
# A New Vision for Center-Based Engineering Research

**DETAILS**

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# A New Vision for Center-Based Engineering Research

Committee on a Vision for the Future of Center-Based Multidisciplinary Engineering Research

National Materials and Manufacturing Board

Division on Engineering and Physical Sciences

National Academy of Engineering

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**NATIONAL MATERIALS AND MANUFACTURING BOARD**

# Preface

In July 2015, the National Science Foundation (NSF) funded the National Academies of Sciences, Engineering, and Medicine to conduct a study on the future of center-based, multidisciplinary engineering research. At that time, NSF's Engineering Research Center (ERC) program had been in operation for 30 years, and NSF felt it was an appropriate time to consider fresh ideas for what it should look like in coming decades. The task was not to evaluate the performance of current ERCs but to articulate a vision that NSF might want to pursue in the future for the program. In response, the National Academies established the Committee on a Vision for the Future of Center-Based, Multidisciplinary Engineering Research (Appendix A) to perform the study, which met for the first time in December 2015.

The committee held four data-gathering meetings to hear from outside presenters as well as a number of conference calls with key individuals (Appendix B). In addition, it held a symposium in April 2016 to solicit ideas from the broader engineering community. The proceedings of the symposium are available as a separate publication of the National Academies at https://www.nap.edu. Through its work, the committee learned about the structure and effectiveness of existing ERCs. The recommendations in this report do not call for a wholesale dismantling of the existing ERC program; rather the committee believes it is important to build upon the existing strengths of the ERCs by framing them to address the biggest challenges society faces both today and in the decades to come.

While it is always important to maintain a certain humility when opining on how things will be decades hence, the committee believes that the vision articulated here is consistent with the observed trends toward engineering solutions that require convergence of knowledge from formerly separate engineering disciplines in technology development, the sciences, as well as the emerging best practices in engineering education, team research, and the deliberate nurturing of innovation. In fact, NSF may wish to use this re-imagined ERC program as a vehicle to explore and engage more fully with these trends in the future.

The committee recognizes that while center-based engineering research has much to contribute to solving the big problems we face, centers cannot do everything. For example, the fraction of U.S. engineering graduates who are directly touched by the centers is less than 1 percent. Nevertheless, the centers should be able to serve as exemplars for innovation to the broader engineering community.

We wish to thank all of the committee members for their engagement in the study and their dedication in producing this report in a short period of time. We also want to thank the many individuals who made presentations to the committee or otherwise provided advice and information. The outside reviewers and National Academies monitor provided insightful comments and improved the quality of the report. Sincere thanks are also due to the terrific National Academies staff: Greg Eyring, Greg Pearson, Jim Lancaster, Proctor Reid, Dick Rowberg, Henry Ko, Joe Palmer, Neeraj Gorkhaly, and Maribeth Keitz. We'd like to give special thanks to Greg Eyring whose tireless efforts helped the committee achieve its goals.

David R. Walt and Maxine L. Savitz, *Co-Chairs*
Committee on a Vision for the Future of Center-Based, Multidisciplinary Engineering Research

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# Acknowledgment of Reviewers

This Consensus Study Report was 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 National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Jeffrey Wadsworth, NAE, Battelle.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Paul R. Gray, University of California, Berkeley, and Arden L. Bement, Jr., Purdue University, who were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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

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Dedicated to

Erich Bloch

NSF Director (1984-1990) who initiated the ERCs and STCs

24th recipient of the National Science Board's Vannevar Bush Award and
distinguished member of the NAE who led the development of IBM 360

1925-2016

# Summary

The future security, economic growth, and competitiveness of the United States depend on its capacity to innovate. Major sources of innovative capacity are the new knowledge and trained students generated by U.S. research universities. However, many of the complex technical and societal problems the United States faces cannot be addressed by the traditional model of individual university research groups headed by a single principal investigator. Instead, they can only be solved if researchers from multiple institutions and with diverse expertise combine their efforts. The National Science Foundation (NSF), among other federal agencies, began to explore the potential of such center-scale research programs in the 1970s and 1980s; in many ways, the NSF Engineering Research Center (ERC) program is its flagship program in this regard.

The 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 at $3 million to $5 million per year 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. ERCs are credited with producing more than 12,000 engineering graduates[2] with interdisciplinary training and entrepreneurial skills, as well as hundreds of millions of dollars of regional and national economic benefits.[3]

However, NSF is well aware that the world has changed in dramatic ways in the past 30 years and will increasingly do so in the future. To ensure that the ERCs continue to be a source of innovation, economic development, and educational excellence, NSF commissioned 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. In response, the National Academies established the Committee on a Vision for the Future of Center-Based, Multidisciplinary Engineering Research (Appendix A) to perform the study.

[1] See the National Science Foundation (NSF) Engineering Research Center Association website at http://erc-assoc.org, accessed January 21, 2016.

[2] NSF, 2015, *Creating New Knowledge, Innovators, and Technologies for Over 30 Years*, https://www.nsf.gov/eng/multimedia/NSF_ERC_30th_Anniversary.pdf.

[3] SRI International, 2008, *National and Regional Economic Impacts of Engineering Research Centers: A Pilot Study*, SRI Project P16906, http://www.sri.com/sites/default/files/brochures/erc_impact__final_report_11_18_08.pdf.

## SELECTED MAJOR FINDINGS AND RECOMMENDATIONS

Below, in this summary, are presented selected findings and recommendations from five key areas discussed in the report: (1) the committee's overall vision for the future of center-based engineering research; (2) the skills needed for effective center leadership; (3) opportunities to enhance engineering education through the centers; (4) expanding diversity and public outreach; and (5) overall goals and metrics. More detailed findings and recommendations on these and other topics may be found in the body of the report.

### Vision for the Centers

In the second decade of the millennium, new technologies are fusing the physical, digital, and biological worlds in what has been called the Fourth Industrial Revolution.[4] Examples include advances in health care, such as new diagnostic and therapeutic modalities, demonstrations of sustainable clean energy, robotics, unprecedented communications and connectivity, and artificial intelligence (AI) to augment human capabilities. The world also faces a complex set of global challenges: threats to the environment and national security, new diseases and health risks, and a rapidly changing world economy and competitive landscape.

Today's engineers stand on the cusp of dramatic advances in materials, information, robotics, energy, transportation, manufacturing, agriculture, and health. These advances can propel the world into a new age of sustainable prosperity through technological innovation coupled with its thoughtful application and use for the benefit of society.

Realizing this promise and finding solutions to complex problems such as those mentioned above requires a new approach to research that brings together teams of experts from multiple disciplines who collaborate deeply—an approach referred to as "convergence."[5]

**FINDING 2-1:** This is a time of enormous opportunity in which exponentially expanding knowledge in previously distinct fields can now be combined in new ways to create innovations of great value for society.

A good illustration of convergence is the human performance enhancement (HPE),[6] which integrates engineering, materials, information technology, life sciences, medicine, and social sciences. An example is robotic ecosystems that allow disabled people to regain mobility.

Today's ERCs are intensely focused on early-stage development of promising new technologies with broad application. Here, the committee proposes a strategic new direction for the program focused on tackling larger, grand-challenge-like problems whose solutions offer the greatest benefits for society. Moving in this direction raises new challenges associated with leading and managing the diverse research teams needed, and it will require a disciplined, systematic effort to ensure that the teams work in concert to maximize the value created for society.[7] Thus, the new direction proposed here has two components: a "what" and a "how." The "what" is a shift from the current focus on developing a promising new technology area to addressing a high-impact societal or technological need. The "how" is the systematic use of team-research and value-creation best practices to focus the effort and stimulate the creation of new, valuable innovations. This report builds on the recommendations of three previous National Academies products: (1) the National Academy of Engineering (NAE) Grand Challenges,[8]

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[4] K. Schwab, 2016, *The Fourth Industrial Revolution*, World Economic Forum, Geneva, Switzerland.

[5] National Research Council (NRC), 2014, *Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond*, The National Academies Press, Washington, D.C.

[6] Another phrase for the same field is human performance modification (HPM). See, for example, National Research Council, 2012, *Human Performance Modification: Review of Worldwide Research with a View to the Future*, The National Academies Press, Washington, D.C.

[7] Discussions of value creation in the literature tend to focus solely on economic value. In this report the committee defines value creation more broadly, in terms of value for society. Generally, the two go hand-in-hand; for example, the Internet, which was initially developed as a research tool, opened up access to information for the general public, as well as opportunities for personal expression and social interaction, while also transforming the business landscape.

[8] National Academy of Engineering (NAE), "NAE Grand Challenges for Engineering," http://www.engineeringchallenges.org, accessed January 21, 2016.

(2) *Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond*,[9] and (3) *Enhancing the Effectiveness of Team Science*.[10] The committee believes all three of these topics should be incorporated into engineering centers of the future.

The latter report discusses best practices for enhancing team-research[11] initiatives, which include the use of task analytic methods to identify knowledge, skills, and attitudes required for effective team performance (Box 2.4).[12] Regarding value-creation best practices, top professionals and enterprises today have the innovative skills and processes to identify and systematically develop major new opportunities. Those that do, such as Apple, Google, P&G, and IDEO, are all leaders in their fields. Improved innovation processes are being implemented, such as Agile,[13] Lean,[14] Six Sigma,[15] the Five Disciplines of Innovation,[16] and "Special Forces" Innovation.[17] In addition, companies are increasingly using other models, such as the X-Prize[18] and Google-X[19] "grand challenges" to drive innovation. Online competitions from Kaggle[20] and many others are producing impressive outcomes. These programs are showing that large systemic improvements in productivity can be made.[21]

While many of these systems were designed to be used in a corporate context as a better way to achieve business objectives, they can be adapted to a university center environment. For example, one value-creation best practice is for team members to present value propositions for their thrusts that include the need being addressed, the proposed approach, the costs and benefits, and the status of the competition. These value propositions are then critiqued by their teammates (Box 2.5). Developing a U.S. workforce where engineering graduates understand and apply these skills will allow the United States to continue to lead in the creation of new, high-value global innovations.

The committee defines the phrase *convergent engineering* as a deeply collaborative, team-based engineering approach for defining and solving important, complex societal problems. All necessary disciplines, skills, and capabilities are brought together to address a specific research opportunity. It is distinguished by resolutely using team-research and value-creation best practices to rapidly and efficiently integrate the unique contributions of individual members and develop valuable and innovative solutions for society.

**RECOMMENDATION 2-1: The National Science Foundation should re-invigorate the Engineering Research Center concept by addressing grand-challenge-like problems whose solutions offer the greatest benefits for society and by adhering to the use of team-research and value-creation best practices, fewer administrative burdens, and greater investment and prestige to attract the superb, diverse talent required.**

Examples of appropriate problems could include the 14 grand challenges identified by the National Academy of Engineering (NAE)[22] and other organizations such as the Millennium Project,[23] the Bill and Melinda Gates

[9] NRC, 2014, *Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond*, The National Academies Press, Washington, D.C.

[10] NRC, 2015, *Enhancing the Effectiveness of Team Science*, The National Academies Press, Washington, D.C.

[11] In this report, which is about engineering research, the committee chose to use the phrase "team research" rather than adopt the earlier NRC report's phrase "team science," but the principles are the same.

[12] NRC, 2015, *Enhancing the Effectiveness of Team Science*, The National Academies Press, Washington, D.C.

[13] Agile Methodology Movement, http://agilemethodology.org, accessed January 21, 2016.

[14] Lean Enterprise Institute, "What Is Lean?," http://www.lean.org/WhatsLean/, accessed January 21, 2016.

[15] *Wikipedia, The Free Encyclopedia*, "Six Sigma," https://en.wikipedia.org/wiki/Six_Sigma, accessed January 21, 2016.

[16] C.R. Carlson and W.W. Wilmot, 2006, *Innovation: The Five Disciplines for Creating What Customers Want*, Crown Publishing Group, New York.

[17] R.E. Dugan and K.J. Gabriel, 2013, "Special Forces" Innovation: How DARPA attacks problems, *Harvard Business Review*, October, https://hbr.org/2013/10/special-forces-innovation-how-darpa-attacks-problems.

[18] Xprize, http://www.xprize.org, accessed January 21, 2016.

[19] X Company, "About Us," https://www.solveforx.com/about, accessed October 27, 2016.

[20] Kaggle, https://www.kaggle.com, accessed December 12, 2016.

[21] NRC, 2015, *Making Value for America: Embracing the Future of Manufacturing, Technology, and Work*, The National Academies Press, Washington, D.C.

[22] NAE, "NAE Grand Challenges for Engineering," http://www.engineeringchallenges.org, accessed January 21, 2016.

[23] The Millennium Project, "Challenges," http://millennium-project.org/millennium/challenges.html, accessed September 23, 2016.

Foundation,[24] and the six "research big ideas" identified by NSF.[25] By placing bold bets on a small number of well-funded, prestigious centers focused on engineering solutions to society's greatest challenges, NSF will create excitement in the engineering community that will attract the best students, faculty, and industry partners.

To emphasize the ambition and the bold new direction of these center-scale investments led by engineering, they should be given a new name, possibly convergent engineering research centers (CERCs).

Specifically, these new CERCs will:

1. Address the grand challenges facing society by leveraging the convergence of science, engineering, medical, and—importantly—social science disciplines to accelerate the discovery of new knowledge, create new methods and tools, and develop new products;
2. Embrace the best practices of team research and value creation, using advances in information technology (IT), AI, social media, and virtual reality to enable deep collaboration that accelerates research advances and innovation in an increasingly interconnected world;
3. Leverage the emerging fields of data science and analytics to inform research directions and enhance team research;
4. Create new engineering platforms and tools upon which others will build, accelerating the pace of research and innovation;
5. Attract the best students, faculty, and industry collaborators, who will accelerate translation and innovation in a dynamic and exciting experiential learning environment;
6. Provide students with the full range of skills they need to be leaders in an increasingly interconnected and multidisciplinary world; and
7. Develop meaningful domestic and international partnerships with industry, government, nonprofit and philanthropic organizations, and the venture capital community to bring about major advances.

## Center Leadership

No ingredient is more important to the success of a center than the quality of its leadership. Leaders of CERCs will face unique challenges.

**FINDING 3-1:** Leaders of CERCs will face unique challenges due to the centers' scale, from the need to integrate knowledge from diverse disciplines and perspectives and from geographically dispersed institutions and research teams.

**RECOMMENDATION 3-1: In order to give the convergent engineering research centers (CERCs) the best opportunity to achieve their goal of deep research collaboration toward solving grand-challenge-like problems, the National Science Foundation should ensure that CERC leaders are accomplished and recognized leaders of large, complex programs and are skilled in the application of best practices in team research and value creation.**

A recent National Academies report devotes a chapter to strategies appropriate for leading diverse science teams.[26]

[24] Bill and Melinda Gates Foundation, "Challenges," http://gcgh.grandchallenges.org/challenges, accessed September 23, 2016.

[25] American Institute for Physics, 2016, "NSF Director Córdova Proposes Nine Big Ideas," June 14, https://www.aip.org/fyi/2016/nsf-director-c%C3%B3rdova-proposes-nine-big-ideas-foundation.

[26] NRC, 2015, *Enhancing the Effectiveness of Team Science*, The National Academies Press, Washington, D.C. Chapter 6.

## Engineering Education

Engineering education is constantly evolving. There is a national trend in engineering education toward more experiential courses, "maker" facilities, design institutes, and entrepreneurship.[27] In the future, the committee believes that most if not all engineering schools will have design institutes and entrepreneurship programs. The challenge for CERCs will not be to reinvent these innovations in engineering teaching and learning, but to build upon the best of these methods and enable the CERC-affiliated students to exercise the skills they learn in these programs developed by the host institutions.

**FINDING 3-3:** Ongoing changes in engineering education include a greater emphasis on collaborative, team-based experiential learning and a focus on creativity and design activities and entrepreneurship, as well as ethical aspects of proposed solutions—all of which better prepare students to succeed in center-like, multidisciplinary environments throughout their careers.

**RECOMMENDATION 3-3a: Centers should offer students opportunities to exercise design and entrepreneurship skills obtained through their departmental coursework by providing experiences such as internships, exposure to industrial and public sector expertise through collaborations, workshops, seminars, personnel exchanges, and opportunities to discuss the ethical dimensions of their work.**

Current ERCs provide students with some of these opportunities, and these should be continued. CERCs would also give students a deeper exposure to team-research and value-creation best practices, which will serve them well throughout their careers.

## Diversity and Public Outreach

Studies have shown that research teams with broader cultural knowledge and perspectives can produce more innovative and robust solutions to science and engineering problems.[28] A more diverse engineering workforce is imperative when addressing complex problems with worldwide societal impacts, and the diversity of the U.S. talent pool can become a competitive advantage. Many studies have pointed to the need to expand U.S. engineering workforce capacity and have proposed strategies for attracting more women and underrepresented minorities to the profession, as well as education outreach to K-12 grade levels to improve understanding and appreciation of engineering. The ERCs have taken this challenge seriously, and, by means of policies such as requiring the lead university to partner with a minority-serving university, have outperformed other engineering programs in terms of the percentages of women, Hispanics, and underrepresented minorities participating in the centers.[29] The committee believes that continued emphasis on expanding diversity and public outreach is good both for accomplishing the center mission and for the country.

**FINDING 3-4:** The goal of expanding diversity in science and engineering is not only good for the creativity and productivity of research teams, it is good for expanding the capacity of the United States to innovate and compete.

**RECOMMENDATION 3-4: The National Science Foundation should insist that convergent engineering research centers continue to build upon the success of engineering research centers in expanding diversity of the engineering workforce.**

[27] See, for example, T. Byers, T. Seelig, S. Sheppard, and P. Weilerstein, 2013, Entrepreneurship: Its role in engineering education, *The Bridge* 43(2):35-40; and S.K. Gilmartin, A. Shartrand, H.L. Chen, C. Estrada, and S. Sheppard, 2016, Investigating entrepreneurship program models in undergraduate engineering education, *International Journal of Engineering Education* 32(5A):2048-2065.

[28] *Nature*, 2014, "Diversity: A Nature and Scientific American Special Issue," October 1, http://www.nature.com/news/diversity-1.15913.

[29] NSF, 2015, "ERC Solicitation 15-589 Webinar: Guidance for Preliminary Proposal Development," August 31, https://www.nsf.gov/attachments/135960/public/NSF15-589_ERCwebinar.pdf.

CERCs should have an advantage over ERCs in this regard, due to their focus on grand-challenge-like problems with great societal impact. Research has shown that if programs emphasize engineering as a source of societal benefit rather than focusing more narrowly on technology per se, they have increased appeal to women and underrepresented minority students.[30,31,32,33] This is borne out, for example, in the enrollment statistics of the NAE's Grand Challenges Scholars Program (Box 3.1) and in Purdue University's EPICS service-learning program.[34] Grand-challenge-like problems are also international in scope and should attract international students and faculty to CERCs.

Most major universities have well-established offices whose aim is to promote diversity and K-12 outreach, staffed by experienced professionals, and there is a body of scholarly literature on these subjects. CERCs should take advantage of these resources and expertise for help in designing their diversity and outreach programs.

## Overall Goals and Metrics

From its inception, the ERC program has had the goal of enhancing U.S. industrial competitiveness by transferring intellectual value and technology developed in the centers into the commercial sphere. NSF has also sought to create economic value indirectly through the training of a diverse group of students with the skills to innovate. The committee believes that the top-level goal of future CERCs should be to solve critical societal problems with engineering research and to equip students with the fundamental knowledge on how to deliver those solutions to society. This goal of maximizing societal benefit will generally go hand-in-hand with creation of far-reaching economic value.

Over time, one indicator that a center has delivered societal benefit is that the results of the center are picked up by industry, and then industry makes economic advances that can be traced back to the centers. Thus, one can use economic value delivered as one metric—but not the only one—to determine if a CERC (or the NSF centers generally) have delivered societal benefit. The committee is agnostic about whether the larger goal of delivering maximum societal benefit is served by centers seeking to translate proprietary technologies to the private sector by either licensing or forming startups, or by giving away their intellectual content through open sourcing. As one example, the Linux operating system is open source, but has created huge economic value.

The goal of metrics is to measure outcomes or impacts, not just outputs. Metrics used to measure center performance in the past have included the following: number of students graduated, number of papers published, number of patents issued, licenses, startups, and so on. These metrics are essentially outputs that may or may not indicate true societal impact. Also, in many cases the numbers can be "gamed," and reliance on these numbers can foster a "box-checking" mentality that is not helpful.

**FINDING 4-3:** Metrics currently used to evaluate centers tend to focus on numbers of students graduated, papers published, patents awarded, and so on. These output numbers do not necessarily measure the true impact of the center, can be gamed, and may encourage a box-checking mentality.

**RECOMMENDATION 4-3: The National Science Foundation should develop metrics that track the impacts of center activities, not just the outputs. Examples might include the placement of graduated students in positions of influence or evidence that intellectual value developed in the center is widely used.**

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[30] I.J. Busch-Vishniac and J.P. Jarosz, 2004, Can diversity in the undergraduate engineering population be enhanced through curricular change?, *Journal of Women and Minorities in Science and Engineering* 10:255-281.

[31] W.A. Wulf and G.M.C. Fisher, 2002, A makeover for engineering education, *Issues in Science and Technology On-Line*, Spring.

[32] R. Williams, 2003, Education for the profession formerly known as engineering, *Chronicle of Higher Education*, January 24.

[33] D. Wormley, 2003, "Engineering Education and the Science and Engineering Workforce," pp. 40-46 in Institute of Medicine, National Academy of Sciences, and National Academy of Engineering, *Pan-Organizational Summit on the U.S. Science and Engineering Workforce: Meeting Summary*, The National Academies Press, Washington, D.C.

[34] W. Oakes, M-C Hsu, and C. Zoltowski, 2015, "Insights from a First-Year Learning Community to Achieve Gender Balance," *2015 IEEE Frontiers in Education Conference (FIE)*, doi:10.1109/FIE.2015.7344114.

Admittedly, metrics of impact—such as placement of students into positions of influence rather than the number of students graduated, or indicators of widespread use of software or adoption of standards rather than the number of programs or standards produced—are more challenging to measure and may only be apparent on longer timescales. Fortunately, emerging technologies such as business analytics and metrics platforms, already in use in major corporations, should be able to help capture this information automatically and thus reduce data gathering and reporting burdens.

**FINDING 6-3b:** Emerging collaboration platforms allow real-time tracking and longitudinal follow-up of research activities at the centers and students, faculty, and collaborators who have been engaged at the centers, all with less burden on the centers.

The committee commissioned a review of international center programs, which indicated that some highlight the importance of performance metrics that are tailored to the "impact logic" of the center being evaluated. For example, generating patents is not an objective for some centers because the participating partners or sectors do not have patents as part of their business logic. Some international programs give funded centers the freedom to identify, track, and report additional novel metrics that are not specified in official reporting forms.[35]

**RECOMMENDATION 6-3: Metrics should be minimal, essential, and aligned with center milestones and processes and should be defined in a center's strategic plan. The convergent engineering research centers should use state-of-the-art web-based collaboration platforms, such as performance dashboards, to amplify team collaboration and simplify reporting requirements.**

Appropriate performance metrics will vary according to the stage of maturity of the centers and on whether the chosen research problem is related more to direct economic benefit or to broader societal benefit. Very few performance metrics of substance can be obtained during the first 1 to 3 years of a CERC's existence.[36] That is because the teams are just beginning the research. The creation of significant new papers and commercial innovations from a CERC's initiatives during that period is unlikely. The best practice is therefore to measure how well the teams are using the team-research and value-creation methodologies, including metrics for collaboration, such as jointly authored papers or conference presentations, weekly discussions with colleagues, and quarterly all-hands forums.

**FINDING 6-4:** Appropriate performance metrics for CERCs will vary according to their time in operation and the type of research problem they have chosen to address.

**RECOMMENDATION 6-4: Early in the life of a convergent engineering research center (CERC), performance metrics should be based on adherence to team-research and value-creation best practices. Later in the CERC's National Science Foundation funding life, metrics should be based on the CERC's impact on the economic, security, or societal domains as laid out in its strategic plan.**

## CENTER MODELS

There are many ways that CERCs might operate and be organized. The most appropriate model will depend on the type of research problem chosen. There will be no optimal, one-size-fits-all approach. In this report, the committee describes three possible models NSF may want to consider: a grand-challenge-based model; a prize-based innovation model; and a federal-state-local partnership model. This set of models is by no means comprehensive, but all of them are consistent with aspects of the committee's vision. They focus on big, complicated problems whose solutions will bring large societal or economic impacts. They depend on the convergence of knowledge

[35] E. O'Sullivan, 2016, "A Review of International Approaches to Center-Based, Multidisciplinary Engineering Research," a commissioned paper for this study, available at https://www.nae.edu/Projects/147474.aspx.

[36] Exceptions may arise when centers grow out of pre-existing collaborative university-industry research efforts.

from different disciplines and on deeply collaborative and diverse research teams. And they will require NSF resources to be leveraged with other resources, including those from other federal agencies, states, international players, and the private sector. CERCs are an integral part of the overall U.S. science and technology enterprise. In today's environment, however, NSF alone cannot be expected to meet all of the financial or the intellectual requirements for this critical initiative.

1. *The Grand Challenge-Based Model*. For this example, the committee chose one of NAE's Grand Challenges: "advancing personalized learning." By design, grand-challenge-like initiatives create excitement and spark imagination and creativity. They transcend national boundaries, cultures, and demographics and have universal appeal. It is desirable, therefore, that part of the future CERC portfolio focuses on grand-challenge-like problems to proactively engage the global engineering research and education community.

