science and Technology Policy (OSTP). He began his remarks by observing that when the NSF ERC program was established in 1984, its focus was on multidisciplinary engineering, research, education, and workforce development in partnership between academia and industry. Today, that focus needs clarifying and updating to reflect the current state of science and engineering research. For example, multidisciplinary engineering research now need to include not only diverse engineering disciplines but also the physical, life, and social sciences. Multidisciplinary also needs to be augmented by interdisciplinary, which Holdren explained means having some individuals who are trained to communicate across disciplinary boundaries and to integrate across disciplinary boundaries. The partnership aspect of the ERCs also need to be expanded beyond those between industry and academia to include government at various levels and civil society as funders, facilitators, and representatives of the user communities who stand to benefit from innovation.

To reflect this new focus, Holdren suggested calling these new enterprises multi-interdisciplinary centers (MIDs), and he listed a number of grand challenges requiring MID solutions. These included the following:

- Ensuring abundant, safe, sustainable food, water, and energy;
- Minimizing harm from changes in climate that are no longer avoidable;
- Engineering materials from abundant elements to substitute for current uses of scarce ones;
- Understanding the brain;
- Combating infectious and vector-borne diseases;
- Defeating cancer;
- Facilitating graceful aging;
- Defending the planet from killer asteroids; and
- Sending humans into space not just to visit but to stay.

Not long after President Obama took office, he released the American Innovation Strategy, developed with input from OSTP and the President's Council of Advisors on Science and Technology (PCAST) and updated most recently in October 2015. This policy, said Holdren, is built on three pillars. The first, investing in the fundamental building blocks of innovation, includes educating Americans with 21st century skills, strengthening leadership in fundamental research through research funding and nurturing research institutions, building a leading physical infrastructure to support innovation, and developing an advanced information technology ecosystem. The second pillar calls for promoting market-based innovation by accelerating business innovation using the Research and Experimentation tax credit, encouraging innovation-based entrepreneurship, growing investment in ingenuity with effective policy on intellectual property rights, and promoting innovative, open, and competitive markets. The third pillar of the innovation strategy aims to catalyze breakthroughs for national priorities, including unleashing a clean-energy revolution; accelerating biotechnology, nanotechnology, and advanced manufacturing;

developing breakthroughs in space applications; driving breakthroughs in health care technology, and creating a leap forward in educational technologies.

Holdren noted there are a number of cross-cutting aspects of these three pillars that the administration has emphasized in its requests for funding. One has been to increase support for scientists and engineers early in their careers. Another has been to increase the engagement of girls and women as well as underrepresented minorities in STEM fields. A third emphasis has been on commercializing university research, while the fourth has been on multidisciplinary and high-risk, high-return research. Holdren also noted that the administration has already established some MIDs, including five Energy Innovation Hubs and the eight centers of the National Network for Manufacturing Innovation, the latter of which have already brought together more than 800 company, university, and nonprofit partners and leveraged a $600 million investment to attract over $1.2 billion in nonfederal investment.

Going forward, there are a number of steps the nation needs to take to scale the successes that MIDs are already producing, said Holdren. These include the following:

- Boosting pre-college STEM inspiration and preparation, particularly in technology and engineering, to encourage more students to pursue careers in STEM fields;
- Accelerating the revolution in undergraduate STEM teaching to promote active learning and early laboratory experience as a means of conveying the excitement that comes from real-world careers in STEM fields, while deemphasizing classroom lectures;
- Growing the interdisciplinary graduate teaching and training pipeline to increase the number of individuals who have the skills to serve as integrators;
- Striving for greater inclusion and success of females and minorities in all STEM fields;
- Propagating the understanding that not all experiments succeed and creating a culture that embraces the idea that knowledge comes from failure as well as success; and
- Overcoming the barriers to adequate investment in basic research.

As a final note, Holdren reminded symposium participants that the legislation that created NSF states that its first responsibility is to promote the progress of science and engineering, which requires investing in fundamental research. “We need to do a better job of educating the public and educating the Congress about what you might call the innovation pipeline,” said Holdren. “Of course, we know it is not really a pipeline, but rather, it is a set of feedbacks between all levels from fundamental research to innovation and scaling. If we fail to sustain the level of societal support for basic research required to meet society’s needs, we will suffer in the long run.”

7

Common Themes and Additional Thoughts from the Breakout Sessions

In addition to the four panel sessions, the symposium featured two breakout sessions designed to elicit a broad range of ideas by dividing symposium participants into working groups and asking the groups to address a set of questions. Each breakout session consisted of six groups, each of which was charged with considering a group of questions and arriving at a set of challenges and opportunities. The challenges and opportunities each group arrived at were displayed to the full symposium membership, although no consensus was sought. The purpose was to provide additional food for thought to the study committee in its deliberations. In the first breakout session, which followed the first two panels, the questions for the breakout groups were as follows:

1. What features of non-U.S. center-based engineering research might be adopted or adapted to improve the performance of U.S. centers?
2. What aspects of globalization are most relevant to center-based engineering research and how can they best be leveraged?
3. How can centers balance the need to be globally connected with the need to create value for U.S.-based industry?
4. What innovative features of university-industry interactions might be adopted or adapted to improve the performance of center-based engineering research programs?
5. How can university-based engineering research centers best position themselves to be relevant to industry?
6. What are the advantages and challenges for centers associated with partnering with small versus large companies?

In the second breakout session, the working groups addressed the following questions:

1. What new or promising developments in engineering education seem most likely to improve the performance of center-based engineering research programs?
2. What role might such centers play in developing and evaluating new approaches/methods/models of engineering education?
3. How might industry engagement in engineering education associated with centers be improved?
4. What features of center-based engineering research are most likely to lead to maximum innovation, namely maximum value creation for society/industry?
5. How can best practices be codified and disseminated so that all centers derive maximum benefit?
6. What features of center-based engineering research are most likely to encourage entrepreneurship, and facilitate technology transfer and start-up formation?

As noted, each working group engaged in wide-ranging discussions covering a number of topics, and they attempted to distill a number of opportunities and challenges associated with major symposium themes. The opportunities and challenges made by the working groups (symposium attendees) are listed below. The breakouts were idea-generation activities. All ideas were welcome, and no special weight should be given to any of the recommendations. They should not be considered consensus statements of the entire symposium, nor recommendations of the study committee.

GLOBAL CONTEXT

Opportunities

- Promoting an exchange of students and faculty between the U.S. centers and foreign countries is a win-win proposition: the U.S. gains access to foreign talent while U.S. students and faculty gain knowledge and experience with foreign cultures and markets.
- Global engagement helps increase faculty's and students' international business acumen as well as sensitivity to the need for solutions to be developed in the context of cultural norms, privacy concerns, and other local considerations.