   The scope of a grand challenge problem suggests that a single CERC will not suffice to address it fully. The challenge will likely need to be broken down into critical subcomponents that are addressed separately, or alliances will need to be formed with other centers working on related problems. For example, a CERC devoted to advancing personalized learning could profitably leverage or interact with a center focused on the NAE Grand Challenge "reverse engineering the brain." Whether or not this kind of alliance is undertaken, targeted collaborations with other research centers in the United States and internationally would certainly be needed.
2. *The Prize-Based Innovation Model*. Historically, a key catalyst in the U.S. innovation ecosystem has been the use of properly posed prizes and competitions to accelerate imagination, invention, innovation, investment, and impact. These prizes often inspire and attract a new generation of technology innovators to the field of engineering to solve technical problems with the hope of being the *first team* to achieve the competition milestones and claim a cash prize.

   CERC leadership teams would manage the prize competition in partnership with NSF to achieve a particular research or translational objective or technical milestone that would constitute one technical thrust within the broader center mission. Funding would be provided by third-party partners (e.g., venture capitalists) who have a vested interest in seeing the technology mature to spur innovation and entrepreneurship. The example given in this report is Elon Musk's Hyperloop Pod Design Competition.
3. *The Federal-State-Local Partnership Model*. NSF has an opportunity to inspire a new funding model that focuses on specific city, state, or regional economic interests driven by engineering ideas and problem solving. From NSF's point of view, these partnerships would raise CERC funding to levels that would attract diverse talent and stimulate local or regional innovation ecosystems. From a city or state's point of view, the partnership would take advantage of not only the cachet of NSF funding but also its support for the talent and capability in a given engineering area and its ability to guarantee the quality of the "product" through an independent review process that focuses on value added or impact on local economic development for the state investment.

   The example the committee chose is a CERC that would develop practical approaches to dealing with the joint issues of sea level rise and extreme weather events for coastal cities. A wide range of disciplines would be involved, such as civil engineering, hydrology, meteorology, data science, law, architecture, political science, and social science. Public sector partners would include city, county, and state agencies. Private-sector partners could include companies dealing with insurance, real estate development, and property management. NSF's investment would be augmented by contributions from a city, state, or consortium of states.

## CONCLUDING THOUGHTS

In some respects, the committee's vision for the new CERCs may sound a lot like the original description of the ERCs quoted in the second paragraph of this Summary. The committee applauds the successes achieved by the ERC program and believes that many capable people at NSF and at the centers have worked hard to develop valuable practices that should continue to evolve in the program going forward. In this report, the committee offers

TABLE S.1 Differences Between Engineering Research Centers (ERCs) and Convergent Engineering Research Centers (CERCs)

| ERCs | CERCs |
|---|---|
| Multidisciplinary research primarily focused on technological innovation. | Transdisciplinary research focused on high-impact societal challenges, exploiting technological convergence and especially bringing in the social sciences as appropriate. |
| Emphasis on creating economic value by enhancing U.S. innovation ecosystems. | Emphasis on maximizing societal value, which in almost all cases will lead to creation of great economic value. |
| Strategic planning based on proceeding from fundamental research through enabling technology research to systems research (test beds). | Strategic planning based on systematic application of best practices in value creation. |
| Researchers and students collaborate through regular meetings and discussions. | Deep research collaboration using both in-person meetings and virtual technology platforms and the best practices in team research. |
| Approximately 20 centers operating at any one time with NSF funding supplemented by industry partner memberships as well as state and local funds. | Larger center budgets through reducing the number of centers or supplementary funding from other federal agencies, international governments, states, the private sector, or foundation support. |
| One basic structural model | Experimentation with various structural models |
| Students benefit from interaction with center faculty from multiple disciplines and industry mentors. | Students gain experience with best practices in convergent engineering research. |
| Pre-proposal process helps to ensure that the final proposal meets all requirements. | Rigorous, staged pre-proposal process to refine the problem to be addressed and choose the right teams, including industry partners. |
| Center directors must answer to numerous boards and site visit recommendations. | Center directors given more authority and autonomy from NSF and site visit groups. |
| Extensive reporting requirements for annual reports and post-graduation plans. | Lean reporting requirements and use of software tools to capture outcomes. |
| Performance metrics largely based on outputs (numbers). | Performance metrics based on outcomes and impacts. |
| Sunset after 10 years but with the expectation of the center continuing with other support. | Opportunity to re-compete after 10 years if transformational results are being achieved. |

a vision for how the centers can build on these successes to achieve even greater benefits for society. The major differences between the proposed CERCs and current ERCs are listed in Table S.1.

The committee recognizes that while center-based engineering research has much to contribute, centers cannot be expected to do everything. Asking centers to take on too much may cause them to lose focus and compromise their primary mission—conducting world-class research. In this report, the committee suggests—in multiple contexts—that the host institution should play a significant role in providing educational and administrative support, diversity program planning, and other support functions to enable the CERC to focus on its core mission. Many of these functions already exist at universities, and CERCs should take advantage of this existing infrastructure.

Accordingly, the committee has made an effort to distinguish between responsibilities that should legitimately be put on the centers and those that should be shared more broadly with the host institutions or other stakeholders. For example, the committee's expectation is that CERCs will continue the valuable work in expanding diversity and education outreach that ERCs have started. However, these functions are also embedded (or should be) in the host institutions. The CERC should take advantage of the expertise and resources of the host institution to help design its diversity and outreach programs.[37] The host institution must have "skin in the game" and share responsibility for

[37] According to a 2015 NSF Webinar, this partnering is already encouraged as part of the ERC's Strategic Inclusion Plan (NSF, 2015, "ERC Solicitation 15-589 Webinar: Guidance for Preliminary Proposal Development," August 31, https://www.nsf.gov/attachments/135960/public/NSF15-589_ERCwebinar.pdf).

these programs if the CERC is to be sited there. This should be one consideration in the proposal evaluation. The CERC diversity and education outreach programs must integrate into the host university infrastructure. Similarly, the CERCs need not be expected to re-invent courses in student innovation, entrepreneurship, and ethics, which are expected to become part of the standard curriculum in engineering schools nationwide. Rather, the CERCs will provide opportunities for students to exercise the principles they learn in their regular coursework.

A final example relates to education research. The relatively long center-funding time horizon (up to 10 years) provides opportunities for longitudinal studies that can collect data on which education initiatives work, and which do not, in a center context. While the committee believes such studies would be valuable, it also believes that they should be carried out in collaboration with the host university or outside institutions specializing in education research.

# 1

# Introduction

In July 2015, the National Science Foundation (NSF) funded the National Academies of Sciences, Engineering, and Medicine to conduct a study on the future of center-based, multidisciplinary engineering research. NSF's Engineering Research Center (ERC) program had been in operation for 30 years. In many ways, the program had transformed the conduct of university-based engineering research.[1]

Whereas the primary model for academic researchers after World War II had been groups headed by a single principal investigator (PI),[2] NSF recognized that many complex technical and societal problems could only be solved if researchers from multiple institutions and with diverse expertise combined their efforts. With the materials research laboratories in the early 1970s,[3] the industry/university cooperative research centers in the early 1980s, the ERCs in the mid-1980s, and the science and technology centers in the late 1980s, NSF has explored a number of center-based research models. One common goal of all of these efforts has been to conduct fundamental research to enhance U.S. economic competitiveness. NSF has also emphasized expanding U.S. workforce capacity through training of students and outreach to underrepresented minorities.

While there are many different models for center-based research, ERCs and similar initiatives generally pursue three goals simultaneously:

1. Conducting world-class research,
2, Educating and training students who will contribute in meaningful ways to the U.S. research and development enterprise, and
3, Promoting technological innovation.

NSF is well aware of the dramatic changes that have occurred in the world and in the research landscape over the past 30 years. For example, the pace of technological change has accelerated dramatically; research efforts around the world are now much more interconnected and involve more international partners; students have many more opportunities for online and experiential learning; and research universities are placing a greater emphasis

[1] National Science Foundation (NSF), 2015, *Creating New Knowledge, Innovators, and Technologies for Over 30 Years*, https://www.nsf.gov/eng/multimedia/NSF_ERC_30th_Anniversary.pdf.
[2] D. Kusnezov and W. Jones, 2012, Beyond the endless frontier: A 20th century model faces 21st century realities, *APS News* 21(3).
[3] Materials research laboratories became known as materials research science and engineering centers in 1994.

on entrepreneurship and innovation. These and other changes present opportunities for enhancing the effectiveness and impact of centers.

At the same time, there are challenges to the success of center-based research at universities.[4] These include the following:

- University departmental culture and incentives that often favor the individual-PI approach;
- High transaction costs of coordination and communication among researchers at multiple universities, industries, and sponsoring institutions;
- Faculty involvement in centers in addition to their departmental responsibilities can induce "role fatigue";
- The clash of university and industry timetables, cultures, and bureaucracies; and
- Unique challenges of forming and integrating a multidisciplinary research team, including researchers with different vocabularies, perspectives on the problems, working modes, and geographical dispersion.

In light of these challenges and opportunities, NSF has sought the National Academies' input on how center-based engineering research might evolve in the coming decades and how NSF might engage these entities most effectively.

## ENGINEERING RESEARCH CENTERS

The ERCs are intended to develop an innovative, globally competitive, and diverse engineering workforce and are expected to conduct transformational, interdisciplinary engineering research that leads to a system proof-of-concept test bed (technology readiness levels [TRLs] 1-3) and eventually to technological innovation. Strategic planning for technology development is based around the "3-plane diagram" (Appendix C) that proceeds from fundamental research through enabling technologies to system test beds.

NSF funding ($3 million to $5 million per year) is provided to the lead university (with up to four other partner universities) for a relatively long period of up to 10 years. This funding is supplemented by membership fees paid by industry partners and other stakeholders.

Over the 30-year history of the program, ERCs have evolved through three generations, with each succeeding generation featuring an increasing number of infrastructure requirements. Generation 1 (1985-1990) aimed for interdisciplinary, transformational research at a single host university with industry engagement. Generation 2 (1994-2006) required the lead university to engage with multiple partner universities, including a minority-serving university, to develop strategic plans to increase diversity (women, underrepresented minorities, disabled) at all levels and to establish outreach programs to pre-college (K-12) educational institutions. Generation 3 (2008 to the present) also sought to enhance the ERC student's exposure to international research opportunities by requiring partnerships with foreign universities.

The ERC program has been judged to be successful in many respects. In the education arena, it has been credited with contributing to interdisciplinary research and education at the host institutions. Research has found that ERCs are very successful at creating new or modified, systems-focused, multidisciplinary coursework and curricula, as well as new academic majors and minors.[5,6] These educational innovations can attract students from outside the center and have other institution-wide impacts. The ERCs have also outperformed other engineering programs in terms of the percentages of women, Hispanics, and underrepresented minorities participating in the centers.[7]

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[4] C. Boardman, D.O. Gray, and D. Rivers, eds., 2013, *Cooperative Research Centers and Technical Innovation,* Springer-Verlag, New York.

[5] C.P. Ailes, I. Feller, and H.R. Coward, 2001, *The Impact of Engineering Research Centers on Institutional and Cultural Change in Participating Universities, Final Report*, National Science Foundation, Arlington, Va.

[6] W. Aung, L. Conrad, A. Donnelly, E. Kannatey-Asibu, T. Martin, and E. Tranter, 2006, *Undergraduate and Graduate Education Activities of Current Engineering Research Centers*, 2006 Report of the ERC Education Assessment and Dissemination Task Group, http://erc-assoc.org/sites/default/files/topics/2006-7-01_Assessment_2006_Report%20rla_2.pdf.

[7] NSF, 2015, "ERC Solicitation 15-589 Webinar: Guidance for Preliminary Proposal Development," August 31, https://www.nsf.gov/attachments/135960/public/NSF15-589_ERCwebinar.pdf.

In terms of economic impact, SRI International[8] developed detailed estimates of the direct and indirect/induced economic impacts of five centers.[9] They found the centers, over their 10-year lifespans, were responsible for between $87 million and $356 million in state and regional impact and between $3 million and $175 million in national impact. The researchers noted that (1) many benefits resulting from ERCs cannot easily be translated into economic terms (e.g., value of trained students, new knowledge, ideas, models, algorithms), especially if one considers impacts only during the 10-year NSF funding life of the center, and (2) a focus on economic benefits alone likely significantly underestimates the broader and larger societal impacts of the centers. Using similar methods of analysis, Roessner et al.[10] determined the Microsystems Packaging Research Center at the Georgia Institute of Technology contributed $191 million to the economy of the state of Georgia. Lewis (in 2010)[11] and, more recently, NSF (in 2015)[12] provide descriptive summaries of many technological innovations that trace their roots to research conducted by the centers. The 2015 NSF report noted that since the program's inception in 1985, ERCs have created 193 spin-off companies, disclosed more than 2,200 inventions, been awarded 739 patents, and these resulted in 1,339 licenses.

According to NSF, of the 67 ERCs funded from 1985 to 2015 (excluding those that had not yet been in operation 10 years), 31 had graduated successfully (i.e., had not been terminated prior to the end of their 10-year NSF funding), and over 80 percent continue as self-sustaining "ERC-like" centers.[13] According to a 2010 survey of graduated centers, most had maintained the ERC culture; that is, they maintained the integration of research, education, and industrial interaction as their organizing principle, although generally with reduced budgets and staff. The loss of the prestige associated with loss of NSF support made it more difficult for these centers to raise money from industry and states. Programs in education and diversity outreach tended to be most difficult to maintain in that environment. All of the graduated centers responding to the survey indicated that the benefits of participating in an ERC were worth the effort, although many cited the burdensome amount of reporting and bureaucratic oversight as significant negatives.[14]

## ERCs IN THE CONTEXT OF OTHER FEDERAL COOPERATIVE RESEARCH CENTERS

Although NSF's ERCs were one of the first examples of the center-based approach to fundamental research, in the intervening years, the center concept has proliferated dramatically, both domestically and internationally. Not only does NSF now support several different kinds of research centers, but so do many U.S. federal agencies (Figure 1.1), and virtually all industrialized countries around the world have followed suit.[15]

The ERCs occupy a unique niche among federal centers. Perhaps their most significant defining characteristic is their strong focus on education. They also have a relatively long funding time horizon (initial funding for 5 years with possible renewal for another 5 years). In contrast to the "top-down" selection of research topics at centers sponsored by mission agencies, such as the Defense Advanced Research Projects Agency (DARPA) or the

[8] SRI International, 2008, *National and Regional Economic Impacts of Engineering Research Centers: A Pilot Study*, SRI Project P16906, https://www.sri.com/sites/default/files/brochures/erc_impact_summary_report_11_18_08.pdf.

[9] Caltech's Center for Neuromorphic Systems Engineering, Virginia Tech's Center for Power Electronics Systems, the University of Michigan's Center for Wireless Integrated Microsystems, Johns Hopkins' Center for Computer-Integrated Surgical Systems and Technology, and the Georgia Tech/Emory Center for the Engineering of Living Tissue.

[10] D. Roessner, S. Mohapatra, and Q. Franco, 2004, *The Economic Impact on Georgia of Georgia Tech's Packaging Research Center*, SRI International's Center for Science, Technology, and Economic Development, P16142, SRI International, Menlo Park, Calif., October.

[11] C.S. Lewis, 2010, Engineering Research Centers—Innovations—ERC-Generated Commercialized Products, Processes, and Startups, SciTech Communications LLC, February, http://erc-assoc.org/sites/default/files/topics/ERC_INNOVATIONS_2010_reprint.pdf.

[12] NSF, 2015, *NSF Engineering Research Centers: Creating New Knowledge, Innovators, and Technology for Over 30 Years*, NSF 15-810, http://erc-assoc.org/sites/default/files/download-files/ERC%20Brochure_final%20proof.pdf.

[13] See the ERC Association website at http://erc-assoc.org.

[14] J.E. Williams, Jr., and C.S. Lewis, 2010, *Post-Graduation Status of National Science Foundation Engineering Research Centers: Report of a Survey of Graduated ERCs*, SciTech Communications LLC.

[15] Examples include the U.K.'s Centres for Innovative Manufacturing, Germany's Collaborative Research Centers, Finland's Strategic Centres for Science, Technology and Innovation, Singapore's Research Centres of Excellence, and China's National Engineering Research Centers. See E. O'Sullivan, 2016, "A Review of International Approaches to Center-Based, Multidisciplinary Engineering Research," a commissioned paper for this study, available at https://www.nae.edu/Projects/147474.aspx.

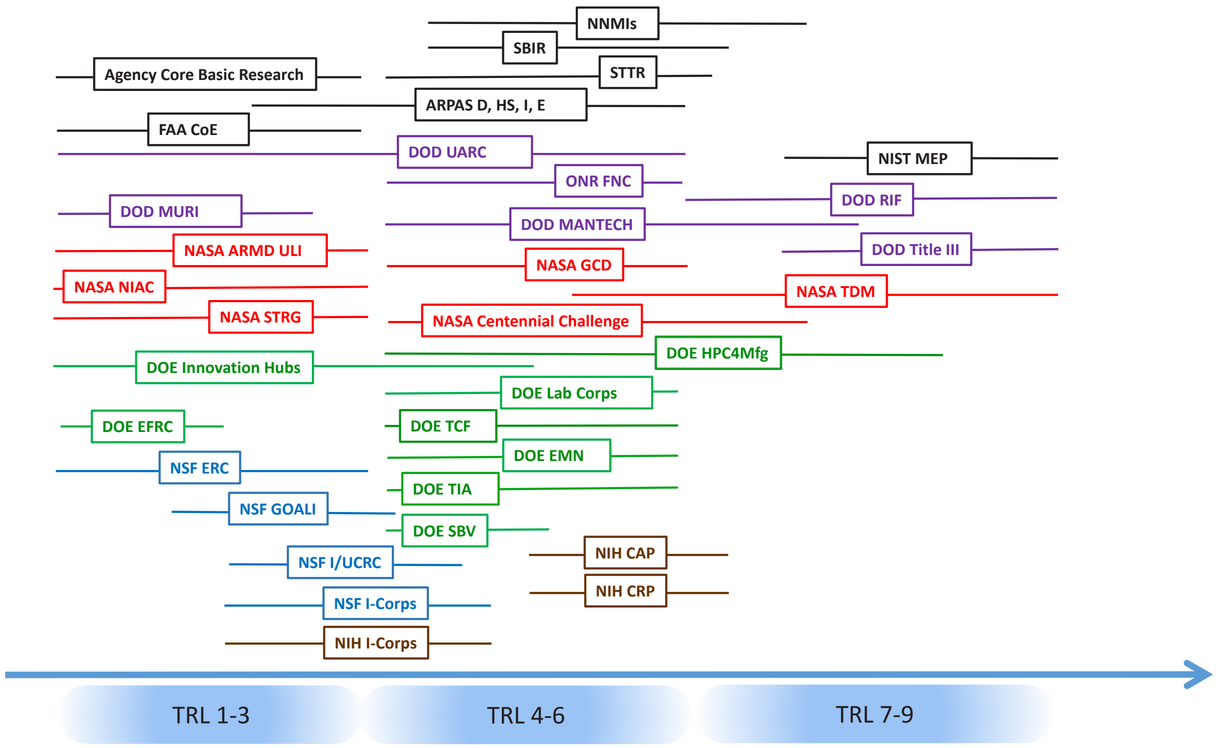


FIGURE 1.1 Research centers and programs sponsored by U.S. federal agencies address different technology readiness levels (TRLs) from the most basic research (TRL 1) to commercialization (TRL 9). The NSF ERCs typically span the range from basic research to proof-of-concept (TRL 1-3). The colors represent: blue, NSF; red, NASA; purple, DOD; green, DOE; black, others. NOTE: CEMI, Clean Energy Manufacturing Initiative; CoE, Center of Excellence; DOD, Department of Defense; DOE, Department of Energy; EFRC, Energy Frontier Research Center; ERC, Engineering Research Center; FAA, Federal Aviation Administration; FNC, Future Naval Capability; GCD, Game Changing Development; GOALI, Grant Opportunities for Academic Liaison with Industry; I/UCRC, Industry/University Cooperative Research Center; I-Corps, Innovation Corps; MANTECH, Manufacturing Technology; MURI, Multidisciplinary University Research Initiative; NASA, National Aeronautics and Space Administration; NIAC, NASA Innovative Advanced Concepts; NNMI, National Network for Manufacturing Innovation; NSF, National Science Foundation; ONR, Office of Naval Research; RIF, Rapid Innovation Fund; SBIR, Small Business Innovation Research; STRG, Space Technology Research Grant; STTR, Small Business Technology Transfer; TCF, Technology Commercialization Fund; TDM, Technology Demonstration Mission; TIA, Technology Investment Agreement; UARC, University Affiliated Research Center; ULI, University Leadership Initiative. SOURCE: National Academies of Sciences, Engineering, and Medicine, 2016, *Triennial Review of the National Nanotechnology Initiative*, The National Academies Press, Washington, D.C.

Department of Energy (DOE), ERC research topics are generally selected from ideas of interest to a core group of academics at the lead university (a "bottom-up" process), although NSF occasionally solicits proposals in broadly defined areas, such as nanotechnology or manufacturing. Consistent with NSF's mission to sponsor fundamental research and education at universities, the ERCs focus on the early stages of technology development—that is, fundamental research to proof of concept (TRL 1-3).

The benefits to industry of engagement in ERCs—which typically occur through service on an industrial advisory board (IAB)—are generally judged to exceed the cost of membership, according to one survey of members.[16] The single most important factor influencing a company's decision to join an IAB, the survey found, was

[16] NSF, 2012, "IAB Involvement in ERCs: Assessing and Strengthening the Role," presentation at the 2012 ERC Annual Meeting, November 13-16, Bethesda, Md., http://erc-assoc.org/sites/default/files/download-files/IAB%20Role%20in%20ERCs_PeterSeoane_11-2012.pptx.

to follow developments in a field related to the firm's business. Other benefits accruing to industry from involvement in ERCs include access to ideas and know-how and the ability to identify potential new employees.[17] Most industry partners neither achieved nor expected to achieve benefits related to tangible product- or process-oriented outcomes as a result of their association with an ERC.[18]

## ERCs IN AN INTERNATIONAL CONTEXT

In 2007, NSF released a study comparing the ERC program to center programs in China, South Korea, Japan, England, Ireland, Germany, and Belgium.[19] The centers were analyzed according to three themes: (1) position on the "innovation continuum" from basic research to product/marketing (similar to TRL level), (2) method of selecting research topics (e.g., "bottom-up" or "top-down"), and (3) approach to international partnerships. Some center programs appeared to have been influenced by the ERC model, while others followed a different path that would be hard to replicate in the university context—for example, Germany's Fraunhofer Institutes are independent legal entities that conduct applied research with the expressed purpose of assisting German industry and use a top-down process for project selection. The report noted that while most centers in the sample featured international collaborations and partnerships, there were no examples of centers that were international in scope from their inception, with international collaboration as a core function.[20]

As part of this study, the committee commissioned a paper aimed at identifying innovative features of foreign centers that might be included in its deliberations.[21] The paper, which considered centers in the United Kingdom, Japan, Germany, China, Sweden, Canada, and Ireland, was based primarily on "desk research," involving a systematic review of center program documents as well as interviews with some funding agency directors and directors of individual centers. It found that almost every country is asking the same questions as those addressed in this study: What should future center models look like in the face of trends and drivers shaping research priorities and innovation systems? However, a number of experts interviewed suggested that centers achieving significant added value, based on systematic collaboration and truly integrated research endeavors, are extremely rare. Some of the other key findings of that work are listed in Appendix D.

## STATEMENT OF TASK

In response to NSF's request, the National Academy of Engineering (NAE) and the National Research Council's Division on Engineering and Physical Sciences formed the Committee on the Future of Center-Based, Multidisciplinary Engineering Research (committee bios are provided in Appendix A). The committee's statement of task was as follows:

> 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.

[17] D. Roessner, D.W. Cheney, and H.R. Coward, 2004, *Impact on Industry of Interactions with Engineering Research Centers—Repeat Study. Summary Report*. SRI International, December.

[18] I. Feller, C.P. Ailes, and J.D. Roessner, 2002, Impacts of research universities on technological innovation in industry: Evidence from engineering research centers, *Research Policy* 31:457-474.

[19] B. Lal, C. Boardman, N.D. Towery, and J. Link, 2007, *Designing the Next Generation of NSF Engineering Research Centers: Insights from Worldwide Practice*, Institute for Defense Analysis Science and Technology Policy Institute.

[20] This may be changing. For example, Singapore's NSF centers are designed to be international from the start.

[21] E. O'Sullivan, 2016, "A Review of International Approaches to Center-Based, Multidisciplinary Engineering Research," a commissioned paper for this study, available at https://www.nae.edu/Projects/147474.aspx.

> 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.

At the committee's first meeting, the sponsor also suggested four questions that the project should consider:

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

Although these questions are not part of the committee's formal statement of task, they helped guide its deliberations.

## REPORT SCOPE AND COMMITTEE APPROACH

There are many possible models of center-based research. These include university-based centers, national laboratory-based centers, independent institutes, public-private partnerships, industry consortia, and so on. Centers may have different missions, governance, and management structures; policies governing the relationships among the partners; and emphases on different stages of technological maturity (Figure 1.1).

Given NSF's longstanding role of funding academic research, the committee has chosen to concentrate its data gathering and analysis on university-based research center models. And while the committee has heeded the admonition in its statement of task not to evaluate the ERCs, it has used the ERC program as a reference point. That is, it has assumed that the three goals—research, education, and innovation—will continue to be the main pursuits of the future centers considered here. Nevertheless, the committee believes that its findings and recommendations are relevant to a variety of types of research centers, not just ERCs.