Challenges

- The logistics of engaging foreign partners are daunting, including intellectual property issues, funding restrictions, and export control concerns.

INDUSTRY-UNIVERSITY RELATIONS

Opportunities

- Centers should consider a fluid two-way movement of personnel and data between universities and industry partners, including professors of practice from industry at universities, university faculty sabbaticals, and student internships in industry. This includes colocation for an extended period of time.
- Centers should consider professional managers to bridge the unique features of university and industry cultures, such as differences in pace of work and funding horizons, university "tech push," and industry "demand pull."
- Centers should attempt to focus on fundamental knowledge that is pre-competitive so that there are no barriers to the free flow of information back and forth.
- If the centers choose to tackle big ideas and grand challenges, it is important to decompose the problem into tractable parts that are well defined.

Challenges

- Becoming too industry-focused could compromise the education mission.
- Large and small companies have different goals and dynamics in partnering with centers.
- Universities may need to relinquish some control of the center to industry.
- Centers will likely need to deal with not-for-profit outcomes such as creative commons, open source, flexible intellectual property licensing.

EDUCATION

Opportunities

- Centers could incorporate a design element to identify possible new products.
- Centers could promote more "systems thinking" in curricula as well as big-picture thinking about desirability, viability, and policy.
- Centers could sponsor competitions and hackathons to solve focused problems to promote innovation and team building.
- Undergraduate and graduate education could be more integrated.
- Undergraduates and graduates could be exposed to and integrated into translational research.

Challenges

- Changing university culture is extremely difficult.

TRANSLATING UNIVERSITY RESEARCH INTO INNOVATION

Opportunities

- Some foreign models, such as the German, British, Dutch, and Swiss models, are better at addressing the entire innovation pipeline and metrics for success from which U.S. centers could learn.
- Centers should consider rethinking the goal of monetizing intellectual property. Open access to all intellectual property should be considered.
- Intellectual property policies should be standardized.
- Centers could develop an organized approach to early discovery of potential customers for their applied research and start to plan a tech transfer path.
- Centers should seek to identify available resources and support system for translational research.

Challenges

- Principal investigators tend to work as individuals rather than as members of a coherent team.

ADDITIONAL THOUGHTS

In addition to these common themes, the working group discussions also produced a number of additional thoughts on challenges and observations made by individual members of the working groups. These included the following:

- Ten to 20 percent of center funds could be set aside for discretionary seed money.
- Locating a center in an industrial setting committed to the free flow of information could be considered, with the university researchers coming to that center.
- Centers should consider finding ways to incorporate national laboratory researchers. National laboratories can help to bridge the valley of death through systems development and integration.

- The centers should consider re-orienting engineering schools to focus on undergraduate and master's degrees, not Ph.Ds.
- Multidisciplinary courses should consider going beyond science and engineering to incorporate social sciences and cultural competency.
- Centers could develop a curriculum in entrepreneurship and leadership skills for the global environment that could be adopted university-wide.
- Engineering schools should consider separate industry versus academic tracks for Ph.D. students. There could also be training for alternative career paths, such as on the not-for-profit and public policy arenas.
- A "National Center/Industry Day" technology fair could help connect companies with centers and promote information sharing. Clearinghouses could advertise available intellectual property and venture capitalists could be brought in to evaluate that intellectual property.
- TED talks, incorporation of social media, and webinars can help in promoting center best practices as well as reasons for failures.

Appendixes

A

Symposium Agenda

Symposium on Exploring a New Vision for Center-Based, Multidisciplinary Engineering Research

National Academies Keck Center
Washington, D.C.

April 6, 2016

7:30 a.m.	Light Breakfast and Registration
8:00	Welcome, Remarks from the Sponsor, and Goals for the Day *Introduction by David Walt, University Professor, Tufts University, Committee Co-Chair* *France Córdova, Director, National Science Foundation*
8:30	Panel 1. The Evolving Global Context for Center-Based Engineering Research *Arvind Krishna, Senior VP for Global Research, IBM* *Eoin O'Sullivan, Director, Centre for Science, Technology, and Innovation Policy, University of Cambridge* *Jean-Lou Chameau, President, King Abdullah University of Science and Technology* Panel 2. New Directions in University-Industry Interaction *David Parekh, Corporate VP for Research, United Technologies, and Director, UTRC* *Thomas Siebel, Founder and CEO, C3 Energy* *Kelly O. Sullivan, Manager, Institutional S&T Investments, Pacific Northwest National Laboratory*
10:30	Breakout 1
11:45	Break and Gallery Walk 1
12:15 p.m.	Lunch and Presentations Panel 3. Trends in Undergraduate and Graduate Engineering Education *Richard Miller, President, Olin College of Engineering* *Katherine Banks, Dean of Engineering, Texas A&M University* *Andreas Cangellaris, Dean of Engineering, University of Illinois*

Panel 4. Emerging Best Practices in Translating University Research into Innovation

Frederic Farina, Chief Innovation and Corporate Partnerships Officer, California Institute of Technology
Orin Herskowitz, Director, Columbia Technology Ventures, Columbia University
Dean Chang, Associate Vice President, Innovation and Entrepreneurship, University of Maryland

2:30 Breakout Group 2

3:45 Break and Gallery Walk 2

4:15 Closing Plenary Talk

Introduction by Maxine Savitz, Honeywell (retired), Committee Co-Chair
John Holdren, Director, White House Office of Science and Technology Policy

4:40 Final Comments

Co-Chairs

4:45 Adjourn and Reception

B

Biographical Sketches of Symposium Speakers and Committee Members

NADINE AUBRY is University Distinguished Professor and dean of the Northeastern University College of Engineering, is a widely known leader in the field of fluid dynamics, particularly the modeling of open flow turbulence and other complex flows and systems using advanced decomposition techniques and dynamical systems theory. She also made noteworthy contributions to the field of microfluidics. For these and other contributions to the profession, Dr. Aubry was elected as a member of the National Academy of Engineering (NAE) and is a fellow of the American Physical Society (APS), the American Society of Mechanical Engineers (ASME), the American Association for the Advancement of Science(AAAS), the American Institute of Aeronautics and Astronautics (AIAA), and the National Academy of Inventors. Other recognitions include the Presidential Young Investigator Award from the National Science Foundation (NSF) and the Ralph R. Teetor Educational Award from the Society of Automotive Engineers. She has served as chair of the U.S. National Committee for Theoretical and Applied Mechanics of the National Academies of Sciences, Engineering, and Medicine, as chair of the U.S. delegation to the International Union of Theoretical and Applied Mechanics (IUTAM), as past chair of the APS Division of Fluid Dynamics and as a member of the bureau of IUTAM. Dr. Aubry has also been serving on many APS and ASME committees, numerous NSF and Academies review panels, and a number of advisory boards and review panels in the United States and in foreign countries, including Austria, France, Portugal, Singapore, and South Korea. She has given numerous invited lectures on her research at various universities and conferences. Before joining Northeastern, she was the Raymond J. Lane Distinguished Professor, University Professor and head of the Department of Mechanical Engineering at Carnegie Mellon University.

M. KATHERINE BANKS is the vice chancellor for engineering for the Texas A&M University System, dean of the Dwight Look College of Engineering at Texas A&M University, and director of the Texas A&M Engineering Experiment Station (TEES). As vice chancellor, Dr. Banks oversees coordination and collaboration among the engineering, academic, and research programs at nine universities throughout the A&M system, as well as three state agencies: TEES, Texas A&M Engineering Extension Service and Texas A&M Transportation Institute. As TEES director, Dr. Banks oversees research administration of more than 4,800 projects and $208 million in sponsored research awards. As dean of the Look College and holder of the Harold J. Haynes Dean's Chair in Engineering, she leads one of the largest engineering schools in the country, with more than 16,700 students and more than 500 faculty. Dr. Banks was previously the Bowen Engineering Head for the School of Civil Engineering at Purdue University and holder of the Jack and Kay Hockema Professorship. She received her B.S.E. from the University of Florida, M.S.E. from the University of North Carolina, and Ph.D. in civil and environmental engineering from Duke University. Dr. Banks is a member of the NAE and a fellow of the American Society of Civil Engineers (ASCE). She has received numerous awards, including the ASCE Petersen Outstanding Woman of the Year Award, ASCE Rudolph Hering Medal, Kate Gleason Medal, a Sloan Foundation Mentoring Fellowship, and a American Association of University Women Fellowship.

CHERYL R. BLANCHARD is the chief executive officer and a member of the board of directors of MicroCHIPS, Inc. Dr. Blanchard has extensive experience in the medical device and biologics sectors.

From 2002 to 2014, she served in roles of increasing responsibility at Zimmer, Inc., a medical device company focused on musculoskeletal products. Her roles at Zimmer included leadership of research and development (R&D), clinical, quality and regulatory affairs, and health economics. She was also a member of Zimmer's executive committee and developed and led the biologics business at Zimmer through disciplined execution of an R&D pipeline, coupled with significant partnering and business development activities. Previous to Zimmer, Dr. Blanchard built and led the medical device practice at Southwest Research Institute while also serving as an adjunct professor at the University of Texas Health Science Center, both in San Antonio, Texas. She has a B.S in ceramic engineering from Alfred University and an M.S. and Ph.D. in materials science and engineering from the University of Texas, Austin.

ROBERT D. BRAUN is the David and Andrew Lewis Professor of Space Technology at the Georgia Institute of Technology and has more than 25 years of experience in performing design and analysis of planetary exploration systems as a member of the technical staff of the NASA Langley Research Center and the Georgia Institute of Technology. His research has focused on systems' aspects of planetary exploration, where he contributed to the design, development, test, and operation of several robotic space flight systems. He has been an active participant in the development of advanced methods for multidisciplinary design and optimization. Dr. Braun developed the Collaborative Optimization architecture while at Stanford University from 1991 to 1996. This architecture was shown to have significant computational and operational benefits in the optimization of large, distributed design problems. Since completing the initial research in this area, several university and industry groups have applied this technique in solving a diverse set of engineering challenges. From 2000 to 2001, he led and integrated NASA's advanced engineering environment development program. Dr. Braun received a B.S. in aerospace engineering from Pennsylvania State University in 1987, M.S. in astronautics from the George Washington University in 1989, and Ph.D. in aeronautics and astronautics from Stanford University in 1996. He has received the inaugural American Astronautical Society Space Technology Award (2014), the 2012 Alvin Seiff Memorial Award, the 2011 AIAA von Karman Astronautics Award, the 1999 AIAA Lawrence Sperry Award, the NASA Distinguished Service Medal, two NASA Exceptional Achievement Medals, two NASA Inventions and Contributions Team Awards, and nine NASA Group Achievement Awards. He is a member of the NAE, vice chair of the Academies' Space Studies Board, editor-in-chief of the AIAA *Journal of Spacecraft and Rockets*, an AIAA fellow, and the author or co-author of more than 275 technical publications in the fields of atmospheric flight dynamics, planetary exploration, multidisciplinary design optimization, and systems engineering. He presently serves on advisory boards for the Jet Propulsion Laboratory (JPL), the Space Systems Sector of the Charles Stark Draper Laboratory, and the Planetary Society.

ANDREAS CANGELLARIS is the dean of the College of Engineering and the M.E. Van Valkenburg Professor of Electrical and Computer Engineering at the University of Illinois, Urbana-Champaign. Professor Cangellaris received his B.S. in electrical engineering from the Aristotle University of Thessaloniki, Greece, in 1981, and his M.S. and Ph.D. degrees in electrical engineering from the University of California, Berkeley, in 1983 and 1985, respectively. Following a 2-year tenure as a senior staff engineer with the Electronics Engineering Department of General Motors Research Labs, he joined the faculty of Electrical and Computer Engineering at the University of Arizona in Tucson, in 1987. In 1997, he joined the University of Illinois, Urbana-Champaign, as a professor in the Department of Electrical and Computer Engineering. He served as head of the Department of Electrical and Computer Engineering from 2009 until 2013. He was appointed dean of the College of Engineering in 2013.

CURTIS R. CARLSON, founder and CEO of Practice of Innovation, was president and CEO of SRI International from 1998 to 2014 and is a prominent technologist. He has helped create more than two dozen new companies, including Siri, which was bought by Apple and is now on the iPhone. The value creation process he developed, Innovation for Impact, is used world-wide, including by companies, universities, and government agencies in the United States, Sweden, Finland, Chile, Singapore, Japan, Denmark, Brazil, and Taiwan. A physics graduate of Worcester Polytechnic Institute (WPI) and a Ph.D. graduate in geophysical fluid dynamics from Rutgers University, he worked at RCA, GE, and then the Sarnoff Corporation. While at Sarnoff, Dr. Carlson led teams that developed the U.S. HDTV standard and a system to assess broadcast digital-video image quality, both of which were awarded engineering Emmy awards. He is fellow of the National Academy of Inventors. He received Suffolk University's first Global Leadership in Innovation and Collaboration Award. He was honored with the Medal of Excellence Award by Rutgers University's School of Engineering and the Dr. Robert H. Goddard Award from WPI for his professional achievements. For his role in advancing the performance and image quality of information displays, he received the Society for Information Display's Otto H. Schade Award. He has received four honorary doctor awards, including from the Malaysian Technical University. He was a member of President Obama's National Advisory Council on Innovation and Entrepreneurship, Taiwan's scientific advisory board, and the U.S. Air Force Scientific Advisory Board. Currently, he is a member of the scientific advisory board for the Singapore National Research Foundation, the advisory council for NSF, and a trustee at WPI. With William Wilmot, he wrote the BusinessWeek Top-10 book, *Innovation: The Five Disciplines for Creating What Customers Want*.