The committee used a number of methods to gather the information it needed. It held four information-gathering meetings that featured presentations by speakers on topics such as education research in the center context, improving student diversity, and innovative practices of domestic research centers. (Meeting agendas are provided in Appendix B.) Between the meetings, the committee held a series of conference calls with key individuals, also listed in Appendix B. Appendix C discusses key aspects of strategic planning and organizational processes at current ERCs, and Appendix D lists some key findings from a commissioned paper on international centers. Appendix E describes the various domestic research centers that the committee heard from.

On April 6, 2016, the committee convened the 1-day symposium, "Exploring a New Vision for Center-Based, Multidisciplinary Engineering Research," to inform the broader community about the study and to solicit ideas from speakers and attendees.[22] Symposium sessions addressed the following topics:

[22] The symposium proceedings was published separately in fall 2016 and is available for free download on the National Academies Press website at http://www.nap.edu (see National Academies of Sciences, Engineering, and Medicine, 2016, *A Vision for the Future of Center-Based Multidisciplinary Engineering Research: Proceedings of a Symposium*, The National Academies Press, Washington, D.C.). Videos of selected presentations from the symposium are available on the project website at https://www.nae.edu/Projects/147474/147561/147730.aspx.

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

The committee also commissioned two papers, one examining foreign research centers[23] and the other focusing on the nature of university-industry interactions in the United States,[24] including, but not limited to, interactions involving centers. These papers informed the committee's deliberations.

It is important to maintain a certain humility when opining on how things will be decades hence. The world is quite different than it was 30 years ago, and the committee assumes that it will be different in the coming decades. Even so, in thinking about centers of the future, the committee has attempted to identify trends that seem likely to continue to shape the environment in which future research centers will have to operate.

The committee recognizes that while center-based engineering research has much to contribute, centers cannot do everything. The fraction of U.S. engineering graduates who are touched by the centers is relatively small. So asking centers to take on too much may cause them to lose focus and compromise their primary mission. Accordingly, the committee has made an effort to distinguish between responsibilities that should legitimately be put on the centers and those that should be shared with the host institutions or other stakeholders.

The committee applauds the successes achieved by the ERC program and believes that many capable people at NSF and at the centers have worked hard to develop valuable practices that should continue to evolve in the program going forward. In this report, the committee offers a vision for how the centers can build on these successes to achieve even greater benefits for society.

## CONTEXT FOR THE VISION

In constructing its vision for the future of center-based engineering research, the committee made the following assumptions about the context within which such research will take place:

- *Engineering will continue to drive innovation*. Engineering is an empowering discipline of our times. It will continue to be an essential discipline behind innovations that create economic impact and societal benefit.
- *Global communication and collaboration will expand*. In the future, the world will be far more interconnected across institutional and national boundaries. Software tools for communication and collaboration will continue to become more user-friendly. Development of artificial intelligence tools and the Internet of Things mean that smart machines will be everywhere, connecting researchers with data, instrumentation, and expertise around the world. Discovery and research processes will continue to become globally more transparent, digitally archived and queried, crowd-sourced and enabled by citizen-science, and disseminated in real time.

  The phenomenon of team research will continue to become more prevalent. Solving complex problems will increasingly require multidisciplinary teams of researchers collaborating effectively.[25]
- *Convergence in research will become the norm*. The greatest research opportunities will increasingly lie at the points where knowledge from formerly distinct disciplines can be combined to create something fundamentally new.[26,27] A good example is human performance enhancement (HPE). HPE has left the domain

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[23] E. O'Sullivan, 2016, "A Review of International Approaches to Center-Based, Multidisciplinary Engineering Research," a commissioned paper for this study, available at https://www.nae.edu/Projects/147474.aspx.

[24] A. Belz, 2016, "Trends in Industry-University Relationships," a commissioned paper for this study, available at https://www.nae.edu/Projects/147474.aspx.

[25] National Research Council (NRC), 2015, *Enhancing the Effectiveness of Team Science*, The National Academies Press, Washington, D.C.

[26] M.C. Roco and W.S. Bainbridge, eds., 2003, *Converging Technologies for Improving Human Performance: Nanotechnology, Biotechnology, Information Technology, and Cognitive Science,* an NSF/DOC sponsored report, Kluwer Academic Publishers (currently Springer), Dordrecht, The Netherlands, http://www.wtec.org/ConvergingTechnologies/Report/NBIC_report.pdf.

[27] M.C. Roco, W.S. Bainbridge, B. Tonn, and G. Whitesides, eds., 2013, *Convergence of Knowledge, Technology, and Society: Beyond Convergence of Nano-Bio-Info-Cognitive Technologies*, a World Technology Evaluation Center, Inc., panel report, http://www.wtec.org/NBIC2/Docs/FinalReport/Pdf-secured/0A-NBIC2-FinalReport-WTECversion--web.pdf.

of science fiction and is now part of engineering—ranging from prostheses and hearing aids to deep brain stimulation and body armor as well as pharmaceuticals and education and training.[28] HPE exemplifies the integration of engineering, materials, information technology, life sciences, medicine, and social sciences.

A recent National Research Council report[29] discusses the phenomenon of "convergence" of formerly distinct research fields. The committee foresees that convergence of the natural, behavioral, and social sciences with engineering will enable researchers to address new classes of problems, including human cognitive challenges such as autism and personalized learning. Convergence will also have implications for the organization of research universities in the future.

- *The pace of innovation will accelerate*. We are in a global innovation economy. As information, communications, and artificial intelligence technologies advance, they create new tools and capabilities. The positive feedback from these developments makes the world increasingly transparent and competitive, further accelerating the pace of innovation.[30] Capturing value for the nation will not occur by focusing on U.S. capacity alone; rather, the successful teams will be global and the "winners" will be those who not only have deep knowledge and superior competencies but also who can adapt and execute the fastest, and then sustain a culture of continuous improvement. Policies that promote this dynamism are consistent with this trend; those that inhibit it are not.
- *U.S. technological lead over the rest of the world—where it still exists—will narrow.* In the coming decades, the United States will be in a profoundly more competitive and challenging world. Going forward, it must significantly improve its innovative performance while educating the world's most innovative workforce. However, the United States will not have the most research, development, and innovation (RD&I) professionals or the most resources. For the United States to win its share of jobs and prosperity, it must leverage its core strengths and work smarter.

  Many reviews have detailed areas of technology and innovation in which the United States is no longer leading the world or is falling behind.[31] This is, in many ways, a natural consequence of globalization of technology, knowledge, and resources. U.S. companies already invest nearly as much research and development (R&D) funding in Europe and Asia as they do at home,[32] and U.S. universities educate large numbers of foreign students in science and engineering fields. While some of these students pursue productive careers in the United States, others increasingly return home and utilize that knowledge to develop their domestic economies.

  At the same time, the United States will continue to enjoy certain competitive advantages, including the quality of its top-tier research universities, strong venture capital markets, a large market that is both willing and able to embrace new technologies, and an entrepreneurial culture that develops new opportunities, encourages risk taking, and does not punish initial failure of new ventures.
- *Value-creation best practices will continue to be a key to success*. Today the top professionals and enterprises have the innovative skills and value-creation processes to identify and systematically develop major new opportunities. Those that do, such as Apple, Google, P&G, and IDEO, are all leaders in their fields. Improved innovation processes are being implemented, such as Agile,[33] Lean,[34] Six Sigma,[35] and

[28] Another phrase for the same field is human performance modification (HPM). See, for example, NRC, 2012, *Human Performance Modification: Review of Worldwide Research with a View to the Future*, The National Academies Press, Washington, D.C.

[29] NRC, 2014, *Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond*, The National Academies Press, Washington, D.C.

[30] Kurzweil Accelerating Intelligence, "The Law of Accelerating Returns," http://www.kurzweilai.net/the-law-of-accelerating-returns, accessed April 10, 2017.

[31] See, for example, a series of reports produced by the National Academy of Sciences, National Academy of Engineering, Institute of Medicine, beginning with the 2007 report *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, available at http://www.nas.edu from the National Academies Press, Washington, D.C.

[32] E. O'Sullivan, 2016, "A Review of International Approaches to Center-Based, Multidisciplinary Engineering Research," a commissioned paper for this study, available at https://www.nae.edu/Projects/147474.aspx.

[33] Agile Methodology, "The Agile Movement," http://agilemethodology.org, accessed September 12, 2016.

[34] Lean Enterprise Institute, "What is Lean," http://www.lean.org/WhatsLean/, accessed September 12, 2016.

[35] *Wikipedia, The Free Encyclopedia*, "Six Sigma," https://en.wikipedia.org/wiki/Six_Sigma, accessed September 13, 2016.

the Five Disciplines of Innovation.[36] In addition, companies are increasingly using other models, such as the X-Prize[37] and Google-X[38] "grand challenges" to drive innovation. Online competitions from Kaggle[39] and many others are producing impressive outcomes. These programs are showing that large systemic improvements in productivity can be made.[40] Developing a U.S. workforce where engineering graduates understand and apply these skills will allow the United States to continue to lead in the creation of new, high-value global innovations.

[36] C.R. Carlson and W.W. Wilmot, 2006, *Innovation: The Five Disciplines for Creating What Customers Want*, Crown Publishing Group, New York.
[37] XPrize, http://www.xprize.org, accessed October 17, 2016.
[38] X Company, "About Us," https://www.solveforx.com/about, accessed October 27, 2016.
[39] Kaggle, https://www.kaggle.com, accessed October 27, 2016.
[40] NRC, 2015, *Making Value for America: Embracing the Future of Manufacturing, Technology, and Work*, The National Academies Press, Washington, D.C.

# 2

# A Vision for Convergent Engineering Research

Today the world faces extraordinary opportunities enabled by technological progress: new technologies for communication and deep collaboration in teams and new ways to collect and process information that are transforming industries and computing technologies and offer the promise of higher levels of automation and intelligence in the devices created. Today's engineers stand on the cusp of dramatic advances in materials, information, robotics, energy, transportation, manufacturing, and health. Use of information technology-enabled tools for collaboration is now the norm, including artificial intelligence and "big data," allowing teams—both large and small—to work more effectively.

The world also faces a complex set of global challenges: threats to the environment, threats to national security, disruptive changes in the workforce, new diseases and health risks, and a rapidly changing world economy and competitive landscape.

Solutions will require research teams capable of bringing together expertise from both natural and social science disciplines to address all facets of these challenges. This approach has been conceptualized as a continuum of increasing disciplinary integration, starting with multidisciplinary, and proceeding through interdisciplinary to transdisciplinary.[1]

"Multidisciplinary research is typically understood as the sequential or additive combination of ideas or methods drawn from two or more disciplines or fields to address the focal problem. Interdisciplinary research involves the *integration* of perspectives, concepts, theories, and methods from two or more disciplines or fields to address the problem. Transdisciplinary research entails not only the integration of discipline-specific approaches, but also the extension of these approaches to generate fundamentally new conceptual frameworks, hypotheses, theories, models, and methodological applications that *transcend* their disciplinary origins."[2]

A 2014 National Research Council report[3] uses a different term for the transdisciplinary research approach—"convergence," and this term will be used in this report (Box 2.1).

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[1] K.L. Hall, A.L Vogel, B.A Stipelman, D. Stokols, G. Morgan, and S. Gehlert, 2012, A four-phase model of transdisciplinary team-based research: Goals, team processes, and strategies, *Translational Behavioral Medicine* 2(4):415-430.

[2] Ibid.

[3] National Research Council (NRC), 2014, *Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond*, The National Academies Press, Washington, D.C.

**BOX 2.1**
**Convergence**

In 2014, the National Research Council published a report[a] describing the opportunities and challenges presented by an old idea that was gaining new currency: "convergence." That is, solving many modern, complex research problems requires that expertise from formerly distinct academic disciplines be brought to bear in a coordinated way. The text below is quoted from the Summary of that report.

> Convergence is an approach to problem solving that cuts across disciplinary boundaries. It integrates knowledge, tools, and ways of thinking from life and health sciences, physical, mathematical, and computational sciences, engineering disciplines, and beyond to form a comprehensive synthetic framework for tackling scientific and societal challenges that exist at the interfaces of multiple fields. By merging these diverse areas of expertise in a network of partnerships, convergence stimulates innovation from basic science discovery to translational application. It provides fertile ground for new collaborations that engage stakeholders and partners not only from academia, but also from national laboratories, industry, clinical settings, and funding bodies. The concept of convergence as represented . . . is thus meant to capture two closely related but distinct properties: the convergence of expertise necessary to address a set of research problems, and the formation of the web of partnerships involved in supporting such scientific investigations and enabling the resulting advances to be translated into new forms of innovation and new products.
>
> Many institutions are interested in how they can better facilitate convergent research. Despite the presence of established models, however, cultural and institutional roadblocks can still slow the creation of self-sustaining ecosystems of convergence. Institutions often have little guidance on how to establish effective programs, what challenges they might encounter, and what strategies other organizations have used to solve the problems that arise.

[a] National Research Council, 2014, *Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond*, The National Academies Press, Washington, D.C.

While convergence of technical science and engineering disciplines is often observed in current research programs, it is less common to see the successful integration of these with the social sciences. Such a comprehensive approach will be important in addressing major societal problems.

**FINDING 2-1:** This is a time of enormous opportunity in which exponentially expanding knowledge in previously distinct fields can now be combined in new ways to create innovations of great value for society.

## SOLVING BIG PROBLEMS

The unprecedented growth and convergence of many technologies in recent decades offers the opportunity to address big, grand-challenge-like problems over a time horizon that is within the timeframe of a major National Science Foundation (NSF) initiative. Examples might include the National Academy of Engineering's (NAE's) Grand Challenges (e.g., provide access to clean water, Box 2.2). This big-problem focus changes the narrative about engineering and its importance to society, and it dovetails well with an NAE initiative to change how engineering is represented.[4]

Developing new technologies with high societal impact might be another theme of future centers. One source for such technologies could be the recently identified six "research big ideas" and the three "process ideas"

[4] National Academy of Engineering, 2008, *Changing the Conversation: Messages for Improving Public Understanding of Engineering*, The National Academies Press, Washington, D.C.

**BOX 2.2**
**NAE's Grand Challenges for Engineering**

In 2008, a blue-ribbon panel at the National Academy of Engineering (NAE) identified the following 14 challenges for engineering in the 21st century (www.engineeringchallenges.org):

- Advance personalized learning,
- Make solar energy economical,
- Enhance virtual reality,
- Reverse-engineer the brain,
- Engineer better medicines,
- Advance health informatics,
- Restore and improve urban infrastructure,
- Secure cyberspace,
- Provide access to clean water,
- Provide energy from fusion,
- Prevent nuclear terror,
- Manage the nitrogen cycle,
- Develop carbon sequestration methods, and
- Engineer the tools of scientific discovery.

The challenges facing engineering are those facing the planet as a whole and all of the planet's people. Meeting the challenges must make the world not only a more technologically advanced and connected place, but also a more sustainable, safe, healthy, and joyous one. In the last 8 years, in addition to the Grand Challenges Scholars Program (GCSP; Box 3.1), which prepares students around the world to address Grand Challenge-like problems, the NAE Grand Challenges initiative has spawned a biannual Global Grand Challenges Summit (with partners in England and China) and a small but growing number of K-12 schools that are using the challenges as the basis for curriculum.

identified by NSF (see Box 2.3). The committee considered three of these big ideas—harnessing data for 21st century science and engineering, shaping the new human-technology frontier, and quantum leap: leading the next quantum revolution—as being particularly relevant for future centers, although all six could incubate technologies essential to the solution of problems with great societal impact.

There are many other opportunities and guiding themes for complex engineering and societal problems that could be appropriate for future NSF engineering centers. Examples include the 15 global challenges identified by the Millennium Project[5] or the health and development grand challenges identified by the Bill and Melinda Gates Foundation.[6] Other entities, such as the President's Council of Advisors on Science and Technology (PCAST) and the Office of Science and Technology Policy (OSTP), have described similar initiatives, including the National Nanotechnology Initiative,[7] the National Robotics Initiative,[8] the Brain Initiative,[9] and the Cancer Moonshot.[10]

[5] The Millennium Project, "Challenges," http://millennium-project.org/millennium/challenges.html, accessed September 23, 2016.
[6] Bill and Melinda Gates Foundation, "Challenges," http://gcgh.grandchallenges.org/challenges, accessed September 23, 2016.
[7] National Nanotechnology Initiative, http://www.nano.gov/, accessed on May 25, 2017.
[8] National Science Foundation, "Funding: National Robotics Initiative 2.0: Ubiquitous Collaborative Robots (NRI-2.0)," https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503641, accessed October 10, 2016.
[9] White House, "Brain Research through Advancing Innovative Neurotechnologies," https://www.whitehouse.gov/BRAIN, accessed September 9, 2016.
[10] National Institutes of Health, "Cancer Moonshot," https://www.cancer.gov/research/key-initiatives/moonshot-cancer-initiative, accessed September 9, 2016.

**BOX 2.3**
**National Science Foundation Big Ideas**

In May 2016, in a presentation to the National Science Board, National Science Foundation Director France Córdova outlined six research big ideas and three process ideas that she believes will lead to major advances.

**Research**

- Harnessing data for 21st century science and engineering;
- Shaping the new human-technology frontier;
- Understanding the rules of life (i.e., predicting phenotypes from genotypes);
- Quantum leap: leading the next quantum revolution;
- Navigating the new arctic (including a fixed and mobile observing network); and
- Windows on the universe: the era of multi-messenger astrophysics.

**Process**

- More convergent research;
- Support for midscale infrastructure (costing tens of millions of dollars); and
- NSF 2050 (i.e., a common fund to seed large, ambitious projects).

SOURCE: American Institute of Physics, "NSF Director Córdova Proposes Nine Big Ideas for the Foundation," June 14, 2016, https://www.aip.org/fyi/2016/nsf-director-c%C3%B3rdova-proposes-nine-big-ideas-foundation.

There appears to be an emerging consensus among international centers that future university-industry research centers should be more challenge-focused—that is, a greater fraction of centers addressing "needs pull" challenges, rather than just tackling "science push" opportunities.[11]

## BEST PRACTICES OF TEAM RESEARCH AND VALUE CREATION

The "big problem" orientation described above should help to inspire future center personnel, but it complicates the tasks of assembling the right research team, managing it efficiently, and maintaining its focus on center goals. These challenges highlight the importance of the systematic use of the best practices of team research and value creation in the centers to give them the best opportunity to succeed.

### Team Research

Team research[12] refers to research conducted by more than one individual in an interdependent fashion, including research conducted by small teams and larger groups. As defined here, it includes all of engineering as well as traditional physical and social science fields. To reach their goal successfully, multidisciplinary research teams must overcome a number of challenges, including the integration of members with different areas of expertise,

[11] E. O'Sullivan, 2016, "A Review of International Approaches to Center-Based, Multidisciplinary Engineering Research," a commissioned paper for this study, available at https://www.nae.edu/Projects/147474.aspx.

[12] In this report, which is about engineering research, the committee chose to use the phrase "team research" rather than adopt the earlier NRC report's phrase "team science," but the principles are the same.

**BOX 2.4**
**Team Research Best Practices**

According to a 2015 National Research Council report, team research best practices include the following:

- Use of task analytic methods to identify knowledge, skills, and attitudes required for effective team performance;
- Use of tools such as research networking systems designed to facilitate assembly of the best scientific teams;
- Development of a common vocabulary to enable integration of data, tools, knowledge, and theories across disciplines;
- Use of knowledge development training to increase sharing of individual knowledge and improve problem solving; and
- Application of technologies to track individual roles and contributions, enabling appropriate allocation of credit.

SOURCE: National Research Council, 2015, *Enhancing the Effectiveness of Team Science*, The National Academies Press, Washington, D.C.

different vocabularies and ways of approaching problems, different understanding of the problems to be addressed, and different working styles.

There is a strong body of research conducted over decades on how team processes influence team effectiveness.[13] While much of the research has been on nontechnical teams, the insights can be applied to engineering research teams. Examples include the following:

- Team composition influences team effectiveness; in particular, task-relevant diversity is critical and has a positive influence on team effectiveness;
- Team professional development training improves team processes and outcomes; and
- Geographically dispersed science teams and groups face more challenges in communicating and developing trust than do face-to-face teams and groups.

Best practices of team research include those listed in Box 2.4. Implementation of these practices is not easy, and requires considerable time.

Adherence to these team research best practices will be particularly important in addressing the challenges of integrating the social science members with the physical science and engineering members of the team.

## Value Creation

Value creation is the name for the learning and creating activity whose goal is the development of new, sustainable value for society, whether as notable new research results or as marketplace innovations. As discussed in Chapter 1, top professionals and enterprises today have the innovative skills and value-creation processes to identify and systematically develop major new opportunities. These programs are showing that large systemic improvements in productivity can be made.[14] In Box 2.5, the committee lists what in its view are examples of value-creation best practices. Suggested best practices for an enhanced proposal process are provided in Box 6.1.

[13] NRC, 2015, *Enhancing the Effectiveness of Team Science*, The National Academies Press, Washington, D.C.

[14] NRC, 2015, *Making Value for America: Embracing the Future of Manufacturing, Technology, and Work*, The National Academies Press, Washington, D.C.

**BOX 2.5**
**Value-Creation Best Practices**

Systematic high-value innovators, such as IDEO, Apple, General Electric, SRI International, and the Defense Advanced Research Projects Agency (DARPA) employ defined value-creation methodologies that support the development, testing, and refinement of project objectives—from fundamental research through the delivery of important new knowledge or marketplace innovations. These methodologies go by many names, including Agile,[1] Scrum,[2] Lean,[3] Six Sigma,[4] the Five Disciplines of Innovation,[5] and "Special Forces" Innovation.[6] They tend to share certain common characteristics, including integrated teams with strong independent leadership, a relatively flat organizational structure, a focused orientation toward maximizing customer value, and the ability to adapt dynamically in response to changing technological environments or customer requirements. The project team is imbued with these concepts and practices from the beginning, which may be codified in a handbook or other reference tool.

A key concept is the "value proposition"; in one formulation, a well-constructed value proposition includes four basic questions that must be answered: (1) what is the important societal need to be addressed? (2) what is the compelling working hypothesis for the proposed approach that addresses this need? (3) what are the benefits per costs (i.e., value) for society from this approach? and (4) why is that new value significantly better than the competition and alternatives?[7]

To ensure that the team keeps its eye on the value proposition, the leadership holds facilitated forums every few months to continuously align the center's thrusts. Team members present value propositions for their thrusts and are critiqued by their teammates. They share their progress and challenges and, as required, realign the center's research plan.

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[1] Agile Methodology, "The Agile Movement," http://agilemethodology.org, accessed September 12, 2016.

[2] *Wikipedia, The Free Encyclopedia*, "Scrum (Software Development)," https://en.wikipedia.org/wiki/Scrum_(software_development), accessed September 12, 2016.

[3] Lean Enterprise Institute, "What is Lean," http://www.lean.org/WhatsLean/, accessed September 12, 2016.

[4] *Wikipedia, The Free Encyclopedia*, "Six Sigma," https://en.wikipedia.org/wiki/Six_Sigma, accessed September 13, 2016.

[5] C.R. Carlson and W.W. Wilmot, 2006, *Innovation: The Five Disciplines for Creating What Customers Want*, Crown Publishing, New York.

[6] R.E. Dugan and K.J. Gabriel, 2013, "Special Forces" Innovation: How DARPA Attacks Problems, Harvard Business Review, October, https://hbr.org/2013/10/special-forces-innovation-how-darpa-attacks-problems.

[7] This Need/Approach/Benefit (per cost)/Competition or "NABC" formulation was developed by SRI International. See, for example, http://sembassy.com/nabc.

Most of the systems mentioned in Box 2.5 are oriented toward delivering economic value for industry—the more commonly accepted definition of value creation—but the principles can easily be adapted to the broader goal of delivering societal value.

## THE CURRENT SITUATION

According to NSF, "the goal of the ERC program is to integrate engineering research and education with technological innovation to transform national prosperity, health, and security."[15] The idea that the Engineering Research Center (ERC) program would provide economic benefits through engagement with industry to enhance U.S. industrial competitiveness and to develop the "innovation ecosystem" has been a common expectation from its inception.

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[15] NSF, "Engineering Research Centers (ERC)," https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5502, accessed October 10, 2016.

As the ERC program has evolved, funded centers have tended to be targeted fairly narrowly on specific technology areas (e.g., the ERC for Translational Applications of Nanoscale Multiferroic Systems or the ERC for Revolutionizing Metallic Biomaterials).[16] This technology focus has the advantage of simplifying the challenges of determining the disciplines needed to address the problem and identifying the key academic and industry research participants.

The successes of the ERC program are described in Chapter 1. However, interviews and reviews of the performance of engineering research centers in different countries suggest that few realize their full potential. Center researchers have tended to work as individual contributors and thus fail to address the center's major opportunity.[17] The committee believes that implementing the practices in Boxes 2.4 and 2.5 would make a profound improvement in center outcomes.

These centers have value only to the degree that their societal or market impact is larger than their transaction costs. Today, those transaction costs are very high and output is limited: opportunity identification, team selection and alignment, collaboration, and bureaucratic overhead are all significant problems. Additional barriers are the inability to access the most current, relevant knowledge, the inability to access the best new talent when needed, and the inability to rapidly pivot the initiative as required by better real-time understanding of the technology and marketplace.