JEAN-LOU CHAMEAU took office as president of the King Abdullah University of Science and Technology (KAUST) in Saudi Arabia on July 1, 2013. Dr. Chameau is president emeritus of the California Institute of Technology (Caltech), which he led for 7 years prior to joining KAUST. After receiving his engineering degree in France at the École Nationale Supérieure des Arts et Métiers and earning his Ph.D. in civil engineering from Stanford University, he had a distinguished career as a professor and administrator at Purdue University and the Georgia Institute of Technology (Georgia Tech). He then served as president of Golder Associates, a geotechnical consulting company, before returning to Georgia Tech as Georgia Research Alliance Eminent Scholar and vice provost for research. He became dean of its college of engineering, the largest in the United States, and then provost and vice president for academic affairs. He has served on a number of public and industry boards, including the Council on Competitiveness, John Wiley & Sons, MTS, Safran, and the Academic Research Council of Singapore. Chameau has received numerous awards for his research and contributions as an educator and academic leader. These include an NSF Presidential Young Investigator Award, the Arthur Casagrande Award from the ASCE, the Rodney Chipp Memorial Award from the Society of Women Engineers, the Prix Nessim Habif from the École Nationale Supérieure d'Arts et Métiers, and the Benjamin Garver Lamme Award from the American Society for Engineering Education (ASEE). In his native France, Dr. Chameau was elected Chevalier de la Légion d' Honneur. He is a member of both the French Académie des Technologies and the U.S. NAE.

DEAN CHANG teaches design thinking and lean startup to students and researchers to cultivate the innovator and entrepreneurial mindset inside. He is the University of Maryland's associate vice president for innovation and entrepreneurship, reporting to the president and provost and tasked with engaging every student in all 12 colleges in innovation. He is also a principal investigator (PI) and instructor in NSF's I-Corps Node program. Prior to the University of Maryland, Dr. Chang spent 15 years in Silicon Valley where he served as the chief technology officer and vice president at Gaming Business of Immersion Corporation. He joined Immersion as employee number 4 and helped transform the venture-backed Stanford University robotics laboratory spinout into a publicly traded licensor of haptics technology embedded in products from Microsoft, Apple, BMW, Samsung, and Electronic Arts. Dr. Chang holds more than 40 patents, a B.S. degree from the Massachusetts Institute of Technology (MIT), M.S. and Ph.D. degrees from Stanford University, and an M.B.A. from the Wharton School.

JIM C.I. CHANG is currently a visiting chair professor at National Cheng Kung University, Tainan, Taiwan. Prior to this, he was an adjunct professor in the Department of Electric and Computer Engineering at North Carolina State University. He received his Ph.D. in theoretical and applied mechanics from Cornell University. He retired as chief scientist of the Army Research Laboratory (ARL).

Prior to joining ARL in 1998, Dr. Chang served as director of the Aerospace and Materials Science Directorate of the Air Force Office of Scientific Research, chief scientist of the Naval Air Systems Command, manager of advanced materials, structures and space systems at NASA, and branch head of the structural integrity branch of the Naval Research Laboratory.

FRANCE A. CÓRDOVA is the 14th director of NSF, the only government agency charged with advancing all fields of scientific discovery, technological innovation, and science, technology, engineering, and mathematics (STEM) education. NSF is a $7.5-billion independent federal agency with a mission that is vital to supporting our nation's economy, security, and ability to remain a global leader. Dr. Córdova is president emerita of Purdue University, where she served as president from 2007 to 2012. Prior to her tenure at Purdue, she was chancellor of the University of California, Riverside, and vice chancellor for research at the University of California, Santa Barbara. From 1993 to 1996, she was chief scientist at NASA. She is a recipient of NASA's highest honor, the Distinguished Service Medal. Dr. Córdova has been a professor of physics and astronomy at University of California, Riverside, University of California, Santa Barbara, and the Pennsylvania State University. She was deputy group leader in the Earth and space sciences division at Los Alamos National Laboratory. Her scientific contributions are in the areas of observational and experimental astrophysics, multispectral research on X-ray and gamma-ray sources and space-borne instrumentation. More recently, Dr. Córdova served as chair of the board of regents of the Smithsonian Institution and on the board of trustees of Mayo Clinic. She also served as a member of the National Science Board (NSB). As NSF director, she is an ex officio member of the NSB. Dr. Córdova has a B.A. from Stanford University and a Ph.D. in physics from Caltech. She is a member of the American Academy of Arts and Sciences, the Association for Women in Science, a National Associate of the National Academies, and has been awarded many honorary doctorates.

MARTHA N. CYR is the director of K-12 Outreach at WPI and is a nationally recognized authority on K-12 educational outreach. Dr. Cyr joined WPI in 2003 after serving as director of the Center for Engineering Educational Outreach at Tufts University, where she had also taught engineering for 9 years. She received a B.S. in mechanical engineering from the University of New Hampshire and an M.S. and Ph.D. in the field from WPI. She also worked as a thermal engineer for Data General Corporation and held a NASA Graduate Student Researchers Program fellowship for 3 years working on computational thermal fluids research on the impact of liquid pooling on the energy transfer within a heat pipe in microgravity. At WPI, Dr. Cyr oversees one of the nation's largest and most comprehensive university-based K-12 STEM outreach programs, which includes programs targeted at students in elementary, middle, and secondary schools; programs that seek to engage girls and students from underrepresented minorities in STEM disciplines; and programs that provide training and classroom resources for teachers. Working with researchers at other universities under a $1 million award from the NSF National Digital Library Program, Dr. Cyr helped develop TeachEngineering, an extensive online resource for K-12 educators who teach engineering. At Tufts, she was also PI on a $1.5 million NSF award that funded the Tufts Engineering the Next Steps Project and a $1.75 million award from the NSF Teacher Enhancement Program for a pre-college engineering project for teachers.

MONICA OLVERA DE LA CRUZ is the Lawyer Taylor Professor of Materials Science and Engineering, professor of chemistry, professor of chemical and biological engineering, and professor of physics and astronomy at Northwestern University; director of the Center for Computation and Theory of Soft Materials; and co-director of the Center for Bio-Inspired Energy Science. Dr. de la Cruz obtained her B.A. in physics from the UNAM, Mexico, in 1981, and her Ph.D. in physics from Cambridge University, U.K., in 1985. She was a guest scientist (1985-1986) in the National Institute of Standards and Technology. She joined Northwestern University in 1986. From 2006 to 2013 she directed the Materials Research Center at Northwestern. From 1995 to 1997 she was a staff scientist in the Commissariat a l'Energie Atomique, Saclay, France, where she also held visiting scientist positions in 1993 and in 2003. She has developed theoretical models to determine the thermodynamics, statistics, and dynamics of macromolecules in complex environments including multicomponent solutions of heterogeneous synthetic and biological molecules, and molecular electrolytes.