NSF funding of ERCs, which amounts to between $3 million and $5 million per center per year, was significant in the mid-1980s, but has declined in real value by almost a factor of three since then due to inflation. Today there are multiple funding opportunities that are in this same range available to individual principal investigators (PIs), and there are significant opportunity costs associated with participating in a center. At the same time, the centers perceive that annual reporting requirements and bureaucratic oversight have increased.[18]

## A STRATEGIC NEW DIRECTION

Here and in later chapters the committee articulates a strategic new direction for future engineering centers. This new direction has two components: a "what" and a "how." The "what" is a shift from the current focus on developing a promising new technology area to addressing a high-impact societal or technological need. The "how" is the systematic use of team-research and value-creation best practices to focus the effort and stimulate innovation.

In the context of engineering, the committee defines the phrase *convergent engineering* as a deeply collaborative, team-based engineering approach for defining and solving important and complex societal problems. All necessary disciplines, skills, and capabilities are brought together to address a specific research opportunity. It is distinguished by resolutely using team-research and value-creation best practices to rapidly and efficiently integrate the unique contributions of individual members and develop valuable and innovative solutions for society.

**RECOMMENDATION 2-1: The National Science Foundation should re-invigorate the engineering research center concept by addressing grand-challenge-like problems whose solutions offer the greatest benefits for society and by adhering to the use of team-research and value-creation best practices, fewer administrative burdens, and greater investment and prestige to attract the superb, diverse talent required.**

To emphasize the ambition and the new direction of these center-scale investments led by engineering, they should be given a new name, possibly *convergent engineering research centers* (CERCs). CERCs should continue the early-stage research focus of current ERCs (fundamental research to proof of concept, or technology readiness level [TRL] 1-3), since higher TRL research is difficult to address in a university environment. However, convergent engineering research is expected to usher in breakthroughs that return lasting societal benefit, create high-technology jobs, and serve as a catalyst to the U.S. innovation economy and security needs. Further, the

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[16] Brief descriptions of current ERCs are available at NSF, Engineering Research Centers, "Center Snapshots," http://erc-assoc.org/centers/snapshots, accessed October 10, 2016.

[17] E. O'Sullivan, "A Review of International Approaches to Center-Based Engineering Research," a commissioned paper for this study, available at https://www.nae.edu/Projects/147474.aspx.

[18] NSF, *ERC Key Features: Designing the Next-Generation ERC*, Report from the 2007 Annual Meeting, Arlington, Va.

possibility of solving important societal problems through the power of engineering will be a great attractor of talented undergraduate and graduate students, particularly from traditionally underrepresented domestic groups (see Chapter 3). New partnership models based on the best practices of team research and value creation will help to bridge the academe–industry–other[19] divide and will provide rapid and significant translation of theory into new commercial products, services, and industries.

Grand challenges such as those in Box 2.2 from the NAE address complex problems, the solutions of which encompass an array of scientific and engineering disciplines. A single CERC may not suffice to address the totality of the challenges. Rather, a number of CERCs in partnership with other related research centers will likely be needed to address them.

The ongoing Internet and information technology (IT) revolutions are redefining organizations, with much of the value coming from transactional efficiency—removing barriers, middlemen, delays, facilities, logistics, etc. There are many examples: autonomous vehicles, ride and residence sharing, real-time 3-D printing, virtual-personal assistants, online shopping, and so on.

The NSF CERC of the future will be part of this transformation. Thanks to high-speed Internet connectivity, engineering and science research and education have become increasingly collaborative efforts on a global scale, leading to the creation of engineering and science platforms accessible to diverse collections of colleagues around the world. These platforms can be physical (large-scale systems, such as the Large Hadron Collider at CERN, or shared manufacturing test facilities), virtual (shared software systems, such as those hosted on GitHub[20]), or data oriented (shared data collection sites, such as GalaxyZoo[21] and OpenStreetMap[22]). CERCs will very likely employ such creation and collaboration platforms, and future centers may be built around them rather than around physical locations.

The rise of data science is one of the biggest changes since the conception of the ERCs in the 1980s. Data science employs techniques and theories drawn from many fields within the broad areas of mathematics, statistics, operations research, information science, engineering, and computer science.[23] Methods that scale to big data are of particular interest in data science, although the discipline is not generally considered to be restricted to such big data, and some big data technologies are focused on organizing and preprocessing the data instead of analysis. The development of machine learning has enhanced the growth and importance of data science and analysis for a variety of research problems.

In regards to CERCs, breakthroughs will be powered by advanced computing capabilities that help researchers manipulate and explore massive data sets. The speed at which any given scientific discovery advances will depend on how well its researchers collaborate with one another, and with technologists, in areas of e-science such as databases, workflow management, visualization, and cloud-computing technologies.[24] It is anticipated that the application of data science methods and approaches will affect advances in many fields of engineering, including machine translation, speech recognition, robotics, search engines, the digital economy, as well as the biological sciences, medical informatics, health care, social sciences, and the humanities. From an engineering perspective, data science has fostered competitive intelligence, a newly emerging field that encompasses a number of activities, such as data mining and data analysis.[25,26]

CERCs could uniquely benefit from incorporating methods and approaches from this emerging field to help further gain insights about trends and patterns in data that will foster research breakthroughs. It will be beneficial for particular CERC teams to leverage advances in data science and analytics and to recruit data science experts to join their research teams.

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[19] Others include nonprofit organizations, government laboratories, etc.

[20] GitHub, https://github.com/, accessed September 12, 2016.

[21] Galaxy Zoo, https://www.galaxyzoo.org/, accessed September 12, 2016.

[22] OpenStreetMap, http://www.openstreetmap.org/#map=5/51.500/-0.100, accessed September 12, 2016.

[23] J. Foreman, 2013, *Data Smart: Using Data Science to Transform Information Into Insight*, Wiley & Sons, p. xiv.

[24] S. Tansley and K.M. Tolle, 2009, *The Fourth Paradigm: Data-Intensive Scientific Discovery*, Microsoft Research, Redmond, Wash.

[25] M. LaPonsie, 2011, "Data Scientists: The Hottest Job You Haven't Heard of," Onlinedegrees.com, August 10, https://www.aol.com/article/2011/08/10/data-scientist-the-hottest-job-you-havent-heard-of/20007479/.

[26] T. Nguyen, 2015, "Data Scientists vs Data Analysts: Why the Distinction Matters," import.io, October, https://www.import.io/post/data-scientists-vs-data-analysts-why-the-distinction-matters/.

### Top-Down Versus Bottom-Up Approach to Identification of Research Topics

Mission agencies such as the Defense Advanced Research Projects Agency (DARPA) or the Department of Energy (DOE) typically use a "top-down" method of setting research priorities; that is, the funding agency puts out a thematic call for proposals in a general area of research or with a particular problem in mind.[27] In contrast, the NSF typically relies on research proposals developed on topics of particular interest to the proposers and submitted to the funding agency ("bottom-up" approach), although there have been times when NSF requested proposals in some targeted areas, such as manufacturing or biotechnology. As one example of the bottom-up approach, Stanford University's School of Engineering conducted an exercise in 2015 in which faculty, staff, and students were asked to reach consensus on important, strategic directions for engineering research over the next 20 years.[28] In this approach, centers would have considerable discretion in defining their research direction, as long as they meet NSF's overall objectives.

Compared with top-down methods, bottom-up approaches may facilitate stronger ties with local research ecosystems, involving academic institutions, established corporations, and venture capital communities. Such ecosystems may also provide a more diverse pool of talent for centers. CERCs can be vehicles to enable transformative research or solve challenges of a local or regional nature. (See the example of the federal-state-local partnership model outlined in Chapter 7.)

Top-down approaches focus on well-recognized problems that are agency priorities, while bottom-up approaches can tap the genius of a broad cross-section of the research community and may promote local and regional economic development. Both approaches help to attract and retain a diverse cadre of researchers, and a mixed approach may have merit for CERCs.

### Funding

Because the proposed CERCs would tackle bigger, more complex problems and likely have more diverse research teams, it follows that their budgets would be larger than those of current ERCs. This more complex undertaking could require more resources for supporting roles such as project, cross-project, and cross-center management and/or emerging integrative roles, such as interdisciplinary scientists and data science professionals.[29]

The funding levels of a number of international center programs are growing and, in some cases, appear to be higher than that of NSF ERCs.[30] For example, centers in Singapore, which are modeled on NSF centers, often receive $10 million to $15 million per year.[31] The committee makes no recommendation on absolute funding levels but notes that $3 million to $5 million for an ERC in 1985 would translate to between $7 million and $11 million in 2016, accounting for inflation.

In the committee's view, the alternative model of tackling big problems with a larger number of smaller, more focused centers would be a recipe for higher overhead and transaction costs.

In the absence of a larger appropriation from Congress, the need for larger CERC budgets could be met by reducing the number of centers funded (currently around 20 per year) or by bringing supplementary funding from other federal agencies, international governments, states, the private sector, or foundations. The three examples of possible CERC models discussed in Chapter 7 all involve some form of cost sharing.

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[27] Note, however, that agencies that fund research via the top-down approach do typically maintain staff technical expertise and receive feedback through the consultative process that program officers have with their research discipline communities.

[28] Stanford Engineering, "Ten Challenges Where Stanford Engineering Can Have Impact," http://soefuture.stanford.edu/impact, accessed August 28, 2016.

[29] National Cancer Institute, "Team Science Toolkit," https://www.teamsciencetoolkit.cancer.gov/Public/ExpertBlog.aspx?tid=4&rid=1838, accessed August 28, 2016.

[30] E. O'Sullivan, 2016, "A Review of International Approaches to Center-Based, Multidisciplinary Engineering Research," a commissioned paper for this study, available at https://www.nae.edu/Projects/147474.aspx.

[31] Curt Carlson, committee member, personal communication.

### Administrative Burdens

The desire for reduced administrative burdens has been frequently expressed in ERC reviews and surveys. Extensive, ongoing data collection for ERCs is needed to fulfill NSF reporting requirements[32] (e.g., annual and renewal reports), and this can be difficult when some key information may be held by dispersed team members. Due to privacy concerns, collecting demographic information to demonstrate progress on diversity goals may pose challenges, and considerable effort may be required to capture data reflective of interaction with industry partners. ERCs also must undergo annual site visits, which require considerable planning, and longer site visits when they apply for renewal in years three and six. Additional staff time and administrative work are needed to establish and maintain the various external and internal boards and councils that NSF requires as part of the ERC infrastructure (see Appendix C).

Many international center programs may have lighter annual reporting requirements compared with ERC programs. Although there is significant variation in practice from program to program in terms of reporting on progress, a number of international center directors interviewed as part of this study quickly volunteered that their annual reporting requirements and midterm reviews are not too onerous. It was also suggested by some of those interviewed that management information tools and IT systems were reducing the burden of annual reporting, making it easier to collect and collate journal articles, conference papers, patents, and so on, and to gather information about outreach and impact activities.[33]

While these concerns are not new, as part of its re-visioning effort, NSF should review its accountability procedures and minimize bureaucratic reporting requirements, with an eye to identifying what outcomes are essential to report, what might be nice to know, and what is unnecessary.

## CONCLUSION

By placing bold bets on a small number of well-funded, prestigious centers focused on engineering solutions to society's greatest challenges, NSF will create excitement in the engineering community, as well as the natural and social science communities, that will attract the best students, faculty, and industry partners to the CERCs. As they reach for grand technological challenges, CERCs will also build U.S. technological competitiveness and capacity by educating a diverse group of students, staff, and faculty in the rapid translation of research results into products with impact.

While only a small fraction of U.S. engineering graduates will be directly touched by these centers during their university experience, each CERC will have impact far greater than the size of the initial federal investment. CERCs can serve as experimental testbeds to develop engineering curriculum modules, research methods, and work products of durable intellectual value that can be scaled up and disseminated widely, such that the overall impact of the centers is magnified many-fold (see Chapters 3 and 4).

In summary, these new CERCs will

1. Address the grand challenges facing society by leveraging the convergence of science, engineering, medical, and—importantly—social science disciplines to accelerate the discovery of new knowledge, create new methods and tools, and develop new products;

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[32] NSF's guidance document (2017), intended to help centers prepare annual reports, is 52 pages long. See NSF, 2017, *FY 2017 Guidelines for Preparing Annual Reports and Renewal Proposals for the Engineering Research Centers and Nanoscience Engineering Research Centers. Classes of 2006-2015*, January, https://www.erc-reports.org/public/download-document?fileName=FY2017_Annual_Reporting_Guidelines.docx; and a separate document (ICF International, 2017) designed to support centers' use of the agency's online data system, ERCWeb, is 60 pages long. See ICF International, 2017, *Guidelines for ERCWeb Data Entry for the Engineering Research Centers. FY2017*, January, prepared for National Science Foundation, Directorate for Engineering, Division of Engineering Education and Centers, https://www.erc-reports.org/public/download-document?fileName=FY2017_ERCWeb_Data_Entry_Guidelines.doc.

[33] E. O'Sullivan, 2016, "A Review of International Approaches to Center-Based, Multidisciplinary Engineering Research," a commissioned paper for this study, available at https://www.nae.edu/Projects/147474.aspx.

2. Embrace the best practices of team research and value creation, using advances in information technology, artificial intelligence, social media, and virtual reality to enable deep collaboration that accelerates research advances and innovation in an increasingly interconnected world;
3. Leverage the emerging fields of data science and analytics to inform research directions and enhance team research;
4. Create new engineering platforms and tools upon which others will build, accelerating the pace of research and innovation;
5. Attract the best students, faculty, and industry collaborators, who will accelerate translation and innovation in a dynamic and exciting experiential learning environment;
6. Provide students with the full range of skills they need to be leaders in an increasingly interconnected and multidisciplinary world; and
7. Develop meaningful domestic and international partnerships with industry, government, nonprofit and philanthropic organizations, and the venture capital community to bring about major advances.

CERC structure and operations (see Chapter 5) will be determined by the goals of the particular initiative and so will not be "one size fits all." One model might employ a challenge- or prize-based approach to research, with different external teams competing to solve a problem; another might combine resources and talent from federal, state, and local sources to address a regionally important need. Examples of what these alternative models might look like are discussed in Chapter 7.

# 3

# People

However ambitious, exciting, and well funded a center's research agenda may be, its success or failure ultimately depends on the quality of the people involved, the relationships among them, and the management methods they use. An engineering research center's (ERC's) human capital includes its leadership, research teams, students, and collaborators.

## CENTER LEADERSHIP

Leadership defines every organization. Team research leaders are often chosen based on their technical expertise, and this is helpful in establishing a vision for the research effort and roadmaps for achieving the goals.[1] Leaders of convergent engineering research centers (CERCs) will face unique challenges in integrating the broad diversity of disciplines involved, vocabularies, perspectives on the problems, and working modes, as well as a research team that is geographically disperse. CERC leaders will have to exhibit an integrative style[2] that

- Empowers all team members to contribute regardless of status and power differences,
- Establishes a culture of deep collaboration,
- Builds consensus around goals and problem definitions,
- Facilitates communication to ensure a common understanding, and
- Resolves conflicts and builds trust.

Given the committee's assumption that CERCs will be based in university settings, the director and her or his senior staff should also have a demonstrated record of success in educating and training students in leading-edge research.

Center leadership will serve as mentors to junior researchers, guiding them as they gain the experience and skills needed to become center leaders of the future. Ideally, some members of center leadership will have experience in forming companies with venture financing, or in leading important public health, environmental protection,

[1] National Research Council (NRC), 2015, *Enhancing the Effectiveness of Team Science*, The National Academies Press, Washington, D.C., Chapter 6.

[2] M.R. Salazar, T.K. Lant, S.M. Fiore, and E. Salas, 2012, Facilitating innovation in diverse science teams through integrative capacity, *Small Group Research* 43(5).

or infrastructure functions. Leadership will have the expertise to guide the entire discovery-to-implementation pipeline. The center director will have significant and demonstrated capability and capacity to raise external funds from the private and public sectors. Leadership will be inspirational and collaborative and will drive teams to success by encouraging innovation, nurturing diversity, and creating a collegial environment.[3]

The skills needed for center leaders include intellectual vision and leadership, management of center activities, successful entrepreneurial experience, a track record of delivering results, and ability to communicate clearly and effectively with diverse audiences such as team members, sponsors, partners, host institutions, press and media, and the public. It is rare that a single individual will have all of these attributes; thus, a strong leader will need to assemble an executive team having expertise in these areas.

**FINDING 3-1:** Leaders of CERCs will face unique challenges due to the centers' scale, the need to integrate knowledge from diverse disciplines and perspectives, as well as geographically dispersed institutions and research team.

**RECOMMENDATION 3-1: In order to give the convergent engineering research centers (CERCs) the best opportunity to achieve their goal of deep research collaboration toward solving grand-challenge-like problems, the National Science Foundation should ensure that CERC leadership are accomplished and recognized leaders of large, complex programs and are skilled in the application of the team-research and value-creation best practices.**

## THE RESEARCH TEAM

Team members should share the center's vision, have complementary skills and roles, and recognize that the rewards of working together far outweigh the costs of collaboration. Team members should not only be extraordinary researchers, but should also fulfill a unique, strategic function in the center.

Some 50 years of research on successes and failures of research teams (mostly in fields other than engineering) is available to be applied to engineering research teams, but it has not been sufficiently exploited.[4]

It is apparent that many important engineering challenges (e.g., smart transportation systems in cities, medical data informatics) cannot be addressed effectively by purely technical means; these challenges have social, political, behavioral, and legal aspects that must be part of the research team's expertise from the beginning. In one well known example, Doug Dietz, a magnetic resonance imaging designer for General Electric Healthcare, was disturbed by the anxiety he observed in young patients about to undergo a scan in his latest machine, and he decided that a new approach was needed. He found that by enlisting a cross-functional team that included experts in child psychology and by designing an "adventure series" MRI scanner environment at the University of Pittsburgh Medical Center, the stress on children undergoing a scan could be greatly reduced, making the experience much more pleasant for both the children and their parents.[5]

**FINDING 3-2:** Formation of effective transdisciplinary research teams is essential for CERC success, and it requires significant effort, careful consideration, and time.

Goals of the development phase include defining the scientific or societal problem to be addressed, the relevant domains of the disciplines involved, and collaborative experts representing diverse backgrounds to delineate boundaries and identify specific challenges.[6]

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[3] NRC, 2015, *Enhancing the Effectiveness of Team Science*, The National Academies Press, Washington, D.C., Chapter 6.

[4] NRC, 2015, *Enhancing the Effectiveness of Team Science*, The National Academies Press, Washington, D.C.

[5] GE Healthcare, "From Terrifying to Terrific: The Creative Journey of the Adventure Series," http://newsroom.gehealthcare.com/from-terrifying-to-terrific-creative-journey-of-the-adventure-series/, accessed August 3, 2016.

[6] K.L. Hall, A.L Vogel, B.A Stipelman, D. Stokols, G. Morgan, and S. Gehlert, 2012, A four-phase model of transdisciplinary team-based research: Goals, team processes, and strategies, *Translational Behavioral Medicine* 2(4): 415-430.

**RECOMMENDATION 3-2: The National Science Foundation should invest significant time and effort in a deliberate, early-stage process for development and formation of the best convergent engineering research centers research teams.**

Application of team-research best practices, including use of research networking tools and team professional development training, have been mentioned in Chapter 2. More specific options are discussed in the Chapter 6, "Suggested Tactics."

## ENGINEERING EDUCATION

Because CERCs reside at universities, whose primary mission is to educate, they must embrace this mission. This makes it crucial for centers not only to generate innovative research but also to lead in producing young engineers from diverse backgrounds who are well trained, collaborative, capable of innovation, and equipped to take on leadership roles. Developing and nurturing talent and creating the future U.S. workforce will require continuous innovation in engineering education.

Engineering education is constantly evolving. The traditional model of an expert lecturing from a podium, while still prevalent, is increasingly being supplemented by more project-based, hands-on student design projects. Much research has been done, for example, on more collaborative, cooperative, and experiential approaches to engineering education in order to determine their value compared with lecture-based instruction.[7,8,9] Across the United States, there is a growing movement to develop flipped, blended, and team-based approaches to significantly improve educational outcomes.[10] More ambitiously, some engineering programs are instituting what might be called an innovation paradigm[11] in which emphasis is placed on the creation of new products identified by the students. In this model, students generate and try out ideas for products or services that do not yet exist, using design thinking and value creation methodologies. Instructors encourage intrinsic student motivation and serve as mentors in the innovation process. Examples of this approach include Finland's Aalto University and Denmark's Aalborg University with comprehensive projects-based curricula; Worcester Polytechnic Institute's Global Projects Program, where student teams go to locations around the world to create innovative solutions to local community needs; Purdue University's EPICS service-learning design program; Stanford University's d.school and Bio-X experiential programs; and Olin College, which has no discipline-specific departments and no tenured professors and has, instead, a projects-based curriculum with an entrepreneurial focus.

This national trend in engineering education toward experiential courses, maker facilities, design institutes, and entrepreneurship[12] is occurring primarily at the undergraduate level. The committee believes that in the future most, if not all, engineering schools will have design institutes and entrepreneurship programs. The challenge for CERCs will not be to reinvent these innovations in engineering teaching and learning, but to build on the best of these methods and enable the affiliated students—including graduate students[13]—to exercise the skills they learn in these programs developed by the host institutions. CERCs are ideally positioned to expand the innovation

[7] S. Freeman, S.L. Eddy, M. McDonough, M.K. Smith, N. Okoroafor, H. Jordt, and M.P. Wenderoth, 2014, Active learning increases student performance in science, engineering, and mathematics, *Proceedings of the National Academy of Sciences* 111(23):8410-8415.

[8] M. Prince, 2004, Does active learning work? A review of the research, *Journal of Engineering Education* 963(3):223-231.

[9] M. Towhidnejad, T. Hilburn, and S. Salamah, 2015, "Transforming Engineering and Science Education Through Active Learning," *2014 IEEE Frontiers in Education Conference (FIE) Proceedings*, doi:10.1109/FIE.2014.7044127.

[10] National Academy of Engineering (NAE), "Frontiers of Engineering Education," https://www.nae.edu/20742.aspx, accessed August 3, 2016.

[11] R. Miller, Olin College of Engineering, "The Future of Engineering Education," presentation at the "Exploring a New Vision for Center-Based, Multidisciplinary Engineering Research" symposium, April 6, 2016, National Academies of Sciences, Engineering, and Medicine, available at https://www.nae.edu/Projects/147474/147561/147730.aspx.

[12] See, for example, T. Byers, T. Seelig, S. Sheppard, and P. Weilerstein, 2013, Entrepreneurship: Its role in engineering education, *The Bridge* 43(2):35-40; and S.K. Gilmartin, A. Shartrand, H.L. Chen, C. Estrada, and S. Sheppard, 2016, Investigating entrepreneurship program models in undergraduate engineering education, *International Journal of Engineering Education* 32(5A):2048-2065.

[13] More than 50 percent of the graduate students in engineering have their bachelor's degrees from outside the United States, so many of the graduate students in CERCs will not have had previous undergraduate design/maker/entrepreneurship experiences. So CERCs need to work to get graduate students experiential learning experiences.

paradigm for engineering education. In many ways, this approach to engineering education mirrors the committee's vision for the centers themselves: addressing significant and complex problems of relevance to society, leveraging convergence and multidisciplinarity, promoting innovation and entrepreneurship (as well as preparing students to work in established companies), and engaging internationally. These attributes constitute the educational blueprint of the modern research university and provide crucial skills for engineering professionals in the global innovation economy. A notable example of this form of engineering education is the NAE Grand Challenges Scholars Program (GCSP; Box 3.1).[14]

Many factors, including the pedagogical skills of the faculty and institutional policies that support less-traditional approaches to educating students, will determine the nature and extent of these opportunities for students.

The value to students of exposure to industry culture and practices has been explored,[15] as have the benefits to industry of engaging students who, through co-ops and internships, may become highly valued employees.[16,17] The NAE has seen the creation of exemplary engineering education programs that engage students in real-world engineering design activities, and nearly all of them involve connections with industry.[18] Research suggests that student opportunity to experience authentic projects is critical to developing engineering expertise.[19]

### Ethics and Decision-Making

Students involved in engineering research centers of the future will need to be well grounded in the ethical and social dimensions of engineering work. Technology development can have unintended consequences that need to be considered from the beginning. An example from the past is the neurotoxicity of lead-containing additives that were intended to increase engine performance. Looking forward, the ethical considerations involved in technologies for genetic manipulation, such as clustered regularly interspaced short palindromic repeats (CRISPR), are complex, and the topic of decision-making in autonomous systems—and human-machine interaction more generally—will need to be considered.

It is not only the technological products of engineering that may pose important ethical issues for engineers, however. Broader ethical and values-related considerations may arise in efforts to prevent or mitigate disasters and hazards, address environmental justice and sustainability, protect human rights, and encourage public and community engagement in the work of engineers and scientists. As appropriate, social, political, and behavioral scientists, as well as policy experts, should collaborate with CERCs to help researchers address the nontechnical aspects of the work.

CERCs can address these issues by proactively including activities in education and outreach. The purpose is, first, to educate the students and other center participants and, second, to inform other constituencies about the societal, national, and global benefits of the research, as well as the importance of the ethical and human values in decision-making that underlie all technological applications.

CERCs will provide ample opportunities for students to exercise their ethical training and human values principles, but the primary responsibility for imparting this training should be with the host institution.

**FINDING 3-3:** Ongoing changes in engineering education include a greater emphasis on collaborative, team-based experiential learning and a focus on creativity and design activities and entrepreneurship, as well as ethical aspects, which better prepare students to succeed in center-like, multidisciplinary environments throughout their careers.

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[14] T. Katsouleas, R. Miller, and Y.C. Yortsos, 2013, The NAE Grand Challenges Scholars Program, *The Bridge* 43(2):53-57.

[15] D.M. Gilbuena, B.U. Sherrett, E.S. Gummer, A.B. Champagne, and M.D. Koretsky, 2015, Feedback on professional skills as enculturation into communities of practice, *Journal of Engineering Education* 104(1):7-34.

[16] M. Fifolt and L. Searby, 2010, Mentoring in cooperative education and internships: Preparing protégés for STEM professions, *Journal of STEM Education* 11(1):17-26.

[17] K.A. Smith, 2011, "Cooperative Learning: Lessons and Insights from Thirty Years of Championing a Rresearch-based Innovative Practice," *2011 Frontiers in Education Conference (FIE)*, pp. T3E-1-T3E-7, doi:10.1109/FIE.2011.6142840.

[18] NAE, 2012, *Infusing Real World Experiences into Engineering Education*, The National Academies Press, Washington, D.C.

[19] T.A. Litzinger, L.R. Lattuca, R. Hadgraft, and W. Newstetter, 2011, Engineering education and the development of expertise, *Journal of Engineering Education* 100(1):123-150.

**BOX 3.1**
**NAE's Grand Challenges Scholars Program**

Students participating in the National Academy of Engineering's (NAE's) Grand Challenges Scholars Program (GCSP) conduct research and design projects connected to the Grand Challenges, engage in interdisciplinary learning with clients and mentors, acquire experience in entrepreneurship and innovation, gain global and cross-cultural experiences, and develop social consciousness through service learning. At this writing, the program exists at 41 engineering schools nationwide, with applications from 10 more schools under review. In March 2015, 122 engineering deans committed to graduate 20 Grand Challenges engineers every year from their institutions for each of the following 10 years.

Efforts to collect matriculation and graduation data from the full set of GCSP institutions are only just beginning. Preliminary information collected by NAE from 14 of these schools suggests that the program is attracting and graduating a more diverse set of students than U.S. engineering programs overall. Of 837 enrolled students at these schools in 2017, 41 percent were women, and just over 14 percent were either black or Hispanic. At Arizona State University, which houses the largest GCSP program, 32 percent of students were women, and almost 23 percent were either black or Hispanic. Of the 258 graduates reported by 9 GCSP schools, 48 percent were women, and 9 percent were from underrepresented minorities.

SOURCE: National Academy of Engineering.

Examples include the GCSP (Box 3.1), opportunities for student internships and co-ops in industry, and bringing in professors of practice and part-time faculty from industry to teach engineering courses.

**RECOMMENDATION 3-3a: Centers should offer students opportunities to exercise design and entrepreneurship skills obtained through their departmental coursework by providing experiences such as internships and exposure to industrial and public sector expertise through collaborations, workshops, seminars, and personnel exchanges, and opportunities to discuss the ethical dimensions of their work.**

Current ERC education programs have been most successful when they were tailored to both the institution strength and the local community needs. An aspect of the variety of experiences mentioned in Recommendation 3-3a is that CERC education programs should be comprised of elements that are flexible and reflect the unique aspects of the technical area the CERC is focused on, the educational resources of the local universities, and the needs of local students—both on campus and in the surrounding PreK-12 communities.

Many industry collaborators have developed educational materials to train their employees that can augment materials available at the participating universities. The centers should encourage and provide opportunities for industry to share these materials with students.

Although less than 1 percent of the nearly 120,000 engineering students who graduate with a B.S., M.S.E., or Ph.D. in the United States are currently engaged with NSF ERCs, future centers, as models for best practices, can have a broader impact on engineering education.

The CERC educational mission can be pursued in two ways: (1) by directly influencing students in the home institutions of the center and (2) by developing new educational modules, tools, and methods that can be scaled up and shared within the host university and with the broader engineering workforce across the nation (see the "Outcomes" section in Chapter 4). Such a multiplier effect will have lasting impacts beyond the life of the center itself or the life of the engineered solutions it creates.

By virtue of their typically longer-term funding cycles, centers are also ideally positioned for evaluation of innovative pedagogical models. They should include formal evaluation and dissemination of successful models as part of their core function.

**RECOMMENDATION 3-3b: The National Science Foundation should facilitate the adoption and broad sharing of successful engineering education innovations developed in its centers and also encourage research to understand how these experiences work to provide effective learning.**

A 2012 National Research Council (NRC) report[20] pointed to the importance of conducting discipline-specific educational research. Following this model, the conduct of research specifically in engineering education is important to advance knowledge of "what works" in engineering teaching. Two recent NAE reports, *The Engineer of 2020*[21] and *Educating the Engineer of 2020*,[22] point to the importance of supporting the growing field of engineering education research. Discipline-specific research on the learning that takes place in the innovative settings provided by CERCs could include investigating such issues as the following:

- How do CERCs function as sites of learning for students and faculty: who learns what when?
- How is learning in the CERC collaborative, interdisciplinary, cutting-edge environment different from the learning that takes place in a traditional engineering education environment? What aspects of the learning environment are transferable?
- What capacities for learning do students exhibit when they are engaged in center activities?
- What kinds of learning do students exhibit over time (taking advantage of the longer CERC funding to conduct longitudinal studies)?

The findings generated by this scholarship will be invaluable to colleges of engineering that did not participate in the CERC program but endeavor to improve both their undergraduate and graduate engineering teaching. These research results will also increase the utility and transferability of the educational modules mentioned in Recommendation 3-3b.

The field of engineering education research has grown significantly in recent years; the establishment of engineering education departments at Purdue University and Virginia Polytechnic Institute and State University (Virginia Tech) in 2004 has been followed by departments at such institutions as Clemson University, Arizona State University, and Ohio State University as well as the growth of campus-based engineering education centers. NSF has funded two large-scale centers with scholarship on engineering learning at their core.[23]

While the committee believes strongly that this kind of engineering education research is valuable and should be a component of CERCs, it suggests that it should be carried out in collaboration with the expertise embedded in the host institution or other institutions such as those mentioned above.

## DIVERSITY

Studies have shown that research teams with broader cultural knowledge and perspectives can produce more innovative and robust solutions to science and engineering problems.[24] A more diverse engineering workforce is an imperative when addressing complex problems with worldwide societal impacts, and the diversity of the U.S. talent pool can become a competitive advantage.

For decades, the U.S. government has been promoting diversity of race, ethnicity, gender, and sexual orientation through training, education, and legislation. Recruiting and training of minorities, building a diverse workforce, and assuring a conducive and productive work environment have been the actions used for achieving diversity goals. While this decades-long effort has shown progress and success, there remains significant work to do in this area.

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[20] NRC, 2012, *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering*, The National Academies Press, Washington, D.C.

[21] NAE, 2004, *The Engineer of 2020: Visions of Engineering in the New Century*, The National Academies Press, Washington, D.C.

[22] NAE, 2005, *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*, The National Academies Press, Washington, D.C.

[23] See the Center for the Advancement of Engineering Education (http://www.engr.washington.edu/caee/), led by the University of Washington, and Epicenter (http://epicenter.stanford.edu/) led by Stanford University.

[24] *Nature*, 2014, "Diversity: A Nature and Scientific American Special Issue," October 1. http://www.nature.com/news/diversity-1.15913.

ERCs have a responsibility to attract and educate a diverse engineering workforce. "People with different backgrounds bring new information. Simply interacting with individuals who are different forces group members to prepare better, to anticipate alternative viewpoints and to expect that reaching consensus will take effort."[25] Diversity often promotes innovative thinking. Besides enhancing creativity, diversity and inclusiveness are the law-of-the-land to be observed and practiced in the workplace.

In 2014, foreign students were awarded 56 percent of doctorates in engineering at U.S. universities.[26] The United States faces a critical workforce imperative: either increase the number of U.S. students in the engineering pipeline, including more American women and minorities, or increase dependency on foreign scientists and engineers. Clearly, the former is the better solution. This need has been documented in many reports, including the 2011 NRC report *Expanding Underrepresented Minority Participation: America's Science and Technology Talent at the Crossroads*,[27] which builds on the 2007 report *Rising above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*.[28] The goal of increasing ethnic and gender diversity remains essential to priming the engineering workforce pipeline of the future. The key to success is to have teammates with the unique perspectives required to explore the opportunity being addressed.

Addressing diversity requires more than setting diversity goals. In order to effectively address this aspect, experts in promoting diversity should guide CERCs in crafting a plan that supports the specific research initiatives and that builds a diverse, supportive, and inclusive team from the beginning. These experts would continue to engage with the leadership team throughout the lifetime of the CERC, providing guidance and sharing best practices. Host institutions that currently have in place best practices for achieving diversity and inclusion are much more likely to be successful in guiding the research team on how to implement these objectives.

While diversity on research teams has been shown to enhance creativity, innovation, and scientific outcomes, it also introduces challenges and faultlines.[29] Team processes and strategies are needed to ensure that the diversity yields its potential benefits. These processes assure that each member has a meaningful role to play in the initiative and that team goals and strategies are aligned. NSF has supported a training intervention designed to facilitate cross-disciplinary communication in science teams and groups.[30]

**FINDING 3-4:** The goal of expanding diversity in science and engineering is not only good for the creativity and productivity of research teams, it is good for expanding the capacity of the United States to innovate and compete.

The diversity requirements that NSF puts on ERCs, including the requirement that the lead university partner with a minority-serving university, have enabled ERCs to outperform other engineering programs in terms of the percentages of women, Hispanics, and underrepresented minorities participating in the centers.[31]

**RECOMMENDATION 3-4: The National Science Foundation should insist that the convergent engineering research centers continue to build upon the success of the engineering research centers in expanding diversity of the engineering workforce.**

CERCs should have an advantage in this regard due to their focus on grand-challenge-like problems with great societal impact. Research has shown that if programs emphasize engineering as a source of societal benefit

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[25] K.W. Phillip, 2014, How diversity makes us smarter, *Scientific American*, October 1.

[26] Department of Education, 2016, IPEDS Completion Survey, National Center for Education Statistics, Data extracted from WebCASPAR, https://ncsesdata.nsf.gov/webcaspar/index.jsp?subHeader=WebCASPARHome, accessed November 4, 2016.

[27] National Academy of Sciences, National Academy of Engineering, and Institute of Medicine (NAS-NAE-IOM), 2011, *Expanding Underrepresented Minority Participation: America's Science and Technology Talent at the Crossroads*, The National Academies Press, Washington, D.C.

[28] NAS-NAE-IOM, 2007, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, The National Academies Press, Washington, D.C.

[29] A.L. Vogel, B.A. Stipelman, K.L. Hall, L. Nebeling, D. Stokols, and D. Spruijt-Metz, 2014, Pioneering the transdisciplinary team science approach: Lessons learned from National Cancer Institute grantees, *Journal of Translational Medicine and Epidemiology* 2(2):1027.

[30] See the Toolbox Project at http://toolbox-project.org.

[31] NSF, 2015, "ERC Solicitation 15-589 Webinar: Guidance for Preliminary Proposal Development," August 31, https://www.nsf.gov/attachments/135960/public/NSF15-589_ERCwebinar.pdf.

rather than focus more narrowly on technology per se, they have more appeal to women and underrepresented minority students,[32,33,34,35] and this is borne out in the enrollment statistics of the NAE's Grand Challenges Scholars Program (Box 3.1) and Purdue University's Engineering Progress in Community Service (EPICS) service learning program, in which more than 50 percent of the students enrolled are women.[36] Grand-challenge-like problems are also international in scope and should attract international students and faculty to the CERCs.

Most major universities have well-established offices whose aim is to promote diversity, staffed by experienced professionals, and there is a body of scholarly literature on the subject. CERCs should take advantage of these resources and expertise to help design their diversity programs.

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[32] I.J. Busch-Vishniac and J.P. Jarosz, 2004, Can diversity in the undergraduate engineering population be enhanced through curricular change?, *Journal of Women and Minorities in Science and Engineering* 10:255-281.

[33] W.A. Wulf and G.M.C. Fisher, 2002, A makeover for engineering education, *Issues in Science and Technology On-Line*, Spring.

[34] R. Williams, 2003, Education for the profession formerly known as engineering, *Chronicle of Higher Education*, January 24.

[35] D. Wormley, 2003, "Engineering Education and the Science and Engineering Workforce," pp. 40-46 in Institute of Medicine, National Academy of Sciences, and National Academy of Engineering, *Pan-Organizational Summit on the U.S. Science and Engineering Workforce: Meeting Summary*, The National Academies Press, Washington, D.C.

[36] W. Oakes, M.-C. Hsu, and C. Zoltowski, 2015, "Insights from a First-Year Learning Community to Achieve Gender Balance," *2015 IEEE Frontiers in Education Conference (FIE)*, doi:10.1109/FIE.2015.7344114.

# 4

# Outcomes and Metrics

According to the National Science Foundation's (NSF's) engineering research center (ERC) website, "The goal of the ERC Program is to integrate engineering research and education with technological innovation to transform national prosperity, health, and security."[1] The committee resonates with this existing goal and suggests that the top-level goal of future convergent engineering research centers (CERCs) should be to solve critical societal problems with engineering research and to advance fundamental knowledge on how to deliver those solutions to society. The goal of maximizing societal benefit will in most cases lead to the creation of great economic value as well. An example is the Internet, which began as a research tool but has transformed both the social and economic landscape.

Various metrics have been used to judge the performance of center-based research programs, such as number of students graduated, number of scientific articles published, number of industry participants, number of patents, number of startups spawned, or products commercialized. According to NSF, since the ERC Program's inception in 1985, it has created 193 spin-off companies, disclosed more than 2,200 inventions, and has been awarded 739 patents, which resulted in 1,339 licenses.[2]

The problem with many of these metrics is that they measure *outputs* that say little about the degree to which the research has achieved center goals. Outputs are indicators of potential impact and are comparatively easy to measure (papers, patents, etc.) Outcomes are related to impacts (e.g., transformational changes). It is *outcomes* or *impacts* that NSF should be most concerned about. And some of these output measures—such as the number of participating companies, number of patents, or number of students involved—can be "gamed." Above all, the metrics of center performance should not foster a "box-checking" mentality. Appropriate metrics are discussed below and in Chapter 6.

## ELEMENTS OF SOCIETAL BENEFIT

Under the top-level goal of delivering societal benefit, the committee believes the following four outcomes will be critical to the success of the CERCs:

[1] National Science Foundation (NSF), "Engineering Research Centers (ERC)," https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5502, accessed October 10, 2016.
[2] NSF, 2015, *Creating New Knowledge, Innovators, and Technologies for Over 30 Years*, https://www.nsf.gov/eng/multimedia/NSF_ERC_30th_Anniversary.pdf.

- Students with the skills to be innovators and leaders,
- New ideas and paradigm-shifting research,
- Development and use of work products of durable intellectual value, and
- Creation of economic value.

### Students with the Skills to be Innovators and Leaders

Top-notch undergraduate and graduate engineering students are not only key to the successful operation of CERCs, as was pointed out in Chapter 3, they are also an important indicator of center success. Center students should have the opportunity to (1) engage in significant, multidisciplinary technical training, (2) experience deep collaboration, (3) take on leadership roles, and (4) gain meaningful exposure to industry practices and culture. See the Chapter 3 section "Engineering Education."

**FINDING 4-1:** Superbly educated and innovation-savvy engineering student leaders capable of addressing current and future societal challenges are likely to be the most important long-term outcome of CERCs.

**RECOMMENDATION 4-1: A key objective of the convergent engineering research centers should be capacity-building through student training and development, at both the graduate and undergraduate level, and direct engagement with industry.**

Metrics that might be used to measure student outcomes can include tracking of student placement in industry, university, government, or nonprofit positions and contributions made in those positions, compared with a non-CERC control student population. As discussed further in Chapter 6, emerging collaboration platforms allow real-time tracking and longitudinal follow-up of center research activities and of students who have been engaged at the centers—all with fewer burdens on the centers. With only a limited number of cohorts of students graduated with degrees during the typical 10-year NSF ERC funding lifetime, this metric may need to have a retrospective component; see further discussion in Chapter 6.

### New Ideas and Paradigm-Shifting Research

Successful centers produce new research ideas and innovative technical approaches to the problems being addressed. In the case of a CERC devoted to a grand-challenge-like problem, a successful outcome may be just understanding how best to address the grand challenge. The center may also produce paradigm-shifting research. An example from the past was the pioneering work of W.E. Deming on statistical process control—a process innovation.[3] It created an entirely new, more productive way to create value for society though lower cost and profoundly higher product quality. A modern example might be the marriage of artificial intelligence, machine learning, and big data technologies to usher in an era of lower-cost, easy-access cognitive health care.[4]

Metrics for this category of outcomes could be evidence of widespread adoption of new research techniques or processes developed.

### Work Products of Durable Intellectual Value

The Internet makes it possible for scientists and engineers to not only to record their own work, but also to create durable work products and platforms that can be instantly shared with others, thereby directly accelerating the progress of science and helping to develop innovative engineering and manufacturing systems. These durable work products can include prototypes, innovative manufacturing processes, software applications, tools, and

[3] D.W. Edwards, 1993, *The New Economics for Industry, Government, and Education*, MIT Press, Boston, Mass., p. 132.

[4] See, for example, S. Smith, 2015, 5 ways the IBM Watson is changing health care, from diagnosing disease to treating it, *Medical Daily*, December 17, http://www.medicaldaily.com/5-ways-ibm-watson-changing-health-care-diagnosing-disease-treating-it-364394.

libraries; data and data repositories; cloud computing platforms and services; physical engineering systems with remote access; international standards; and other enabling technologies with broad application. Their development is enabled by the availability of distributed software development platforms such as GitHub, cloud computing platforms such as Microsoft Azure and Amazon AWS, the maturation of IoT (Internet of Things); hardware, software, and data aggregation tools; and the broad use of standardized REST Internet interface tools for connecting physical systems to applications and services. Examples of such systems include software such as the BLAST tool for comparing primary biological sequence information; the World Wide Telescope, which provides astronomers with new ways to visualize observational data from the world's great telescopes; and data repositories such as the Network for Earthquake Engineering Simulation Hub (NEEShub), which provide a web-based gateway for earthquake engineering results and information.

Metrics for measuring impact in this category might include widespread use of center-developed software, tools, or standards, or the frequency with which data repositories are accessed.

**FINDING 4-2:** The development and dissemination of engineering and intellectual work products with durable value accelerates innovation and scientific progress.

**RECOMMENDATION 4-2: Future convergent engineering research centers should be encouraged to produce broadly accessible engineering prototypes, tools, data repositories, platforms, and enabling technologies that foster broad scientific, engineering, and manufacturing innovation. Such work products might form useful interim deliverables from large-scale projects.**

Development of research and education products can be shared widely through collaboration platforms. NSF should explore ways of disseminating CERC innovation, student training, and entrepreneurship activities that scale beyond the centers and participating institutions. Universities frequently develop tools of this type, but these may only be usable by their developers, because they do not put in the large amount of effort required to make them user-friendly. To make these tools usable by a wider audience, NSF may need to make funds available for professionals to refine them. As appropriate, NSF should consider leveraging existing federal initiatives, such as the Small Business Technology Transfer program, to help disseminate these tools.

### Economic Value

From its inception, the ERC program has had the goal of enhancing U.S. industrial competitiveness by transferring intellectual value and technology developed in the centers into the commercial sphere. NSF has also sought to create economic value indirectly through the training of a diverse population of students with the skills to innovate.

The challenges associated with the commercialization goal for ERCs are often underappreciated. For example, it is generally not realistic to expect intellectual property developed in a center working in biology and materials sciences to become a commercial product in the center's typical 10-year life span. Most medical or materials-based start-up companies take about 10 years before they produce products at sufficient scale to generate profits. However, information technologies can be developed much faster and, as recommended here, centers using value-creation best practices can engage industry much earlier in valuable commercial initiatives.

Today, companies often engage with centers to gain access to new knowledge and future employees and do not expect to develop specific processes or products as a result of these relationships.[5] This is reasonable for ERCs, given that they initially sit at the early stages of the continuum of technology readiness levels (see Figure 1.1).

[5] I. Feller, C.P. Ailes, and J.D. Roessner, 2002, Impacts of research universities on technological innovation in industry: Evidence from engineering research centers, *Research Policy* 31(3):457-474.

**BOX 4.1**
**Examples of Commercial Products and Processes Resulting from ERC Research**

- Mass-market fingerprint recognition device (ERC for Neuromorphic Network Systems).
- Severe storm forecasting via short-range X-band radar arrays (ERC for Collaborative Adaptive Sensing of the Atmosphere).
- Minimally invasive surgery (da Vinci robot) (ERC for Computer-Integrated Surgical Systems and Technology).
- Artificial retina (ERC for Biomimetic Microelectronic Systems).
- Increased fuel economy through hybrid hydraulic systems (tested in prototype and near-market vehicles) (ERC for Compact and Efficient Fluid Power).

SOURCE: National Science Foundation, 2015, *Creating New Knowledge, Innovators, and Technologies for over 30 Years,* https://www.nsf.gov/eng/multimedia/NSF_NRC_30th_Anniversary.pdf.

Researchers have documented considerable direct and indirect economic impact of selected ERCs.[6,7,8] While commercial successes do occur (Box 4.1), they are relatively rare. Orin Herskowitz, director of Columbia University's Columbia Technology Ventures, told the committee that about 85 percent of the technology transfer activities of U.S. universities lose money, with the bulk of licensing revenues accruing to a small subset of institutions from a small number of blockbuster products.[9]

Part of the challenge is that some center-related economic impacts are very difficult to quantify, while others may not be evident until many years after a center has ceased operation. External center funding, increased employment, and improvements in the technical workforce comprise the larger categories of quantifiable economic value.

Over time, one way to measure the success of delivering social benefit is that the results (e.g., intellectual work products) of the center are picked up by industry and then industry makes economic advances that can be traced back to the centers. Thus, one can use economic value delivered as *one metric*—but not the only one—to determine if CERCs (or the NSF centers generally) have delivered societal benefit.

The committee is agnostic about whether the larger goal of delivering maximum societal benefit is served by centers seeking to translate proprietary technologies to the private sector by either licensing or forming startups, or by giving away their intellectual content through open sourcing. As one example, the Linux operating system is open source, but has created huge economic value.

Metrics for measuring economic value are relatively well developed and quantitative and are not discussed further here.

**FINDING 4-3:** Metrics currently used to evaluate centers tend to focus on numbers of students graduated, papers published, patents awarded, and so on. These output numbers do not necessarily measure the true impact of the center and the metrics can be gamed and may encourage a box-checking mentality.

[6] SRI International, 2004, *The Economic Impact on Georgia of Georgia Tech's Packaging Research Center*, Arlington, Va.

[7] SRI International, 2008, *National and Regional Economic Impacts of Engineering Research Centers: A Pilot Study. Final Report*, Arlington, Va., November.

[8] D. Roessner, L. Manrique, and J. Park, 2010, The economic impact of engineering research centers: Preliminary results of a pilot study, *Journal of Technology Transfer* 35(5), 475-493.

[9] National Academies of Sciences, Engineering, and Medicine, 2016, *A Vision for the Future of Center-Based Multidisciplinary Engineering Research: Proceedings of a Symposium*, The National Academies Press, Washington, D.C.

**RECOMMENDATION 4-3: The National Science Foundation should develop metrics that track the impacts of center activities, not just the outputs. Examples might include the placement of graduated students in positions of influence, or evidence that intellectual value developed in the center is widely used.**

## OPPORTUNITIES FOR CENTERS TO ENHANCE THE DELIVERY OF SOCIETAL VALUE

While the considerable achievements of the ERC program have been recently documented,[10] the committee believes that a qualitative improvement in the delivery of societal value is possible in future centers through dissemination and systematic use of team-research and value-creation best practices among all center personnel (Boxes 2.4 and 2.5, respectively). In the committee's experience, this is not occurring now. Programs such as NSF's Innovation Corps (I-Corps)[11] are a good start, but more will be needed to fully immerse students and faculty in an entrepreneurial environment (see Chapter 6).

[10] NSF, 2015, *Creating New Knowledge, Innovators, and Technologies for Over 30 Years*, https://www.nsf.gov/eng/multimedia/NSF_ERC_30th_Anniversary.pdf.

[11] NSF, "NSF Innovation Corps (I-Corps)," https://www.nsf.gov/news/special_reports/i-corps/, accessed August 3, 2016.

# 5

# Structure and Operations

Convergent engineering research centers (CERCs) need not be one-size-fits-all in their structure or in their operations, because each grand-challenge-like initiative requires its own unique team, partnerships, and methodologies for achieving success. At the same time, all CERCs should share certain fundamental characteristics, including agility, effective collaboration across institutional boundaries, flexibility, and the option to recompete for federal funding after 10 years, providing that rigorous performance criteria are met.

## AGILITY

The continuing acceleration of research, development, and innovation in the global economy has been well documented,[1] as have the impacts of this pace of change on research universities and industry. In order to reach their original milestones as well as strive toward aspirational goals, CERCs will need the freedom to thoughtfully adapt to changing circumstances, without the fear of being punished for taking calculated risks. Agility implies making modifications to the research agenda,[2] staffing, and partnerships in order to take advantage of new opportunities; constant monitoring of and adaptation to the competition; and phasing out unproductive or outdated activities.