FREDERIC FARINA is Caltech's chief innovation and corporate partnerships officer. His responsibilities include commercializing inventions made at Caltech and the JPL/NASA through the creation of new startup ventures and partnerships with established companies. His office is responsible for evaluating inventions, supervising patent prosecution, and portfolio management, negotiating licensing deals with industry, assisting Caltech/JPL entrepreneurs with the creation of new startup companies, and establishing research collaborations with industry. Prior to joining the office, Mr. Farina worked as a research engineer in the GPS field at JPL and the University of Miami. He subsequently joined a law firm where he prosecuted patent applications on various technologies before the U.S. and European patent offices. Mr. Farina holds a "diplôme d'ingénieur" in electrical engineering from the Institut National des Sciences Appliquees, Lyon, France, and is a graduate of Caltech from which he received a master's degree in electrical engineering in 1992. He is a registered patent agent with the U.S. Patent and Trademark Office.

MIKE GREGORY is head of the Manufacturing and Management Division of the University Engineering Department and of the Institute for Manufacturing (IfM). Following an early career in industry, he was the founder member of the team which established the Manufacturing Engineering Tripos, a senior undergraduate programme covering, marketing, design, production, distribution, and service with very close industrial engagement. Subsequent developments in research and collaboration with industry reflected this broad view of manufacturing and led to the establishment of the IfM in 1998. Linking science, engineering, management, and economics and integrating education, research, and practice, the IfM now has more than 230 staff and research students and a further 100 undergraduate and masters students. Mr. Gregory's work continues to be closely linked with industry and government, and he has published in the areas of manufacturing strategy, technology management, international manufacturing, and manufacturing policy. External activities have included membership of various government and institutional committees. He served as executive director of the Cambridge MIT Institute from 2005 to 2008 and was a Springer Visiting Professor at University of California, Berkeley, in 2008 and 2009. He chairs the U.K. Manufacturing Professors Forum and is a member of the U.K. government's Manufacturing Analytical Group on Manufacturing. He is a fellow of Churchill College Cambridge.

WILLIAM HARRIS is the president and CEO of Science Foundation Arizona (SFAz). Prior to joining SFAz, Dr. Harris was in Ireland serving as director general of Science Foundation Ireland (SFI), a new Irish agency that helped facilitate tremendous growth in Ireland's R&D sector during his tenure. Immediately prior to going to Ireland, Dr. Harris was vice president of research and professor of chemistry and biochemistry at the University of South Carolina (USC). There, he oversaw research activities throughout the USC system, several interdisciplinary centers and institutes, the USC Research Foundation and sponsored research programs. Dr. Harris served at the U.S. NSF from 1978 to 1996, including as the director for mathematical and physical sciences (1991-1996). He was responsible for federal grants appropriation of $750 million. He also established 25 science and technology centers to support investigative, interdisciplinary research by multi-university consortia. Earlier in his career, he catalyzed the Research Experience for Undergraduates program in the chemistry division and it became an NSF-wide activity. In 2005, Dr. Harris was elected a member of the Irish Royal Academy and received the Wiley Lifetime Achievement Award from California Polytechnic State University. He has authored more than 50 research papers and review articles in spectroscopy and is a fellow of the AAAS. Dr. Harris earned his undergraduate degree at the College of William and Mary and received his Ph.D. in chemistry from the University of South Carolina.

ORIN HERSKOWITZ is vice president of intellectual property and tech transfer at Columbia University. In addition to his role as vice president, Mr. Herskowitz serves as executive director of Columbia Technology Ventures, which manages more than 350 invention disclosures emerging from Columbia's research laboratories each year, leading to more than 100 license deals and more than 20 new startups annually. Mr. Herskowitz has served on boards or as the PI for several innovation and entrepreneurship-focused initiatives, including the NYC Media Lab, PowerBridgeNY, and the Columbia Coulter Translational Partnership. Prior to joining Columbia, he spent 7 years with the Boston Consulting Group's New York office.

JOHN P. HOLDREN is Assistant to the President for Science and Technology, director of the White House Office of Science and Technology Policy, and co-chair of the President's Council of Advisors on Science and Technology (PCAST). Prior to joining the Obama administration, Dr. Holdren was the Teresa and John Heinz Professor of Environmental Policy and director of the Program on Science, Technology, and Public Policy at Harvard University's Kennedy School of Government, as well as a professor in Harvard's Department of Earth and Planetary Sciences and director of the independent, nonprofit Woods Hole Research Center. Previously, he was on the faculty of the University of California, Berkeley, where he co-founded in 1973 and co-led until 1996 the interdisciplinary graduate-degree program in energy and resources. During the Clinton administration Dr. Holdren served as a member of PCAST through both terms and in that capacity chaired studies requested by President Clinton on preventing theft of nuclear materials, disposition of surplus weapon plutonium, the prospects of fusion energy, U.S. energy R&D strategy, and international cooperation on energy-technology innovation. Dr. Holdren holds advanced degrees in aerospace engineering and theoretical plasma physics from MIT and Stanford University. He is a member of the National Academy of Sciences, the NAE, and the American Academy of Arts and Sciences, as well as a foreign member of the Royal Society of London and former president of the AAAS. He served as a member of the MacArthur Foundation's board of trustees from 1991 to 2005, as chair of the Academies' Committee on International Security and Arms Control from 1994 to 2005 and as co-chair of the independent, bipartisan National Commission on Energy Policy from 2002 to 2009. His awards include a MacArthur Foundation Prize Fellowship, the John Heinz Prize in Public Policy, the Tyler Prize for Environmental Achievement, and the Volvo Environment Prize. In December 1995, he gave the acceptance lecture for the Nobel Peace Prize on behalf of the Pugwash Conferences on Science and World Affairs, an international organization of scientists and public figures in which he held leadership positions from 1982 to 1997.

ARVIND KRISHNA is senior vice president and director, IBM Research. In this role, he helps guide the company's overall technical strategy, leading a global organization of approximately 3,000 scientists and technologists located at 12 laboratories on six continents. Dr. Krishna was most recently general manager of IBM Systems and Technology Group's Development and Manufacturing organization, responsible for the advanced engineering and development of a full technology portfolio, ranging from advanced semiconductor materials to leading-edge microprocessors, servers, and storage systems. He was previously general manager of IBM Information Management, which included database, information integration, and big data software solutions. Prior to that, he was vice president of strategy for IBM Software. He has held several key technical roles in IBM Software and IBM Research, where he pioneered IBM's security software business. Arvind has an undergraduate degree from the Indian Institute of Technology, Kanpur, and a Ph.D. from the University of Illinois, Urbana-Champaign.