Agility has implications for budgeting, funding, and reporting. Agile management of CERCs will require dynamic budgeting to flexibly adjust to a center's need to modify its program. Dedicated funds, included in or in addition to those provided in the main center award, may be necessary to permit centers to explore potential new research directions. One existing mechanism for providing such flexibility can be seen in the seed-funding opportunities offered to NSF's Materials Research Science and Engineering Centers and the Energy Frontier Research Centers of the Department of Energy. Some multidisciplinary research center initiatives in other parts of the world, including Germany's Collaborative Research Centers program and the Spokes program of Science Foundation Ireland, provide supplementary grants to help centers engage new industrial partners.[3] Foreign centers have recognized the importance of being agile and adaptable in terms of addressing opportunities and barriers to translation, scale-up, and industrialization.[4]

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[1] See, for example, R. Kurzweil, 2001, "The Law of Accelerating Returns," March 7, http://www.kurzweilai.net/the-law-of-accelerating-returns.
[2] This must be done carefully, because graduate students are on a 4- to 5-year schedule where changes in research direction can be damaging.
[3] E. O'Sullivan, 2016, "A Review of International Approaches to Center-based Multidisciplinary Engineering Research," a paper commissioned for this study, available at https://www.nae.edu/Projects/147474.aspx.
[4] Ibid.

While accountability to funding organizations is important, time spent by key personnel filling out forms and writing lengthy annual reports curtails their efforts on breakthrough research and can inhibit center agility.

**FINDING 5-1:** The fast pace of innovation and the production of new science knowledge can create new opportunities not necessarily envisioned at the time a center is established.

**RECOMMENDATION 5-1: To keep pace with a rapidly evolving technological and economic landscape, National Science Foundation program managers should give the convergent engineering research centers director and leadership team the flexibility and authority to adapt their research plans and add and subtract partners as required, so long as they remain accountable for these changes.**

The CERC's vision will evolve over its NSF funding lifetime, as will the stakeholders and key players. Accordingly, center teams should consist of members who are complementary, synergistic, and adaptive, with a strong sense that attacking a problem from many (often orthogonal) perspectives can often unlock solutions that would not be available to a more homogeneous team.

## COLLABORATION

Collaboration at multiple levels is necessary for successful convergence-based research, development, and innovation. The committee believes that most complex, societally relevant problems demand strong multidisciplinary teams spanning academia and industry. Increasingly, these teams will need to be global in scale, such as Singapore's Campus for Research Excellence and Technological Enterprise (CREATE), which engages university partners in the United States, Europe, China, and Israel. Other new models of global collaboration are being developed—for example, within international teams pursuing the X-Prize. These and similar efforts aspire to leverage the entire global innovation economy to accomplish their missions.

*A defining characteristic of CERCs is that they benefit from the fundamentals of team research, which means establishing structures and methods for deep and meaningful collaboration*. Formal collaboration plans in proposals can help to ensure that needed infrastructure and processes are in place.[5]

Addressing grand challenge opportunities successfully requires deep, real-time collaboration to refine common research goals and strategies. This means almost continuous interaction, not just yearly meetings where participants give presentations. David Kelley, director of the Stanford University d.school, has made "radical collaboration" one of its foundational principles.[6] Communication among partners is obviously critical, but regular in-person collaboration may be impossible for teams that are widely distributed geographically. Fortunately, the limitations of remote collaboration are being addressed by social media, as well as synchronous communication platforms such as those available with virtual reality,[7] and others.[8] Experts can be added to solve specific problems as needed. CERCs will need to optimize such platforms to accelerate research and development (R&D) and innovation from their global contributors.

The following question arises about how distributed a CERC should be: Is a fully virtual "center" consisting of a network of geographically distributed researchers collaborating electronically even feasible? Evidence suggests that innovation frequently comes when a core group of researchers with diverse backgrounds have frequent

[5] National Research Council (NRC), 2015, *Enhancing the Effectiveness of Team Science*, The National Academies Press, Washington, D.C., p. 208.

[6] Hasso Platter Institute of Design at Stanford University, "Our Point of View," http://dschool.stanford.edu/our-point-of-view/, accessed August 4, 2016.

[7] See, for example, C. Zakrzewski, 2016, Virtual reality takes on the videoconference, *Wall Street Journal*, September 18, http://www.wsj.com/articles/virtual-reality-takes-on-the-videoconference-1474250761.

[8] ETEC 510 contributors, "Synchronous and Asynchronous Communication:Tools for Collaboration," ETEC 510, http://etec.ctlt.ubc.ca/510wiki/index.php?title=Synchronous_and_Asynchronous_Communication:Tools_for_Collaboration&oldid=57264, accessed August 7, 2016.

face-to-face interactions, both formal and informal.[9] Collaboration over long distances can be successful when it is already established that the parties can work together, but the committee's vision is that CERCs would have a common physical location where researchers can interact to promote team building and team "maintenance." Thus, while frequent face-to-face interactions for geographically distributed centers may not be practical, centers should plan and budget for appropriate in-person interactions. CERC kick-off events and annual review meetings will benefit particularly from in-person meetings.

**FINDING 5-2:** Problems of global scale and convergence require continuous and deep collaboration.

**RECOMMENDATION 5-2: The National Science Foundation should only support new convergent engineering research centers whose members exhibit the collaboration skills, experiences, and personal attitudes required to be successful. Each member must have a unique, complementary role to play and be excited about the opportunity to work collaboratively with their other teammates. The management processes used must support deep, real-time collaboration.**

Center plans need to create faculty reward systems that support teams as they engage in deep collaboration. Future centers should facilitate frequent virtual interactions as well as frequent face-to-face meetings of team members at central facilities to promote communication and collaboration and avoid duplication of effort.

## Collaboration with Industry

Collaboration with industry and venture capitalists will be essential to the success of CERCs. Current engineering research centers (ERCs) are advised by industry advisory boards (IABs), and these IABs are used to critique internally solicited research proposals for center initiatives. Engaging with potential industrial partners early in the proposal process would be optimal, but, realistically, at this stage companies will not be able to assess a center's offerings in terms of knowledge, technology, and intellectual property (IP).[10] Successful relationships with industry require engagement, trust, and an incubation process to develop meaningful commercial value.[11,12] One way to encourage these outcomes is to involve industrial partners early in discussions about a CERC's strategic direction and in the ongoing creation of commercial value propositions. The committee believes that formulation and presentation of well-constructed value propositions, as described in Box 2.5, will enhance industry involvement. Experienced industrial partners can serve as mentors for the center's students and faculty to become future innovation leaders.

Different universities typically have their own IP policies and contracting processes. Before a CERC forms, the contracting officers of the participating universities will have to agree on a common policy. Different industries also have different IP policies. In the case of IP, each CERC will likely have to work out an approach that fits with its relevant industry and community partners. This can be difficult and often complicates collaboration. Nevertheless, other government agencies, such as the Defense Advanced Research Projects Agency (DARPA) and I-ARPA (Intelligence Advanced Research Projects Activity), have succeeded in facilitating the conditions required for deep collaboration.

**FINDING 5-3:** There are barriers related to issues such as IP rights and academic appointments that can hinder or prevent the meaningful collaboration among institutions required for center success.

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[9] L.R. Blenke, 2013, "The Role of Face-to-Face Interactions in the Success of Virtual Project Teams," doctoral dissertation, Missouri University of Science and Technology, http://scholarsmine.mst.edu/cgi/viewcontent.cgi?article=3306&context=doctoral_dissertations.

[10] Exceptions may arise when centers grow out of pre-existing collaborative university-industry research efforts.

[11] S.C. Betts and M.D. Santoro, 2011, Somewhere between markets and hierarchies: Controlling industry university relationships for success, *Academy of Strategic Management Journal* 10(1):19-44.

[12] M.D. Santoro and P.A. Saparito, 2003, The firm's trust in its university partner as a key mediator in advancing knowledge and new technologies, *IEEE Transactions on Engineering Management* 50(3):362-373.

**RECOMMENDATION 5-3: To receive funding, convergent engineering research centers should demonstrate clear plans that enable potential center partners in universities, industry, or other sectors to engage in open and transparent collaboration. Anyone, from any institution—international, government, university, nonprofit, or industry—who can contribute to the center's mission should be able to join the team in a seamless way. Mechanisms should be in place from the outset to remove or minimize institutional, budget, intellectual property, export control, attribution of credit, or other barriers.**

NSF's insistence on submission of formal collaboration plans in CERC proposals will help to ensure that cross-institutional barriers are addressed from the outset.[13]

## Cross-Agency Collaboration

CERCs are an integral part of the overall U.S. science and technology enterprise. In today's environment, however, NSF alone cannot be expected to meet either the financial or the intellectual requirements for this critical initiative. Cross-agency collaboration and cross-agency fertilization can help address this challenge.

Expertise located within other government agencies, national laboratories, nonprofits, and even citizen scientists can contribute to CERCs. In addition, the government collects a large amount of data (e.g., satellite imagery, economic and trade data, demographic data, environmental data) that can be valuable to specific research projects. However, there are often legal, budgetary, or institutional barriers to accessing this expertise or data in a timely way.

Interagency collaboration allows the federal government to leverage and integrate the skills, expertise, and interests of multiple agencies and their respective innovator communities. Such collaborations are an excellent way for the federal government to focus investments, pool resources, and create public awareness of engineering or technology challenges of societal importance. Recent interagency initiatives that have substantially engaged NSF include the National Nanotechnology Initiative (NNI), the Materials Genome Initiative (MGI), the Advanced Manufacturing Partnership (AMP), the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative, and the National Robotic Initiative (NRI; see Box 5.1).

Another form of interagency collaboration involves the sharing of unique instruments and facilities available at core facilities, such as Department of Energy's (DOE's) national laboratories. Unique technical instrumentation and facilities can accelerate fundamental discoveries leading to new knowledge. Examples are the light and neutron sources located at the national laboratories of DOE's Office of Science. CERCs will leverage unique instrumentation and facilities at different sites, both experimental and computational, to help achieve major research results. CERCs lacking local capabilities must reach out to entities in those regions that can provide the needed resources.

**FINDING 5-4:** Unique technical instrumentation and facilities can accelerate fundamental discoveries leading to new knowledge.

**RECOMMENDATION 5-4: Whenever possible and appropriate, future centers should leverage unique instrumentation and facilities at different sites, both experimental and computational, to help achieve major research results.**

**FINDING 5-5:** Center-based engineering research focused on grand-challenge-like problems of significant complexity and scale invites collaboration among multiple agencies.

There appears to be a growing consensus in foreign university-industry research centers that they should be *networked* and *aligned*; that is, collaborating with and leveraging the complementary capabilities and resources of other national, regional and international innovation actors.[14]

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[13] NRC, 2015, *Enhancing the Effectiveness of Team Science*, The National Academies Press, Washington, D.C. p. 208.

[14] E. O'Sullivan, 2016, "A Review of International Approaches to Center-Based, Multidisciplinary Engineering Research," paper commissioned for this study, available at https://www.nae.edu/Projects/147474.aspx.

**BOX 5.1**
**Examples of Existing NSF Interagency Collaborations in Science, Technology, and Engineering**

The National Nanotechnology Initiative (NNI), launched in 2000, is a major research and development (R&D) initiative in nanoscale science, engineering, and technology involving the nanotechnology-related activities of 20 departments and independent agencies. The Materials Genome Initiative (MGI), launched in 2001, is designed to create a new era of policy, resources, and infrastructure that support U.S. institutions in the effort to discover, manufacture, and deploy advanced materials twice as fast as typically occurs today and at a fraction of the cost. MGI generated $63 million in fiscal year (FY) 2012 research grants across multiple agencies and catalyzed commitments from more than 60 companies and universities. The Advanced Manufacturing Partnership (AMP), established in 2011, is focused on advancing U.S. manufacturing R&D. Through AMP, federal agencies have been encouraged to identify advanced manufacturing technologies that are ripe for expanded investment and collaboration between government, industry, and academia. The Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative, launched in 2014, aims to help researchers find new ways to treat, cure, and even prevent brain disorders, such as Alzheimer's disease, epilepsy, and traumatic brain injury. The goal of National Robotics Initiative, started in 2012 as part of AMP, is to develop robots that can safely coexist with humans and operate in proximity to them.

SOURCE: Office of Science and Technology Policy, 2016, "Initiatives," https://www.whitehouse.gov/administration/eop/ostp/initiatives, accessed August 7, 2016.

**RECOMMENDATION 5-5: Cognizant program staff at the National Science Foundation (NSF) should have responsibility for identifying and collaborating with other agencies' programs that relate to the missions of NSF centers. Where appropriate, multiple agency financial, technical, and human resources should be leveraged to support the work of centers.**

## DURATION OF NSF SUPPORT

Current ERCs receive a maximum of 10 years of funding from NSF; during this time they are encouraged to develop strong relationships with industry, other universities, and government and nonprofit entities that can sustain them after that period. The defined period of support imposes a discipline on operations and helps to ensure that funding is available to a variety of different centers.

A 10-year program in the global innovation economy, where technology improves so rapidly, represents a major opportunity for creating significant advances. It is expected that CERCs will be able to demonstrate dramatic advances by the end of this period. However, given the scope and complexity of the grand-challenge-like problems to be addressed by CERCs, the extra time required for the formation and management of convergent research teams,[15] and the comparatively low maturity level of the technologies explored by the ERCs (Figure 1.1), the full impact of a center's research may not be apparent within 10 years.

Under those circumstances, provided sufficient progress against the goals of the center is being made, CERCs should have the option of competing for a renewal of NSF funding after the initial funding period is over. The

[15] K.L. Hall, A.L Vogel, B.A Stipelman, D. Stokols, G. Morgan, and S. Gehlert, 2012, A four-phase model of transdisciplinary team-based research: Goals, team processes, and strategies, *Translational Behavioral Medicine* 2(4):415-430.

option for competitive renewal is common practice for large, center-based, multidisciplinary research centers at the international level and in many U.S. agencies.[16]

**FINDING 5-6:** Current ERCs receive a maximum of 10 years of funding from NSF. Although major advances should be expected of CERCs, the full impact of a CERC's research may not be apparent after 10 years.

**RECOMMENDATION 5-6: "Sun-setting" of National Science Foundation funding for convergent engineering research centers should not be automatic; the centers should be allowed to continue to compete for renewals, assuming rigorous performance criteria are met.**

The committee believes that artificially cutting-off funding at a pre-determined date, without regard for consideration of performance or contributions being made, would be wasteful. Although many international center programs have traditionally been funded for lifetimes similar to NSF ERCs—that is, 5 years with the potential for one further 5-year funding period—several programs have recently extended center lifetimes.[17]

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[16] E. O'Sullivan, 2016, "A Review of International Approaches to Center-Based Engineering Research," paper commissioned for this study, available at https://www.nae.edu/Projects/147474.aspx.

[17] Ibid.

# 6

# Suggested Tactics

This chapter provides some illustrative examples for implementing the committee's vision for convergent engineering research centers (CERCs). They are for the National Science Foundation's (NSF's) consideration only and are not intended to be prescriptive. Three examples are provided: creating a CERC handbook, options for improving the proposal process, and considerations for choosing appropriate performance metrics.

## CERC HANDBOOK

In multidisciplinary teams, such as CERCs, each technical discipline has its own words, concepts, methods, and, ultimately, business models. As described in the 2015 National Research Council (NRC) report *Enhancing the Effectiveness of Team Science*,[1] unless the team shares a common language, poor results are the rule. An NSF CERC handbook would describe the basic concepts and collaboration processes that partners use to work together successfully.[2] The NSF Innovation Corps (I-Corps) program utilizes a prescribed customer and partner discovery process for technology innovations.[3] The NSF CERC handbook would include some of those ideas plus others required for forming major new innovations that would address grand-challenge-like opportunities.

As documented in the 2015 NRC report on team science, the only effective way for people to understand novel concepts is by using them while working on their projects. Training that is not task-focused is generally ineffective. Introducing the NSF CERC handbook to teams at the start of their projects in a workshop-like format is a best practice. Early introduction allows the teams to learn and apply the concepts while improving their proposals. The CERC handbook would also describe best practices for promoting innovation during the execution of the project.

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[1] National Research Council, 2015, *Enhancing the Effectiveness of Team Science*, The National Academies Press, Washington, D.C.

[2] Enterprises that are systematic high-value innovators, such as IDEO, Apple, GE, SRI International, the Defense Advanced Research Projects Agency, ARPA-E (Advanced Research Projects Agency-Energy), I-ARPA (Intelligence Advanced Research Projects Activity), and the National Science Foundation's I-Corps (Innovation Corps), have value-creation handbooks.

[3] I-Corps teams are made up of a principal investigator (PI), typically a faculty member; an entrepreneurial lead (EL), typically a graduate student or postdoctoral researcher; and an industry mentor (IM), drawn from the business community. During the 7-week course, the team conducts 100 interviews with potential customers and partners while developing and refining a business model. This intensive engagement between the academic team and the business world mimics that of a startup.

Rapid improvement is driven by continuous, constructive feedback. The CERC handbook could facilitate recurring forums in which research teams come together in person or virtually to present their value propositions, listen to critiques from their teammates, and learn from one another.[4]

**FINDING 6-1:** Successful innovation programs in industry and government often rely on common reference tools that describe best practices for the formation of research and development (R&D) teams and facilitating innovation.

**RECOMMENDATION 6-1: The National Science Foundation should consider creating a convergent engineering research centers (CERC) handbook describing best practices in team research and facilitation of innovation that is appropriate for use by CERC researchers and students.**

## PROPOSAL PROCESS

NSF has a proposal process that has been effective for decades.[5] It is based on white papers, pre-proposals, full proposals, and site visits. These remain essential steps in creating high-performance CERCs.

Compelling CERC proposals must include an important societal research opportunity, a deep understanding of the key technical challenges involved, a working hypothesis for the solution to address these challenges, identification of the multiple disciplines needed to solve it, and the formation of the best academic and industry teams. Addressing these issues requires a rigorous preproposal process. Specifically, it is improbable that the appropriate team can be assembled until the opportunity and its specific technical challenges are understood.

There is significant consensus across many international programs that effective pre-proposal planning can lead to stronger proposals (in terms of team formation, commitment, and identifying integrated challenge goals). In particular, structured exercises designed to support proposal development can help ensure more effective identification (and refinement) of collective research goals and elicit more detailed commitment from industrial partners. Pre-proposal development exercises can also support more effective team formation by more clearly identifying capability and expertise gaps, more clearly revealing the complementary capabilities of potential team members, and creating awareness among potential team members (or collaborators) of individual expectations regarding project outcomes and impact.[6]

NSF currently has a pre-proposal requirement for ERCs that contains detailed instructions for what must be included. However, the committee believes that achieving the formation of an outstanding team and deep collaboration in future CERCs will require more upfront work by NSF and the proposing teams before the submission of final proposals. Today this upfront effort is to a great degree done after the center is formed, which is inefficient. The committee looked at models used by other agencies, especially the Defense Advanced Research Projects Agency (DARPA), and came up with ideas for NSF to consider for how to optimize a pre-proposal process for future CERCs. An example is provided in Box 6.1.

**FINDING 6-2:** NSF is to be commended for using a pre-proposal process in the development of ERC proposals. However, to facilitate the success of its CERCs, it could employ still other models for this process that call for greater focus on developing a center's initial value proposition and optimizing team formation.

**RECOMMENDATION 6-2: The National Science Foundation should consider developing a rigorous pre-proposal process that allows for the identification and incubation of high-value societal opportunities with a compelling working hypothesis for the solution of the underlying challenges and for the formation of the best research team. This process should be codified in its convergent engineering research centers (CERC) handbook and reviewed and improved periodically to assure its value for achieving the vision for new CERCs.**

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[4] C.R. Carlson and W.W. Wilmot, 2006, *Innovation: The Five Disciplines for Creating What Customers Want*, Random House, New York.

[5] National Science Foundation, "Gen-3 Engineering Research Centers (ERC) Partnerships in Transformational Research, Education, and Technology," http://www.nsf.gov/pubs/2015/nsf15589/nsf15589.htm#prep, accessed November 19, 2016.

[6] E. O'Sullivan, 2016, "A Review of International Approaches to Center-Based, Multidisciplinary Engineering Research," paper commissioned for this study, available at https://www.nae.edu/Projects/147474.aspx.

**BOX 6.1**
**Example of an Enhanced Proposal Process for CERCs**

The National Science Foundation (NSF) may wish to consider what the committee believes are three best practices to enhance the convergent engineering research centers (CERC) proposal process. These practices can be both effective and cost efficient and can address the requirements for constructive CERC project and team formation.

1. Before a request for proposal (RFP) is posted for a new CERC, a workshop is held for the research community to describe the purpose and expectations for the CERC. Explaining the importance and use of the NSF CERC handbook is part of that meeting. At the Defense Advanced Research Projects Agency (DARPA), for example, this workshop is called an "industry day."
2. Small initial research grants (often called "seedlings") are provided to teams with potentially valuable ideas so they can flesh out critical elements of their working hypothesis for the solution. Paradigm-shifting initiatives often contain high-risk elements that can preclude funding. Eliminating aspects of that risk can transform such initiatives into attractive CERCs.
3. Once the new CERCs have been selected, a workshop is held with the entire team. The objectives are to gain team alignment, further clarify the CERC's objectives and milestones, and gain agreement on the management practices to be followed. This experiential workshop is conducted as a value-creation forum, which allows the entire team to understand and apply the practices described in the NSF CERC handbook.

## METRICS

Various metrics can be used to judge the performance of CERCs: number of students graduated, number of scientific publications published, standing within the research community, industry participation, number of innovations and start-ups spawned, products commercialized, and overall economic and social impact. Many of these metrics—for instance, the number of participating companies, patent disclosures, and underrepresented minorities or women—can foster a "box-checking" mentality that is not useful. In addition, intellectual property that is not used and companies that are formed with little or no capitalization are not indications of success. Today's ERC performance metric reports can be hundreds of pages long. Such detailed reporting takes precious resources from the centers and provides only limited useful information.

### Meaningful Quantitative Metrics

The goal for metrics is to measure results, not just outputs. Commonly used metrics include licenses, start-ups, and students graduated with the right skills. However, to a great extent, these measures are outputs. The metric that matters is the economic, health, or security impacts created across society. An example would be evidence of widespread use of a center's intellectual property within high-value commercial products or in other applications that have broad, recognized societal benefits, such as new standards or tools. Metrics should not discourage CERCs from taking calculated risks in the name of making breakthroughs or from changing course and redefining objectives in response to a changing technological environment. Metrics for the CERCs must be serious but flexible enough to allow the right decisions to be made over the lifetime of the CERC. The goal is to accelerate learning and achievement.

Metrics should not discourage CERCs from taking calculated risks in the name of making breakthroughs or from changing course and redefining objectives in response to a changing technological environment. Metrics for the CERCs must be serious but flexible enough to allow the right decisions to be made over the lifetime of the CERC. The goal is to accelerate learning and achievement.

The committee observed that often, in attempts to hold centers to high standards in order to ensure transformative activities and outputs, the load of measuring every activity can impede innovation, especially in an evolving or emergent discovery environment. In the future, emerging technologies such as business analytics and metrics platforms, already in use in major corporations, should be able to capture this information automatically and thus reduce reporting burdens.

These metrics can be part of a performance "dashboard" that is easily updated continuously, rather than producing an overly detailed written report every year. Yearly reports are out of date when delivered, and they do not allow continuous adjustments as the CERC progresses. A one-page dashboard containing the essential metrics can provide valuable and effective feedback.

With emerging collaboration platforms, all CERC activities will be open to all appropriate partners. The dashboard, NSF CERC Handbook, the value propositions being developed by the teams, and the progress toward center goals will be visible to everyone. Thus, everyone, including students and the government, will be fully apprised of the team's ongoing performance. This will greatly accelerate research and team learning while allowing new teammates to be rapidly added.

Collaboration in today's workplaces is increasingly mediated by communication tools, whether for asynchronous communication (e.g., e-mail and document creation and management tools such as Office 365), synchronous communication (e.g., real-time collaboration tools such as Slack), and in-person and online meetings (e.g., Skype and Go-To-Meeting). These tools allow universities and businesses to track, document, and analyze the effectiveness of collaboration in their environments in ways that previously were not possible. For example, a company called VoloMetrix,[7] recently acquired by Microsoft, created software that monitors e-mail traffic and meetings along with other metrics and provides analytic insights that tie employee activities to business results. Microsoft's Office 365 Delve Analytics can track the document creation and modification and give people insights on the progress of their work group and the tasks that remain to be performed. These are just a few examples. The number of new business intelligence tools being introduced into the market is increasing. Looking forward, these tools will provide the opportunity to improve not only traditional corporate work but also the way research is performed, managed, and documented.

**FINDING 6-3a:** Reporting requirements for centers can be burdensome and often do not reflect important impacts or the dynamism of center activities.

**FINDING 6-3b:** Emerging collaboration platforms allow real-time tracking and longitudinal follow-up of center research activities and of students, faculty, and collaborators who have been engaged at the centers, all with less burden on the centers.

**RECOMMENDATION 6-3: Metrics should be minimal, essential, and aligned with center milestones and processes and should be defined in a center's strategic plan. The convergent engineering research centers should use state-of-the-art web-based collaboration platforms, such as performance dashboards, to amplify team collaboration and simplify reporting requirements.**

### Evolution of Metrics

Appropriate performance metrics vary according to the stage of maturity of the centers, and on whether the research problem is related more to economic or other measures of societal benefit. Very few performance metrics of substance can be obtained during the first 1 to 3 years of a CERC's existence.[8] That is because the teams are just beginning their research. The creation of significant new papers and commercial innovations from a CERC's

[7] H. Clancy, 2015, "Microsoft buys 'people analytics' startup VoloMetrix," *Fortune*, September 3, http://fortune.com/2015/09/03/microsoft-buys-volometrix/.

[8] Exceptions may arise when centers grow out of pre-existing collaborative university-industry research efforts.

initiatives during that period is unlikely. The best practice is therefore to measure how well the teams are using the team research and value-creation methodologies, including metrics for collaboration such as jointly authored papers or conference presentations, weekly discussions with colleagues, and quarterly value-creation forums.