FRED C. LEE is currently a university distinguished professor and founder and director of the NSF ERC for Power Electronics Systems (CPES), a preeminent academic center in power electronics research at Virginia Polytechnic Institute and State University (Virginia Tech). He is a member of the NAE, an academician of Academia Sinica, and a foreign member of the Chinese Academic of Engineering. As CPES director, Dr. Lee leads a program encompassing research, technology development, educational outreach, industry collaboration, and technology transfer. CPES focuses its research to meet industry needs and allows industry to profit from the center's research and outputs. The CPES program enables its principal industry members to sponsor graduate fellowships and provides the opportunity to direct research in areas of mutual interest, as well as the ability to access intellectual property generated collectively by all industry-funded fellowships on a royalty-free and non-exclusive basis. To date, more than 150 companies worldwide have benefited from this industry partnership program. The center has been cited by NSF as a model ERC for its industry collaboration and technology transfer, education, and outreach programs. Dr. Lee has served as major advisor to 83 M.S. and 76 Ph.D. students. He holds 74 U.S. patents and has published 270 journal articles and more than 660 refereed technical papers. His research interests include high-frequency power conversion, magnetics and EMI, distributed power systems, renewable energy, power quality, high-density electronics packaging, and integration, and modeling and control.

RICHARD K. MILLER was appointed president and first employee of Olin College of Engineering in 1999. He served as dean of the College of Engineering at the University of Iowa from 1992 to 1999. The previous 17 years were spent on the engineering faculty at USC in Los Angeles and University of California, Santa Barbara. With a background in applied mechanics and current interests in innovation in higher education, Dr. Miller is the author of more than 100 reviewed journal articles and other technical publications. Together with two Olin colleagues, he received the 2013 Bernard M. Gordon Prize from the U.S. NAE for innovation in engineering and technology education. A member of both the NAE and the National Academy of Inventors, he received the Marlowe Award for creative and distinguished administrative leadership from the ASEE in 2011. Dr. Miller served as chair of the Engineering Advisory Committee of the U.S. NSF and has served on advisory boards and committees for Harvard University, Stanford University, the NAE, and the U.S. Military Academy at West Point in addition to others. Furthermore, he has served as a consultant to the World Bank in the establishment of new universities. A frequent speaker on engineering education, he received the 2002 Distinguished Engineering Alumnus Award from the University of California, Davis, where he earned his B.S. He earned his M.S. from MIT and Ph.D. from Caltech, where he received the 2014 Caltech Distinguished Alumni Award.

PHILIP M. NECHES is the founder of Teradata Corporation. Dr. Neches served as the chief technology officer at idealab! in 1999.He served as a vice president and chief technology officer at Multimedia Products and Services Group, AT&T Corporation, from 1994 to 1996, senior vice president and chief scientist at NCR Corporation from 1989 to 1994, and led both the repositioning of their computer product family and the product plan for a merger at AT&T. He founded Teradata in 1979, where he served as vice president and chief scientist from 1979 to 1988. Dr. Neches began his career as a manager of Systems Evaluation Group at Transaction Technology, Inc., where he led analysis of consumer banking networks, including the first large-scale deployment of automated teller machines in the United States. He has been an independent consultant and advisor at a number of public and private information technology companies since 1996. He serves on the advisory boards of Foundation Ventures, LLC (chairman), Evolution Venture Partners, LLC, Tizor Systems, Inc., Simulmedia, Inc., EarthLink, TACODA, LLC, Luxtera, Inc., and the Technology Group of Merrill Lynch. Dr. Neches serves on the board of directors of PeopleLink, Inc.; he also serves on Caltech's board of trustees, sits on its audit, investment, business and finance, development, JPL, and executive committees, and chairs the Technology Transfer Committee. He has been a director of International Meta Systems, Inc., since 1996 and served as a director of Expand Beyond Corporation, Vendquest, Inc., Evolving Systems, Inc., International Rectifier Corporation DemoGraFx, and MediaMap. He is one of America's leading technologists and has more than 30 years of leadership in the field. Dr. Neches received his formal training at Caltech, where he completed his B.S. degree with honors in 1973, M.S. in engineering science in 1977, and Ph.D. in computer science in 1983.

EOIN O'SULLIVAN is the director of the Center for Science, Technology and Innovation Policy in the Engineering Department of Cambridge University, U.K. Dr O'Sullivan's research interests include comparative analysis of national innovation systems, intermediate R&D institutes, university-industry partnership models, and emerging technology foresight methodologies. He works closely with a range of U.K. research and innovation agencies and policy makers. Recent policy work has included projects for the Department of Business, Innovation and Skills, the Engineering and Physical Sciences Research

Council; the Higher Education Funding Council, Innovate UK, and the British Standards Institute. He has also been a consultant and programme reviewer for research foundations and economic development agencies in a number of countries. From late 2006 through 2007, Dr. O'Sullivan was a research programmes director at the Cambridge-MIT Institute. Before that he was special advisor to the director general at Science Foundation Ireland, where he also led the Centers for Science, Engineering and Technology program. He was also a senior policy advisor at Forfás, the Irish Government's National Policy Board for Enterprise, Trade, Science, Technology and Innovation. Dr. O'Sullivan has a D.Phil. from the Physics Department of Oxford University.

DAVID PAREKH is a fellow of the AIAA and a member of the Connecticut Academy of Science and Engineering. He serves on the board of the Connecticut Technology Council, the executive board of the U.S. Department of Energy's (DOE's) Energy Efficient Buildings Hub and the advisory board of the Georgia Tech College of Engineering. He is a member of the Academies' Aeronautics Research and Technology Roundtable and previously served on the Defense Science Board's Task Force on DOD Energy Strategy. He earned a Ph.D. in mechanical engineering, master's degrees in mechanical and electrical engineering from Stanford University and a B.S. degree in mechanical engineering from Virginia Tech.

DARRYLL J. PINES is dean and Nariman Farvardin Professor of Aerospace Engineering at the Clark School since 2009. He first arrived at the Clark School in 1995 as an assistant professor and then served as chair of the Department of Aerospace Engineering from 2006 to 2009. During a leave of absence from the university (2003-2006), Dr. Pines served as program manager for the Tactical Technology Office and Defense Sciences Office of the Defense Advanced Research Projects Agency (DARPA). While at DARPA, he initiated five new programs primarily related to the development of aerospace technologies, for which he received a Distinguished Service Medal. He also held positions at the Lawrence Livermore National Laboratory (LLNL), Chevron Corporation, and Space Tethers, Inc. At LLNL, Dr. Pines worked on the Clementine Spacecraft program, which discovered water near the south pole of the Moon. A replica of the spacecraft now sits in the National Air and Space Museum. Dr. Pines received a B.S. in mechanical engineering from the University of California, Berkeley. He earned M.S. and Ph.D. degrees in mechanical engineering from MIT.