Later in the life of the center, metrics should be based on progress toward the projected impact in the economic, security, or societal domains—that is, on outcomes rather than specific outputs such as papers or patents. Given the scope and complexity of problems that are expected to be tackled by CERCs, the full impact of a CERC's work may not be apparent during the life of the center itself, so the assessment of progress must be based on the strategic plan's milestones.

The CERC, as part of its strategic plan, should identify and collect the metrics appropriate for the Center during its lifetime. Many of these may initially be qualitative and not outputs or outcomes. During the later years of NSF funding of the CERC, there may be significant numbers of papers published, patents filed, and so on. The real measures of outcomes resulting from CERC activities, such as economic value, innovation-savvy engineering graduates who rise to be leaders, and the like, may not be ascertainable until years after NSF funding has ended. Developing and implementing a framework for measuring and assessing the actual impact of the CERCs will enable NSF to demonstrate the value and impact of the CERC. NSF can develop a robust database, including economic and noneconomic outcomes over the short and long terms. The framework would need to include a system to track outcomes from a center for at least 10 years after NSF funding has ended. To observe real economic value, it may in some cases need to be longer.

**FINDING 6-4:** Appropriate performance metrics for CERCs will vary according to their time in operation and the type of research problem they have chosen to address.

**RECOMMENDATION 6-4: Early in the life of convergent engineering research centers (CERCs), performance metrics should be based on their adherence to team research and value creation best practices. Later in the CERC's National Science Foundation funding life, metrics should be based on the CERC's impact on the economic, security, or societal domains as laid out in its strategic plan.**

Some international center programs highlight the importance of performance metrics that are tailored to the "impact logic" of the center being evaluated. For example, generating patents is not an objective for some centers because the participating partners or sectors do not have this as part of their business logic. Some international programs give funded centers the freedom to track and report additional novel metrics that are not specified in official reporting forms, but identified by the centers themselves.[9]

**FINDING 6-5:** The real impact of a CERC, including the career contributions of its students and faculty, changes resulting from new science, and creation of novel technologies, will usually not be fully apparent during the NSF funding life of the center.

**RECOMMENDATION 6-5: The National Science Foundation should develop and implement a framework for retrospective studies of the economic and societal impacts of the convergent engineering research centers (CERCs) and apply lessons learned in the establishment of new CERCs.**

[9] E. O'Sullivan, 2016, "A Review of International Approaches to Center-Based, Multidisciplinary Engineering Research," paper commissioned for this study, available at https://www.nae.edu/Projects/147474.aspx.

# 7

# Center Models

There are many ways that convergent engineering research centers (CERCs) might operate and be organized. The most appropriate structure will depend on the type of research problem chosen and other circumstances. There may be no optimal, one-size-fits-all approach. In this chapter, the committee describes three possible models the National Science Foundation (NSF) may want to consider: a grand-challenge-based model, a prize-based model, and a federal-state-local partnership model.

All of the models discussed here would likely involve mandatory cost sharing on the part of the center research partners. In order to avoid distortion of the type of research it funds, NSF follows clear guidelines from the National Science Board regarding mandatory cost sharing, considering it to be a requirement for eligibility for an award, but not part of the review process for the award.[1] There are also limits on the amount of cost sharing that NSF can ask for. The engineering research centers (ERC) program is one of several already approved for mandatory cost sharing.[2]

These three models have very different organizational structures and management challenges. What they have in common is a commitment to solving problems of great societal significance and strict adherence to team-research and value-creation best practices. By studying different models, additional best practices can be identified and applied to future CERCs.

## GRAND CHALLENGE-BASED MODEL

Scientific and technological advances of the past few decades have created the real possibility that solutions to many complex problems, up to now considered unsolvable in the near term, are within reach. A manifestation of this expectation is the promotion by certain organizations and communities of the idea of "grand challenges." The U.S. Agency for International Development, for instance, has launched eight Grand Challenges for Development,[3] one of which is stopping the spread of the Zika virus and outbreaks of other infectious diseases. The American Academy of Social Work and Social Welfare has proposed 12 Grand Challenges for Social Work,[4] including the

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[1] National Science Foundation, "Implementation of the 2nd NSB Cost Sharing Report: NSF Revised Cost Sharing Policy Statement," https://www.nsf.gov/bfa/dias/policy/csdocs/principles.pdf, accessed November 9, 2016.

[2] Ibid.

[3] USAID, "The Grand Challenges," https://www.usaid.gov/grandchallenges, accessed September 21, 2016.

[4] American Academy of Social Work and Social Welfare, "Grand Challenges for Social Work," http://aaswsw.org/news/grand-challenges-for-social-work-policy-actions-and-advice-on-advancing-social-policy/, accessed September 21, 2016.

goal of stopping family violence. And, as previously noted and of particular relevance to this report, the National Academy of Engineering (NAE) has outlined 14 Grand Challenges for Engineering (Box 2.2).

By design, grand-challenge-like initiatives create excitement and spark imagination and creativity. They transcend national boundaries, cultures, and demographics and have universal appeal. It is desirable, therefore, that a CERC with a grand-challenge focus proactively engage the global engineering research and education community. Such engagement might involve crowdsourcing and the use of open, Internet-based educational and research platforms; institutional interactions between allied programs or institutions in different countries; exchanges of scientists or educators; and the sharing of facilities or other critical infrastructure.

What might a CERC based on a grand-challenge-like problem look like? Consider the NAE Grand Challenge "advancing personalized learning" (Box 7.1).

**BOX 7.1**
**A CERC Addressing the NAE Grand Challenge to Advance Personalized Learning**

Achieving this goal—instruction that can be tailored to a student's individual needs—will require research and innovation by multidisciplinary teams comprising computer scientists; electrical, biomedical, biochemical, and neuro-engineers; education researchers and teachers; neuroscientists and psychologists; social scientists; ethicists; and others.

Convergence in such a convergent engineering research center (CERC) could manifest in at least two distinct ways. The first might involve the application or adaptation of existing technologies to the center's mission of improving student learning. For instance, wearables and other cyberphysical sensors that are part of the Internet of Things could have a role in both the classroom and nontraditional learning settings. Building on efforts by EdEx, Coursera, the Khan Academy, and others, the CERC might aim to develop next-generation distance and interactive teaching and learning tools. Machine learning, data analytics, and artificial intelligence tools could be leveraged to assess learning behavior in order to better tailor individual learning experiences.

A second approach could combine expertise in engineering, neuroscience, and the learning sciences to better understand how humans learn and to apply such knowledge to produce new educational technologies. The involvement of computer scientists and communication and signal-processing engineers might also be expected, given the centrality of information processing and analysis to learning.

Understanding how human brains process information will help not only to advance personalized learning but also to spur the development of new information-processing technologies, such as neuromorphic computing as well as advances in machine learning and artificial intelligence. One might also imagine innovations such as restoring lost learning functions in individuals with traumatic brain injuries or debilitating neurological diseases to ripple through the biomedical device and pharmaceutical industries. Convergence between neuroscience and engineering might also lead to completely new convergent systems, such as cyber–neural systems (a counterpart to cyberphysical systems). Finally, findings from a CERC devoted to improving personalized learning might be applied beyond the individual to better understand how complex organizations "learn," how they assess themselves, and how they can improve their performance.

A CERC dedicated to advancing personalized learning will have global impact. It will impact the way mass communication messages, from advertising to marketing to political campaigns, are crafted and disseminated—for instance, via social media or otherwise. And it might also produce findings that can be used to advance society at large by helping to democratize access to education at all levels, strengthening individual decision making by eliminating implicit or anchor biases, empowering individuals to maximize learning based on their individual characteristics, and creating a more equitable and informed global society. It will actively engage communities, from K-12 students to policy makers, and policy-making agencies, from city to state to federal. Such a CERC might attract industry from a variety of disciplines: education, digital media, communications, entertainment, and medical and biomedical.

The large scope of a grand challenge problem would be both the greatest strength and the greatest weakness of this type of model. As mentioned, these problems would attract a diverse, motivated group of students and faculty from many countries, and would likely attract new sources of funding. Managing such a diverse and geographically distributed group would be a major challenge, as would maintaining focus on an achievable set of goals. One of the major societal benefits of such an effort might be to understand how best to approach the problem, and how to parse it into pieces that can be meaningfully addressed in an engineering center context.

The scope of a grand challenge suggests that a single CERC would not suffice to address it fully. In addition, there would be points where research programs on different grand challenges overlap. For example, a CERC devoted to improving personalized learning could profitably leverage or interact with a center focused on the NAE Grand Challenge to "reverse engineer the brain." Whether or not this kind of alliance is undertaken, targeted collaborations with other research centers in the United States and around the world would certainly be needed. The biannual Global Grand Challenges Summits,[5] which bring together leaders in engineering, industry, and government from the United States, the United Kingdom, and China to share information on progress toward addressing the 14 NAE challenges, are a potential platform for building cross-national collaborations. In addressing its educational mission, a CERC based on an NAE Grand Challenge would naturally leverage the Grand Challenges Scholars Program (Box 3.1), whose five components[6] mirror key elements of the committee's vision for the future of engineering research. In the grand challenge context, NSF may wish to consider a truly international center—that is, one that is international in scope from its inception, with international collaboration as a core function—although there appear to be few if any examples of centers structured this way.[7]

## PRIZE-BASED INNOVATION MODEL

The future security, economic growth, and competitiveness of the United States depend on its capacity to innovate. Americans believe that it is possible to create jobs by doing what the United States does well, which is cultivating the creativity and innovative processes developed by its people. Innovation and value creation have historically kept the United States at the forefront of technology advances that have been the keys to its national security policy and economic growth. A crucial catalyst in this innovation ecosystem has been the use of properly posed prizes and competitions to accelerate imagination, invention, innovation, investment, and impact.

In the Defense Authorization Act of fiscal year 2000,[8] Congress authorized the following: "The Secretary of Defense, acting through the Director of the Defense Advanced Research Projects Agency [DARPA], may carry out a program to award cash prizes in recognition of outstanding achievements in basic, advanced, and applied research, technology development, and prototype development that have the potential for application to the performance of the military missions of the Department of Defense." In 2003, DARPA management determined that the prize authority granted by Congress should be used to accelerate the development of autonomous ground vehicles that could one day be used to transport cargo and other military supplies into combat zones without endangering the lives of human drivers. The contest was also DARPA's first major attempt to use prize money as an incentive for innovation within the research community. The first DARPA Grand Challenge offered a $1 million prize for the fastest autonomous vehicle to complete a difficult course through the desert in less than 10 hours. Although no vehicle completed the course or even got very far, this first Grand Challenge is considered a success by many for the interest and spirit the event created. The DARPA Grand Challenge has provided a template for the use of prize-induced challenges to advance basic, advanced, and applied research, technology development, and systems engineering.

[5] The third summit, hosted by the National Academy of Engineering, will take place in Washington, D.C., in July 2017.

[6] The five components are as follows: hands-on project or research experience, interdisciplinary curriculum, entrepreneurship, global dimension, and service learning (see National Academy of Engineering, "NAE Grand Challenges Scholars Program," http://www.engineeringchallenges.org/GrandChallengeScholarsProgram.aspx, accessed May 24, 2017).

[7] B. Lal, C. Boardman, N.D. Towery, and J. Link, 2007, *Designing the Next Generation of NSF Engineering Research Centers: Insights from Worldwide Practice*, Institute for Defense Analysis, Science and Technology Policy Institute, Arlington, Va.

[8] Public Law 106-65, Section 244.

President Obama, as part of the America Competes Act,[9] strongly encouraged every federal agency to use prizes to solve grand-challenge-like problems as a means of spurring creativity and innovation. In addition to the continuing programs at DARPA, other federal agencies that have sponsored research inducement prizes include the Department of Energy, the National Aeronautics and Space Administration, and the Department of Health and Human Services.[10]

In June 2016, as part of its Smart City Challenge, the Department of Transportation (DOT) awarded more than $40 million to Columbus, Ohio, to prototype the future of urban transportation; 78 cities competed for the award. The city's plan will also leverage over $100 million in private resources.[11]

A 2007 National Research Council (NRC) report[12] offered the following: "The committee recommends that [NSF] take an experimental approach to implementing its congressional directive to award such prizes, especially during the program's formative period." Serving on the study committee was Erich Bloch, under whose leadership as director of NSF, the ERC program was begun. An NAE report on how NSF and other federal agencies might implement such an approach is *Concerning Federally Sponsored Inducement Prizes in Engineering and Science*.[13]

These prizes often inspire and attract a new generation of technology innovators to the field of engineering to solve technical problems with the hope of being the first team to achieve the competition milestones and claim a cash prize. One well-known example is Elon Musk's Hyperloop Pod Design Competition (Box 7.2).

CERCs could leverage the prize/competition model not only to accelerate and translate research discoveries, but also to encourage participation by diverse teams outside the existing CERC core team members to address real-world problems.

A 1999 NAE workshop report[14] describes several ways in which the federal prize competitions could be funded and administered: "agency funded and administered; agency administered and privately funded; agency initiated and privately funded and administered; or joint agency-private sector funded and administered." Here, the committee is proposing the second option: agency-administered and privately funded. CERC leadership teams would manage the competition in partnership with NSF to achieve a particular research or translational objective or technical milestone within the context of a larger NSF-funded research program. By analogy to the example given in Box 7.2, the hypothetical CERC might oversee a prize competition to design a new vehicle as part of its broader mission to design a new transportation system. Funding for the prize would be provided by third-party partners (e.g., venture capitalists) who would have a vested interest in seeing the technology mature. One disadvantage of this approach is that third-party funding could complicate budgeting and auditing of how these monies are spent.

## FEDERAL–STATE–LOCAL PARTNERSHIP MODEL

NSF has an opportunity to inspire a new funding model that focuses on specific city, state, or regional economic interests driven by engineering ideas and problem solving. This model would support the bottom-up identification of research focus, described in the Chapter 2 section "Problem Focus." From NSF's point of view, these partnerships would leverage CERC funding to levels that would attract the best talent and stimulate innovation for local or regional ecosystems. From a city or state point of view, the partnership would take advantage not only of the cachet of NSF funding, but also of its support for talent and capability in a given engineering area and its ability

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[9] Public Law 110-69, signed into law by President George W. Bush on August 9, 2007.

[10] D.D. Stine, 2009, *Federally Funded Innovation Inducement Prizes*, R40677, Congressional Research Service, June 29, https://fas.org/sgp/crs/misc/R40677.pdf.

[11] The White House, "FACT SHEET: Announcing Over $80 Million in New Federal Investment and a Doubling of Participating Communities in the White House Smart Cities Initiative," https://obamawhitehouse.archives.gov/the-press-office/2016/09/26/fact-sheet-announcing-over-80-million-new-federal-investment-and, accessed October 20, 2016.

[12] National Research Council, 2007, *Innovation Inducement Prizes at the National Science Foundation*, The National Academies Press, Washington, D.C.

[13] National Academy of Engineering, 1999, *Concerning Federally Sponsored Inducement Prizes in Engineering and Science*, National Academy Press, Washington, D.C.

[14] Ibid.

**BOX 7.2**
**Prize-Based Design Competition: Hyperloop Pod Example**

An interesting example of an active prize competition that has captured the imagination of thousands around the world is a concept called the hyperloop. In 2012, Elon Musk, founder of SpaceX and co-founder of Tesla, announced that he would soon make public a set of plans for something new he had been designing. It turns out that Mr. Musk had made so many trips between his Tesla (Fremont, California) and SpaceX (Hawthorne, California) plants that he began considering better ways to commute. He was aware that California was considering a high-speed rail line for travel between northern and southern California. Certainly *some* high-speed rail would be better than what exists today. However, the existing plans would not be realized until 2025, with a rail line to be built between Bakersfield and San Jose at an estimated cost of $64 billion dollars.

Because the high-speed rail time frame and costs were of great concern to Mr. Musk, he decided to come up with an alternative. In August 2013, he released his hyperloop plan on the Internet for all to see. The plan featured a low-pressure tube and an air-levitated train traveling at high speeds, with low energy consumption. Immediately following the release of the plan, Mr. Musk focused his efforts on pod design and getting more engineers to work on innovative concepts. On June 15, 2015, SpaceX announced that it would sponsor a hyperloop pod design competition, with no mention of a prize amount, and would build a 1-mile-long (1.6 km) subscale test track near SpaceX's headquarters in Hawthorne for the competitive event. The first phase of the design competition generated more than 700 submitted designs. Final design packages were due on January 13, 2016. A Design Weekend was held at Texas A&M University in January 2016 for all 120 invited entrants. Judges recommended that 30 pod teams be allowed to build their designs and compete for a prize at the SpaceX Hyperloop Test Track in January 2017. Since initiating the Hyperloop concept and the Pod Design competition, three start-ups have emerged with external funding for ideas to commercialize the technology and realize the vision put forth by Mr. Musk. These firms include Hyperloop One, Hyperloop Transportation Technologie, and Transpod.

Thus, the Hyperloop Pod Design Competition illustrates that when prizes are properly posed they have several positive effects, among them the following:

- Inspiring imagination, invention, innovation, investment, and impact;
- Leveraging external financial investment that is typically 5 to 10 times the value of the prize;
- Bringing diverse groups of people together to solve a single problem;
- Accelerating advances in key enabling technology over a shorter period of time; and
- Potentially setting off entirely new industries that result in improved security, job creation, and economic development.

to guarantee quality of the "product" through an independent review process that focuses on value added or impact of the city or state investment.

In a similar vein, as part of the Smart Cities Initiative of the Obama administration, NSF announced programs to bring academic researchers and community stakeholders together to promote transformational advances in health, energy efficiency, building automation, transportation, and public safety.[15]

Many cities and states recognize the importance of fostering collaboration between their research universities and industries to propel economic growth and competitiveness. This type of collaboration has already happened in the ERC program. For example, the state of Georgia invested $32.5 million in the Microsystems Packaging Research

[15] The White House, "FACT SHEET: Administration Announces New "Smart Cities" Initiative to Help Communities Tackle Local Challenges and Improve City Services," https://obamawhitehouse.archives.gov/the-press-office/2015/09/14/fact-sheet-administration-announces-new-smart-cities-initiative-help, accessed October 20, 2016.

Center at Georgia Tech from 1994 to 2004. Direct impact from the investment was estimated at $192 million with an additional $159 million in indirect and induced impacts.[16] A recent National Governors Association (NGA) report[17] catalogs a number of existing programs and suggests some best practices. As the NGA report notes, a number of states (New York, Texas, California, Ohio, and Georgia) have made significant research and development (R&D) investments in recent years and have created funding models that will continue to benefit from refinement and, perhaps, appropriate replication by other states. On the other hand, in some states, barriers to funding these efforts include a poor understanding on the part of state legislatures of the multiplier effect of federally funded intellectual property development, as well as a lack of long-term commitment and stability on innovation policy.

As one example, the NGA report suggests a state will be advantaged by establishing an independent entity such as the Georgia Research Alliance (GRA) (see Box 7.3).[18] The NGA report provides examples of programs in other states, some with similar structures and processes and others with different structures and processes.

Many European Union (EU) countries have adopted practices that are consistent with the NGA report. These countries support their universities to address important, modern engineering and manufacturing R&D challenges that are connected to economic prosperity. Importantly, the funding models detailed in the NGA report are for countries that, because they vary greatly in size and population, might serve as additional case studies for U.S. states. Sweden, for example, compares to either Georgia or Michigan in population; Ireland compares to Louisiana, Kentucky, or South Carolina.

Some country-level programs of EU member countries receive additional support from the EU itself. The U.S. equivalent would be state programs that receive additional collaboration and/or support from federal agencies such as NSF. The convergence of federal, state, academic, and industry intellectual capital focused on an emerging technology challenge is a powerful multiplier that has been shown to yield dramatic results. In this public-private partnership model, private dollars may match or even exceed state investment, encouraging U.S. universities to become engines of innovation that operate in close partnership with industry.

Consider the following hypothetical example of a federal–state partnership CERC that is working on the NAE Grand Challenge to “restore and improve urban infrastructure,” clearly a topic of interest to large cities and states.[19] Most such cities are near sea level, as water transportation was typically a crucial factor in their original location and historical growth. That means that many cities are vulnerable to sea level rise, which is a predictable consequence of climate change.

Suppose that a major research university located in one of those cities decided to launch a new CERC to develop practical approaches to the joint issues of sea level rise and extreme weather events. A wide range of disciplines would be involved, such as civil engineering, hydrology, meteorology, data science, law, architecture, political science, and social science. Public sector partners would include city, county, and state agencies. Private sector partners could include insurers, real estate developers, and property managers.

Even this opportunity seems so broad that the CERC being hypothesized could choose to focus on an important but limited subset of the broader problem. Possibilities include, but are hardly limited to, the following:

- Approaches to hardening existing critical buildings that cannot be replaced and/or whose functions cannot be easily moved;
- Approaches to securing, renovating, or relocating public transportation infrastructure;
- Improving advance warning systems; and
- Maintaining continuity of operations of information and telecommunications infrastructure during extreme events.

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[16] SRI International, 2008, *National and Regional Economic Impacts of Engineering Research Centers: A Pilot Study, Summary Report*, SRI Project P16906, https://www.sri.com/sites/default/files/brochures/erc_impact_summary_report_11_18_08.pdf.

[17] National Governors Association, 2012, *Growing State Economies: Twelve Actions*, National Governors Association Chair’s Initiative, Washington, D.C.

[18] Georgia Research Alliance, “Driving Science and Technology Economic Development in Georgia,” http://gra.org/page/1025/about_gra.html, accessed November 9, 2016.

[19] Modeled on work at the Center for Urban Science and Progress at New York University, headed by Dr. Steve Koonin, formerly Under Secretary of the U.S. Department of Energy, chief technology officer of British Petroleum, and Provost of the California Institute of Technology.

**BOX 7.3**
**The Georgia Research Alliance**

The Georgia Research Alliance (GRA) is connected directly to the state's economic development agency by co-location, and its success has been a priority of every Georgia governor since its inception 25 years ago. The GRA has helped recruit exceptional new talent to Georgia's universities and is helping to seed the future economy. It uses a competitive review akin to the National Science Foundation (NSF) process so that the highest possible standards and performance expectations are set.

The GRA invests in Georgia's educational capacity through an Eminent Scholars program designed to bring the nation's brightest minds to Georgia universities, with 23 such scholars at Georgia Tech alone. In diverse areas such as advanced manufacturing, biomedical engineering, computer science and energy, GRA Eminent Scholars drive Georgia's technology-rich economic development strategy, in which start-up companies are often born from the work of these scientists.

Bringing Georgia universities and small businesses together to tackle major federal challenges, the GRA also brings state resources to bear at critical early stages. It also provides business and commercialization guidance that is essential to new enterprises.

The GRA also invests in unique engineering infrastructure. Building on seed funding from NSF and GRA, Georgia Tech established the Institute for Electronics and Nanotechnology (IEN) with the goal of providing a central entry point and a central organization to enable interdisciplinary electronics and nanotechnology education and research. No federal funds were used in the construction of the IEN's facility, and the state's investment was only 12 percent, with the balance provided by donations. The IEN became the southeastern regional hub for the NSF's National Nanotechnology Coordinated Infrastructure (NNCI) and the national headquarters for NNCI educational programs. This example demonstrates the growth possible over a decade when federal, state, academic, and industrial research priorities are aligned on a grand research challenge.

A recent GRA brochure reveals the multiplier effect of GRA's impact on Georgia's economy.[1]

[1] Georgia Research Alliance, "Breakthroughs in Georgia," brochure, undated, http://gra.org/uploads/documents/2015/10/2015101414580948/GRABrochure_Final.pdf.

NSF's review would ensure that the appropriate talent is available and the problem being addressed is significant. It would also give participating cities and/or states confidence that the "product" will contribute to regional economic development. NSF's investment would be leveraged by contributions from a city, a state, or a consortium of states. This would help ensure that the best talent would be attracted to the CERC. The hypothesized CERC would require leadership versed in academic, public, and private institutions. It could provide an extraordinary opportunity for scholars, students, and practitioners to interact and learn from one another.

A potential disadvantage of this type of model, when very large funding amounts are involved, is that it could invite political meddling by regional or federal government bodies.

## FINAL THOUGHTS

This set of research problems and funding models is by no means comprehensive, but all of the models are consistent with aspects of the committee's vision. They focus on big, complicated problems whose solutions will bring large societal or economic impacts. They depend on the convergence of knowledge from different disciplines and on deeply collaborative, diverse research teams. They require skillful and effective leadership to guide the centers through their formation to the realization of their goals and impact. And they will require the resources of NSF to be combined with those from other sources, including other federal agencies, states, international collaborators, and the private sector.

# Appendixes

# A

# Biographical Sketches of Committee Members

MAXINE L. SAVITZ, *Co-Chair*, 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 the Department of Energy (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, Sandia National Laboratories, and the Jet Propulsion Laboratory (JPL). She serves on the Massachusetts Institute of Technology (MIT) visiting committee for sponsored research activities. In 2009, Dr. Savitz was appointed to the President's Council of Advisors on Science and Technology and served as vice president of the National Academy of Engineering (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, 1998), the DOE Outstanding Service Medal (1981), the President's Meritorious Rank Award (1980), recognition by the Engineering News Record for Contribution to Construction Industry (1975 and 1979), and the U.S. Mobility Equipment Research and Design Command (MERDC) Commander Award for Scientific Excellence (1967). She is the author of about 20 publications.