RICHARD F. RASHID is chief research officer at Microsoft Research, which he founded in 1991, and between 1991 and 2013, he oversaw the worldwide operations for Microsoft Research, an organization that grew to encompass more than 850 researchers across nearly a dozen laboratories worldwide. His teams collaborated with the world's foremost researchers in academia, industry, and government on initiatives to expand the state of the art across the breadth of computing and to help ensure the future of Microsoft's products. During his time at Microsoft, Dr. Rashid has held the positions of director, vice president, senior vice president, and chief research officer. He is currently chief technology officer of Microsoft's Applications and Services Division. He was presented with the Institute of Electrical and Electronics Engineers (IEEE) Emanuel R. Piore Award in 2008 and inducted into the NAE in 2003. He was also inducted into the American Academy of Arts and Sciences and received the SIGOPS Hall of Fame Award in 2008. In 2009, Dr. Rashid was given the Microsoft Technical Recognition Award for exceptional career achievements and was inducted into the Royal Academy of Engineering in 2014. He is a past member of the NSF Computer Directorate Advisory Committee, the DARPA UNIX Steering Committee, and the Computer Science Network Executive Committee. He is a trustee for the Anita Borg Institute for Women and Technology, as well as a former chair of the Association for Computing Machinery Software System Awards Committee. Dr. Rashid received master of science (1977) and doctoral (1980) degrees in computer science from the University of Rochester. He graduated with honors in mathematics and comparative literature from Stanford University in 1974.

S. SHANKAR SASTRY is currently the dean of engineering at University of California, Berkeley, and the faculty director of the Blum Center for Developing Economies. From 2004 to 2007, Dr. Sastry was the director of the Center for Information Technology in the Interests of Society (CITRIS), an interdisciplinary center spanning the University of California in Berkeley, Davis, Merced, and Santa Cruz. He has served as chair, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, from January 2001 through June 2004. From 1999 to early 2001, he was on leave from Berkeley as director of the Information Technology Office at DARPA. From 1996 to 1999, he was the director of the Electronics Research Laboratory at Berkeley. Dr. Sastry received his Ph.D. degree in 1981 from the University of California, Berkeley. He was on the faculty of MIT as an assistant professor from 1980 to 1982 and at Harvard University as a chaired Gordon Mc Kay Professor in 1994. His areas of personal research are resilient network control systems, cybersecurity, autonomous and unmanned systems (especially aerial vehicles), computer vision, nonlinear and adaptive control, control of hybrid and embedded systems, and software. Most recently, he has been concerned with critical infrastructure protection, in the context of establishing a 10-year NSF Science and Technology Center Team for Research in Ubiquitous Secure Technologies. He has coauthored more than 550 technical papers and nine books. Dr. Sastry was elected into the NAE in 2001 and the American Academy of Arts and Sciences in 2004, and a fellow of the IEEE. He also received the President of India Gold Medal in 1977, the IBM Faculty Development award for 1983-1985, the a NSF Presidential Young Investigator Award in 1985, the Eckman Award of the of the American Automatic Control Council in 1990, the Ragazzini Award for Distinguished Accomplishments in teaching in 2005, the Distinguished Alumnus Award of the Indian Institute of Technology in 1999, and the David Marr Prize for the best paper at the International Conference in Computer Vision in 1999, and the C.L. Tien Award for Academic Leadership in 2010. Dr. Sastry earned an M.A. (honoris causa) from Harvard University in 1994 and an honorary doctorate from the Royal Swedish Institute of Technology in 2007. He has been a member of the Air Force Scientific Advisory Board (2002-2005) and the Defense Science Board (2008), among other national boards. He is currently on the corporate boards of C3-Carbon and HCL Technologies (India) and on the scientific advisory boards of Interwest, LLC, GE Software, and Eriksholm.

MAXINE L. SAVITZ is the retired general manager for Technology Partnerships at Honeywell, Inc., formerly AlliedSignal. Previously, she was the general manager of AlliedSignal Ceramics Components. Dr. Savitz was employed at DOE and its predecessor agencies (1974-1983) and served as Deputy Assistant Secretary for Conservation. She serves on the board of the American Council for an Energy Efficient Economy and on advisory bodies for Pacific Northwest National Laboratory (PNNL), Sandia National Laboratories, and JPL. She serves on the MIT visiting committee for sponsored research activities. In 2009, Dr. Savitz was appointed to PCAST and served as vice president of the NAE from 2006 to 2014. She is a member of the NAE, a fellow of the California Council on Science and Technology, and a member of the American Academy of Arts and Sciences. Past board memberships include the National Science Board, the Secretary of Energy Advisory Board, the Defense Science Board, the Electric Power Research Institute, Draper Laboratories, and the Energy Foundation. Dr. Savitz's awards and honors include the Orton Memorial Lecturer Award (American Ceramic Society) in 1998, the DOE Outstanding Service Medal in 1981, the President's Meritorious Rank Award in 1980, recognition by the Engineering News Record for Contribution to Construction Industry in 1979 and 1975, and the MERDC Commander Award for Scientific Excellence in 1967. She is the author of about 20 publications.

THOMAS M. SIEBEL is the chairman and CEO of C3 IoT. He was the chairman and CEO of Siebel Systems, which merged with Oracle Corporation in 2006. Founded in 1993, Siebel Systems became a leader in application software with more than 8,000 employees in 32 countries, more than 4,500 corporate customers, and annual revenue in excess of $2 billion. Mr. Siebel is also chairman of the Siebel Energy Institute, a global consortium for innovative and collaborative energy research for the public domain. Through the Thomas and Stacey Siebel Foundation, Mr. Siebel provides support for energy solutions, bioengineering and stem cell research programs, and other projects that work to improve the quality of life, environment, and education of its community members. He serves on the boards of advisors for the Stanford University College of Engineering, the University of Illinois College of Engineering, and the University of California, Berkeley, College of Engineering. Mr. Siebel is a graduate of the University of Illinois, Urbana-Champaign, where he received a B.A. in history, an M.B.A, and an M.S. in computer science.

KELLY O. SULLIVAN joined PNNL in 2001 and currently works with the deputy director for science and technology to provide leadership in developing PNNL's long-term scientific vision and strategy for distinguishing PNNL within the scientific community and enabling its researchers to advance the boundaries of both scientific and engineering achievement. Dr. Sullivan has had multiple roles at PNNL. She has led the laboratory's science and technology investments—a more than $80 million annual investment portfolio for capability and business development—since April 2012 and has managed the Linus Pauling Distinguished Postdoctoral Fellowship Program since its inception in 2009. She served as the interim director of institutional strategy from April-October 2015. Prior to coming to PNNL, she was a chemistry professor at Mankato State University in Minnesota and at Creighton University in Nebraska. Dr. Sullivan's research interests focus on the electronic structure of small molecules and ions. She received a B.S. in chemistry from Christian Brothers College and a Ph.D. in physical chemistry from Texas Tech University.

EDWIN L.THOMAS is the William and Stephanie Sick Dean of the George R. Brown School of Engineering. He holds joint appointments in the Departments of Materials Science and Nanoengineering and Chemical and Biomolecular Engineering and collaborates with scientists and engineers in the Richard E. Smalley Institute for Nanoscale Science and Technology at Rice University. Dr. Thomas is a materials scientist and mechanical engineer and is passionate about promoting engineering leadership and student design competitions. His research is currently focused on using 2D and 3D lithography, direct-write, and self-assembly techniques for creating metamaterials with unprecedented mechanical and thermal properties. Dr. Thomas is the former head of the Department of Materials Science and Engineering at MIT, a position he held from 2006 until his appointment at Rice in July 2011. He was named Morris Cohen Professor of Materials Science and Engineering in 1989 and is the founder and former director of the MIT Institute for Soldier Nanotechnology (2002-2006). Before joining MIT, Dr. Thomas founded and served as co-director of the Institute for Interface Science and was head of the Department of Polymer Science and Engineering at the University of Massachusetts. He is a recipient of the 1991 High Polymer Physics Prize of the APS and the 1985 American Chemical Society Creative Polymer Chemist award. He was elected to the NAE and the American Academy of Arts and Sciences in 2009, and he is an inaugural fellow of the Materials Society in 2008, a fellow of the AAAS (2003), and a fellow of the APS in 1986. He wrote the undergraduate textbook *The Structure of Materials* and has coauthored more than 420 papers and holds 16 patents. Dr. Thomas received a B.S. in mechanical engineering from the University of Massachusetts and his Ph.D. in materials science and engineering from Cornell University.

DAVID R. WALT is a university professor, the Robinson Professor of Chemistry, a professor of biomedical engineering, a professor of genetics, and a professor of oral medicine at Tufts University and is a Howard Hughes Medical Institute professor. Dr. Walt is the founding scientist of Illumina, Inc., and has been a director and chairman of its scientific advisory board since 1998. He is also the founding scientist of Quanterix Corporation and is a director and chairman of its scientific advisory board since 2007. Dr. Walt has received numerous national and international awards and honors for his fundamental and applied work in the field of optical sensors, arrays, and single molecule detection. He is a co-chair of the Board on Chemical Sciences and Technology of the Academies. Dr. Walt is a member of the NAE, American Academy of Arts and Sciences, a fellow of the American Institute for Medical and Biological Engineering, a fellow of the National Academy of Inventors, and a fellow of the AAAS.

KARAN L. WATSON is provost and executive vice president of Texas A&M University. Dr. Watson had served in the interim position since July 2009. She previously served as vice provost at Texas A&M from December 2008 to July 2009 and as dean of faculties and associate provost from February 2002 to December 2008. She joined the faculty of Texas A&M in 1983 and is currently a Regents Professor in the Department of Electrical and Computer Engineering and in the Department of Computer Science and Engineering. Before assuming the position of dean of faculties and associate provost, Dr. Watson served as the associate dean for graduate studies in the Dwight Look College of Engineering. She also served the Look College as associate dean for academic affairs and as a member of the faculty senate. She was interim vice president and associate provost for diversity from November 2005 to September 2006, a role that she again held from December 2008 until July 2009. Dr. Watson is a fellow of the IEEE and the ASEE. Her awards and recognitions include the U.S. President's Award for Mentoring Minorities and Women in Science and Technology, the AAAS mentoring award, the IEEE International Undergraduate Teaching Award, the College of Engineering Crawford Teaching Award, and two university-level Distinguished Achievement Awards from the Texas A&M University Association of Former Students—one in student relations in 1992 and one in administration in 2010. Dr. Watson has chaired the graduate committees of 34 doctoral students and more than 60 master's degree students. In 2003 to 2004, she served as a senior fellow of the NAE Center for the Advancement of Scholarship in Engineering Education. Since 1991, she has served as an accreditation evaluator and commissioner and is now on the board of directors for ABET, Inc., formerly the Accreditation Board for Engineering and Technology. She served as ABET president for 2012 to 2013.

YANNIS YORTSOS has served as dean of the USC Viterbi School of Engineering since 2005. He is the Chester F. Dolley Professor of Chemical and Petroleum Engineering and holds the Zohrab A. Kaprielian Dean's Chair in Engineering. Dr. Yortsos is well known for his work on fluid flow, transport, and reaction processes in porous and fractured media with applications to the recovery of subsurface fluids and soil remediation. He has been actively involved in the peer review of the Yucca Mountain Project for the disposal of high-level radioactive waste. The recipient of many honors for research, teaching, and service, Dr. Yortsos is a member of the NAE and serves as the liaison of Section 11 to the Academies. He received his B.Sc. from the National Technical University, Athens, Greece, and his M.Sc. and Ph.D. from Caltech, all in chemical engineering. An invited scholar at several institutions in the United States and abroad, Dr. Yortsos joined the faculty of USC in 1978. He is an associate member of the Academy of Athens and is the recipient of the Ellis Island Medal of Honor. He currently serves on the executive committee of the Engineering Deans Council as well as the executive committee of the Global Engineering Deans Council.

C

Statement of Task

An ad hoc study committee will develop a vision and high-level, strategic recommendations for the future of NSF-supported center-scale, multidisciplinary engineering research. The study will be forward-looking—focusing on the forces that are likely to shape engineering research, education, and technological innovation in the future, as well as the associated challenges and opportunities. It will consider and evaluate the most promising models and approaches for multidisciplinary engineering research that can successfully address these challenges and opportunities. NSF's Engineering Research Centers will be used as prominent examples or cases in the study, but the intent is not to evaluate them. The study will also be informed by other models of large-scale, multidisciplinary engineering research in the United States and other parts of the world.

The products of the committee's work will be: (1) a rapporteur-authored summary of a symposium, and (2), a final consensus report containing committee findings and strategic recommendations that include inspiring visions for center-scale research in engineering over the next 10-20 years, new models for innovation that connect center research to real-world impacts, the appropriate role and emerging models for such centers in education and broadening participation, and how to continuously enable breakthrough engineering research by attracting the most innovative and diverse talent in the field. The report will focus on describing visions and opportunities for the future of multidisciplinary center-scale engineering programs, and presenting guiding principles and strategic recommendations for realizing the new visions and opportunities rather than evaluating the current center construct and suggesting evolutionary improvements.