DAVID R. WALT, *Co-Chair*, is a university professor, professor of biomedical engineering, 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., where he was a director from 1998 to 2016 and is currently chairman of its scientific advisory board. He is also the founding scientist of Quanterix Corporation and 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 served as co-chair of the Board on Chemical Sciences and Technology of the National Academies of Sciences, Engineering, and Medicine from 2013 to 2016. Dr. Walt is a member of the NAE, the National Academy of Medicine, and the American Academy of Arts and Sciences. He is a fellow of the American Institute for Medical and Biological Engineering, the National Academy of Inventors, and the American Association for the Advancement of Science (AAAS).

NADINE AUBRY is a university distinguished professor and dean of the Northeastern University College of Engineering and an expert in the field of fluid dynamics, including the modeling of open flow turbulence and other complex flows using advanced decomposition techniques and dynamical systems theory, and microfluidics. Dr. Aubry is a member of the NAE and is a fellow of the American Physical Society (APS), the American Society of Mechanical Engineers, the AAAS, the American Institute of Aeronautics and Astronautics (AIAA), and the National Academy of Inventors. She is a recipient of the G.I. Taylor Medal from the Society of Engineering Science and the Presidential Young Investigator Award from the National Science Foundation (NSF). She currently serves as president of the International Union of Theoretical and Applied Mechanics (IUTAM) and as section secretary of the NAE mechanical engineering section, and on the NAE Membership Policy Committee, the NAE Bernard M. Gordon Prize for Innovation in Engineering and Technology Education selection committee, the International Council for Science, the U.S. National Committee on Theoretical and Applied Mechanics (USNC/TAM) of the National Academy of Sciences (NAS), and the AAAS Engineering Section executive committee. Past positions include chair of USNC/TAM, chair of the U.S. delegation to IUTAM, chair of the APS Division of Fluid Dynamics and chair of the NAE Frontiers of Engineering Education advisory committee. Before joining Northeastern, Dr. Aubry was the Raymond J. Lane Distinguished Professor, university professor, and head of the Department of Mechanical Engineering at Carnegie Mellon University. She holds a Diplome d' Ingenieur from Institut National Polytechnic Grenoble and a Diplome d'Etudes Approfondies from Universite Grenoble Alps, both in mechanical engineering, and a Ph.D. from the Sibley School of Mechanical and Aerospace Engineering.

CHERYL R. BLANCHARD is the CEO and a member of the board of directors of Microchips Biotech, 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. She was elected to the NAE in 2015.

ROBERT D. BRAUN is dean of the College of Engineering and Applied Science at the University of Colorado, Boulder. He 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, an M.S. in astronautics from George Washington University in 1989, and a 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 National 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 JPL, the Space Systems Sector of the Charles Stark Draper Laboratory, and the Planetary Society.

CURTIS R. CARLSON is founder and CEO of Practice of Innovation, LLC, was president and CEO of SRI International from 1998 to 2014, and is a prominent innovator and pioneer in developing innovation best practices. 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, "Five Disciplines of Innovation," is used worldwide, 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 Business Week Top-10 book *Innovation: The Five Disciplines for Creating What Customers Want*.

JIM C.I. CHANG is an adjunct professor in the Department of Electric and Computer Engineering at North Carolina State University and formerly a visiting chair professor at National Cheng Kung University, Tainan, Taiwan. 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.

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 science, technology, engineering and mathematics (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 Teach Engineering, an extensive online resource for K-12 educators who teach engineering. At Tufts, she was also the principal investigator on a $1.5 million NSF award that funded the Tufts Engineering 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 was elected to the NAS in 2012. She obtained her B.A. in physics from the National Autonomous University of Mexico (UNAM, Mexico) in 1981, and her Ph.D. in physics from Cambridge University, U.K., in 1985. She was a guest scientist (1985-1986) at 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.

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 program 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 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 founding 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 assistant director for Mathematical and Physical Sciences (1991-1996). He was responsible for federal grants appropriation of $750 million. He also established the initial 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.

FRED C. LEE is currently a university distinguished professor and founder and director of the NSF Engineering Research Center (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 nonexclusive 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 electromagnetic interference, distributed power systems, renewable energy, power quality, high-density electronics packaging, and integration, modeling, and control.

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., and at Caltech, he serves on the 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.

DARRYLL J. PINES is dean and the Nariman Farvardin Professor of Aerospace Engineering at the Clark School of Engineering at the University of Maryland, College Park, 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, and his 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 McKay 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 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.

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 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. He was the Morris Cohen Professor of Materials Science and Engineering from 1989-2011 and founding director of the MIT Institute for Soldier Nanotechnology (2002-2006). 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 450 papers and holds 18 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.

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. From 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, where she served as president from 2012 to 2013.

YANNIS YORTSOS has served as dean of the University of Southern California (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 chair of Section 11. 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 served on the executive committee of the Engineering Deans Council as well as the executive committee of the Global Engineering Deans Council.

# B

# Committee Meeting Information and Teleconference Speakers

## MEETING 1: DECEMBER 14-15, 2015, WASHINGTON, D.C.

*Speakers*

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|---|---|
| Persis Drell | Dean of Engineering, Stanford University |
| Pramond Khargonekar | Director of Engineering, National Science Foundation (NSF) |
| Robert Nerem | Georgia Institute of Technology |
| Colin Rementer | Graduate Student, University of California, Los Angeles Translational Applications of Nanoscale Multiferroic Systems Engineering Research Center (ERC) |
| Donna Riley | Department of Engineering Education, Virginia Polytechnic Institute and State University |
| Jagannathan Sankar | ERC Director, North Carolina A&T State University |
| Gerald Stanley | Harman Crown Audio, Liaison to the Center for Power Electronics Systems ERC |
| Galip Ulsoy | University Michigan, graduated ERC Deputy Director |
| Michael Ward | Director, New York University Materials Research Science and Engineering Center |
| Ronald Young | General Motors Corp. |

## MEETING 2: APRIL 6-7, 2016, WASHINGTON, D.C.

*Speakers*

| | |
|---|---|
| Katherine Banks | Dean of Engineering, Texas A&M University |
| Andreas Cangellaris | Dean of Engineering, University of Illinois |
| Jean-Lou Chameau | President, King Abdullah University of Science and Technology |
| Dean Chang | Associate Vice President, Innovation and Entrepreneurship, University of Maryland |
| France Córdova | Director, NSF |
| Frederic Farina | Chief Innovation and Corporate Partnerships Officer, California Institute of Technology |
| Orin Herskowitz | Director, Columbia Technology Ventures, Columbia University |
| John Holdren | Director, White House Office of Science and Technology Policy |
| Arvind Krishna | Senior Vice President for Global Research, IBM |
| Richard Miller | President, Olin College of Engineering |

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| Eoin O'Sullivan | Director, Centre for Science, Technology, and Innovation Policy, University of Cambridge |
| David Parekh | Corporate Vice President for Research, United Technologies, and Director, United Technologies Research Center |
| Thomas Siebel | Founder and CEO, C3 IoT |
| Kelly O'Sullivan | Manager, Institutional S&T Investments, Pacific Northwest National Laboratory |

**MEETING 3: JUNE 29-30, 2016, WASHINGTON, D.C.**

*Speakers*

| | |
|---|---|
| Jenna Carpenter | Dean of Engineering, Campbell University |
| Frederick Cartwright | Executive Director, Clemson University International Center for Automotive Research |
| Marcus Huggans | Senior Director for External Relations, The National GEM Consortium |
| Donald Ingber | Founding Director and Core Faculty, Wyss Institute (via WebEx) |
| Nickolas Justice | Executive Director, PowerAmerica |
| William King | Senior Advisor to the Digital Manufacturing and Design Innovation Institute (DMDII) |
| Nathan Lewis | Principal Investigator, Joint Center for Artificial Photosynthesis (via WebEx) |
| Pamela McCauley | Professor, University of Central Florida |
| Edward Morris | Vice President and Director, America Makes, the National Additive Manufacturing Innovation Institute |
| Blake Simmons | Division Director for Biological Systems and Engineering, Joint BioEnergy Institute (via WebEx) |

**MEETING 4: AUGUST 30-31, 2016, IRVINE, CALIFORNIA**

*Speakers*

| | |
|---|---|
| Michael Crow | President, Arizona State University (by WebEx) |
| Pramond Khargonekar | Vice Chancellor for Research, University of California, Irvine |

**COMMITTEE TELECONFERENCES**

*Speakers*

| | |
|---|---|
| Chad Mirkin | Director, International Institute for Nanotechnology, Northwestern University (March 2, 2015) |
| Arati Prabhakar | Director, Defense Advanced Research Projects Agency (March 24, 2015) |
| Nancy Cooke | Professor, Arizona State University (May 19, 2015) |

# C

# Strategic Planning and Organizational Infrastructure of Engineering Research Centers

## ERC STRATEGIC PLANNING

Strategic planning for technology development is currently based around the "3-plane diagram" (Figure C.1) that proceeds from fundamental knowledge through enabling technologies to system test beds. An industry/practitioner advisory board conducts an annual analysis of strengths, weaknesses, opportunities, and threats (SWOT) of the engineering research center's (ERC's) operations and progress. Ideally, the ERCs form productive relationships with university and industry partners such that after their 10-year NSF funding life, they "graduate" into independently funded "ERC-like" entities whose stakeholders will translate the ERC work product into useful new products and other innovations. The convergent engineering research center (CERC) model described in this report emphasizes the need for much greater collaboration between the levels and with stakeholders at all levels.

## ERC ORGANIZATIONAL INFRASTRUCTURE

ERCs, particularly multi-institution centers of the Gen-3 variety, which have additional elements compared with their predecessor Gen-2 cousins, are complex entities with many moving parts. As noted in the ERC Association's *Best Practices Guide*:[1]

> The challenges for multi-institution ERCs are obvious. They are more intricate organizations, composed of many institutions with different systems, complex administrations, and varied financial needs and accounting systems. Getting things done requires cooperation, communication, and talented administration.

The committee recognizes the need for oversight but also emphasizes the need for making the processes more efficient and effective.

Today's ERCs answer to a number of advisory boards: a Scientific Advisory Board that meets annually with the ERC and site visit review teams to guide the research; an Industrial/Practitioner Advisory Board, which meets at least twice a year (including a private meeting with the site visit team) to provide feedback to the ERC leadership on research directions and positioning with respect to the state-of-the-art; a Workforce Development

[1] ERC Association, 2012, Section 9.3.1, "Administrative Challenges Unique to Multi-Institution ERCs," in *Best Practices Manual*, http://erc-assoc.org/best_practices/best-practices-manual.

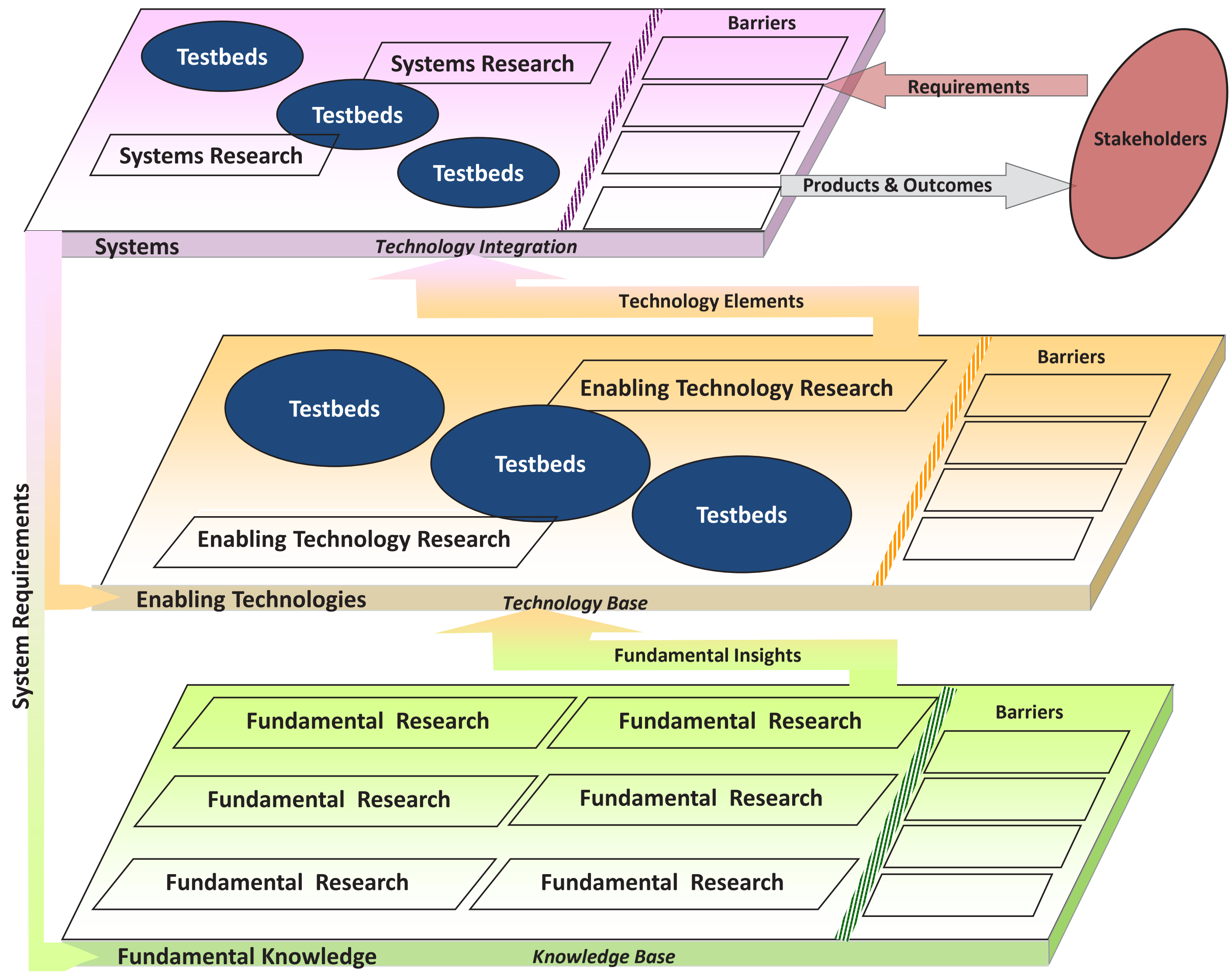


FIGURE C.1 The National Science Foundation's "3-Plane Diagram" is the basis for strategic planning at the engineering research centers.
SOURCE: National Science Foundation, 2015, "ERC Solicitation 15-589 Webinar: Guidance for Preliminary Proposal Development," August 31, https://www.nsf.gov/attachments/135960/public/NSF15-589_ERCwebinar.pdf.

Advisory Board, which meets annually with ERC and site visit teams to provide guidance for achieving diversity and pre-college outreach objectives; a Deans' Council, which oversees both internal departmental interactions and cross-university partnerships and policies; and a Management Systems group, which meets annually or biennially to discuss project selection, refinement, or sunsetting with input from Advisory Boards, site visitors, and NSF. ERCs are required to produce an extensive annual report to NSF and, in years 8-10, an extensive "post-graduation" plan.

Thus successful management of centers entails layers of administrative processes that take staff time to develop and execute. For example, extensive, ongoing data collection is needed to fulfill NSF reporting requirements[2] (e.g., annual and renewal reports), and this can be hard when some key information may be held by dispersed team members. Due to privacy concerns, collecting demographic information to demonstrate progress on diversity goals may pose challenges, and considerable effort may be required to capture data reflective of interaction with industry partners. ERCs also must undergo annual site visits, which require considerable planning, and longer site visits when they apply for renewal in years three and six.

Additional staff time and administrative work are needed to establish and maintain the various external and internal boards and councils NSF requires as part of the ERC structure. ERCs must also design and maintain a website for outside constituents, negotiate intellectual property and member agreements with industry partners, and craft agreements with foreign university partners.

[2] The 52-page National Science Foundation (NSF) guidance document intended to help centers prepare annual reports is entitled *FY 2017 Guidelines for Preparing Annual Reports and Renewal Proposals for the Engineering Research Centers and Nanoscience Engineering Research Centers: Classes of 2006-2015* (NSF, 2017, January, https://www.erc-reports.org/public/download-document?fileName=FY2017_Annual_Reporting_Guidelines.docx). The 60-page ICF International document designed to support centers' use of the agency's online data system, ERCWeb, is entitled *Guidelines for ERCWeb Data Entry for the Engineering Research Centers. FY2017* (ICF International, 2017, prepared for National Science Foundation, Directorate for Engineering, Division of Engineering Education and Centers, January, https://www.erc-reports.org/public/download-document?fileName=FY2017_ERCWeb_Data_Entry_Guidelines.doc).

# D

# Findings Related to Foreign Centers

As part of this study, the committee commissioned a paper aimed at identifying innovative features of foreign centers that might be included in its deliberations.[1] The paper, which considered centers in the United Kingdom, Japan, Germany, China, Sweden, Canada, and Ireland, was based primarily on "desk research" involving a systematic review of center program documents as well as interviews with some funding agency directors and directors of individual centers. The following are key points that emerged:

- This is a time of experimentation with center models and innovation programs: A repeated theme that emerged from interviews with center program officials was that, in response to the innovation-related trends and drivers, many agencies have been experimenting with new center models (in terms of new missions, functions, or practices) as well as introducing "course corrections" to existing models. One of the consequences of this recent experimentation is that there has not yet been any formal evaluation of these programs.
- There are few substantial and systematic attempts to capture center "best practices." This makes it more challenging to compare, contrast, and make relative value judgments on particular practices of international center programs.[2]
- There appears to be some emerging consensus on broad "qualities" that future university-industry research centers should have: challenge-focused, flexible, and networked.
  - *Challenge-focused* (in terms of a greater fraction of centers addressing industrial "needs pull" challenges, rather than just tackling "science push" opportunities);
  - *Agile and adaptable* (in terms of addressing opportunities and barriers to translation, scale-up, and industrialization); and
  - *Networked and aligned* (in terms of collaborating with and leveraging the complementary capabilities and resources of other national, regional, and international innovation actors).
- There is significant consensus about the "added-value" (i.e., collaborations delivering "*whole is greater than the sum of the parts*" impact) that centers can offer in principle, through real collaboration within

[1] E. O'Sullivan, 2016, "A Review of International Approaches to Center-Based, Multidisciplinary Engineering Research," paper commissioned for this study, available at https://www.nae.edu/Projects/147474.aspx.

[2] Several of those interviewed raised the idea of a potential international workshop or forum for agency officials to share their experiences and experiments with new center models and practices.

integrated research endeavors. However, a number of experts interviewed suggested that centers achieving significant added-value, based on systematic collaboration and truly integrated research endeavors, are extremely rare.

- Several international center programs offer supplementary grants, which can support the integration of new partners. In particular, supplementary funding mechanisms appear to have the potential to facilitate the addition of new industrial partnerships based around translational research project opportunities, which have emerged in the course of the initial research agenda.
- A number of recent center programs appear to be more proactively encouraging center linkages to other national research and innovation institutions. The emphasis on the potential of such linkages often appears in programs with a particular "grand challenge" focus, where the capabilities and infrastructure to address a challenge may be distributed across a wider range of innovation actors.
- The funding levels of a number of international center programs are growing, and in some cases appear to be higher than that of the National Science Foundation's (NSF's) engineering research centers (ERCs). Although it is beyond the scope of this project to carry out a careful audit of center budgets, there appears to be a danger that—despite the headline budget numbers—NSF center funding levels may in fact be lower than their international comparators in many cases. There may be merit in carrying out more careful analysis of this issue, in particular paying attention to budget composition, comparison of the funding levels per faculty investigator (or per project), and comparison of funding levels for centers addressing higher technology readiness level research endeavors.
- There is significant consensus across many international programs that effective preproposal planning can lead to stronger proposals (in terms of team formation, commitment, and identifying integrated challenge goals). In particular, structured exercises designed to support proposal development can help ensure more effective identification (and refinement) of collective research goals, and elicit more detailed commitment from industrial partners. Pre-proposal development exercises can also support more effective team formation by more clearly identifying capability and expertise gaps, more clearly revealing the complementary capabilities of potential team members, and creating awareness among potential team members (or collaborators) of individual expectations regarding project outputs and impact. A number of interviewees highlighted the value of more systematic and substantial pre-proposal planning in ensuring real collaboration. In particular, it was suggested that such planning ensures a stronger "social contract" commitment from individual researchers to the center leadership to work on projects addressing collective goals. There are interesting examples of how pre-proposal planning can be facilitated formally by funding agencies, for example through thematic calls which are part of broader initiatives involving community workshops and "roadmapping exercises."
- The design of review processes and (agency) program management activities for some new center programs are increasingly focused on assessing the quality of "added value" collaboration and impact. Some of those interviewed pointed to (1) the value of pre-proposal planning in delivering more substantial collaborative research proposals, which could be scrutinized in more detail; (2) the potential for supplementary grants to incentivize collaborative behavior and impact; (3) the opportunities to use midterm reviews to ensure appropriate levels of collaboration (and not just count conventional research outputs).
- Student education and training activities within some international centers are putting increasing effort into giving students greater insight into real-world industrial environments and the variety of future career options. Several of these activities, such as research experiences of undergraduates and international research experiences for students, are well known within the U.S. ERC system.
- Facilitating the movement of people between universities and industry is considered an important and valuable function of center programs. Examples identified include: industrial "Professors of Practice," university-"embedded" industry researchers (or even embedded laboratories), and student placements in industry.
- Many international center programs may have lighter annual reporting requirements relative to the ERC program. Although there is significant variation in practice from program to program in terms of reporting on progress, a number of international center directors interviewed as part of this study quickly volunteered

that their annual reporting requirements and midterm reviews are not too onerous. It was also suggested by some of those interviewed that management information tools and information technology systems were reducing the burden of annual reporting, making it easier to collect and collate journal articles, conference papers, patents, etc.; and gather information about outreach and impact activities, etc.

- Some international center programs highlight the importance of performance metrics that are tailored to the "impact logic" of the center being evaluated. For example, generating patents is not an objective for some centers because the participating partner/sectors do not have this as part of their business logic. Some international programs give funded centers the freedom to track and report additional novel metrics that are not specified in official reporting forms, but identified by the centers themselves.
- Most of the new (or next generation) center programs explored in this study have longer center lifetimes. Although many international center programs have traditionally been funded for similar lifetimes to NSF ERCs—that is, 5 years with the potential for one further 5-year funding period—several programs have recently extended center lifetimes. A number of those interviewed in the initial scoping phase of this study highlighted the importance of longer center lifetimes for "challenge-led" research, where multidisciplinary teams may take longer to learn how to work together; and where new "tools" and resources to address the challenge have to be developed as part of the center endeavor.

# E

# Center Descriptions

## THE JOINT BIOENERGY INSTITUTE

The Joint Bioenergy Institute (JBEI; https://www.jbei.org/) at the University of California, Berkeley (UC Berkeley), is a partnership led by four national laboratories (Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories) and three academic research partners (UC Berkeley, UC Davis, and the Carnegie Institution for Science). They receive $25 million a year from the Department of Energy (DOE) as one of three DOE bioenergy research centers. They were founded in 2007 and subsequently renewed in 2012. The main leadership includes Jay Keasling (chief executive officer), Nick Everson (chief operating officer), and Blake Simmons (chief scientific and technology officer).

JBEI's mission is to provide the scientific basis for converting lignocellulosic biomass into renewable, drop-in, liquid transportation fuels, as well as the production of renewable chemicals that enable a thriving U.S. bioeconomy. JBEI is focused on creating a future where cellulosic biofuels can provide transformative advantages for the United States. This mission is supported by a selection of core values that include advancing basic science for public benefit, reducing the nation's dependence on foreign oil, reducing organic waste by transforming nonedible biomass—such as corn stover and wheat straw—into biofuels, and keeping the United States at the vanguard of scientific discovery by providing educational experiences for students and teachers and developing future generations of scientists. Their research areas span basic research in cell wall structure and functions, engineering of microbes for the production of advanced ("drop-in") biofuels and renewable chemicals, ionic liquid deconstruction of lignocellulose into targeted intermediates, and developing and engineering an industrially relevant conversion technology for scalable and affordable biofuel production—this puts them between technology readiness levels (TRLs) 1-5, with a heavy emphasis on technology feasibility and development, with targeted activities in scale-up.

Their evidence of impact lies in the vast amounts of research and technology that is available for collaboration and licensing—from biomass to feedstocks, deconstruction, fuel synthesis, and technologies and software. Over the span of their lifetime they have 608 publications, with more than 50 percent cross-divisional and more than 25 percent involving external collaborators. They also have more than 18,000 total citations, averaging around 27 citations per paper. Lastly, their efforts have launched 5 startups: Afingen, Evodia, Illium Technologies, Lygos, and TeselaGen Biotechnology. Their educational impact is also palpable, with 50 undergraduates trained every year in addition to summer programs for high school students. They provide biofuel educational materials for K-16 and routinely host educational visits that include tours, hands-on science, seminars, and career exploration activities.

JBEI has an Industry Advisory Committee that consists of Agilent Technologies, Amyris, Boeing, BP, Ceres, DuPont, FuturaGene, General Motors, Genomatica, Monsanto, Novozymes, Pacific Ethanol, POET, Proionic, and TOTAL. These companies work together with the research staff to push technology into more integrated systems, as well as advising the institute on which scientific and technical challenges JBEI is best suited to tackle (too risky or long term for companies to handle).

Some of the unique competitive advantages of JBEI include them housing three scientific divisions and one technology division in one location for better collaboration and integration, a multi-institutional partnership that combines a scientific, operational, and proactive approach to industry engagement and market transformation and administrative expertise, and its location in the Bay Area as an academic and biotech innovation center.

## THE JOINT CENTER FOR ARTIFICIAL PHOTOSYNTHESIS

The Joint Center for Artificial Photosynthesis (JCAP; http://www.solarfuelshub.org/) is an Energy Innovation Hub funded by DOE, with $75 million over 5 years. It is led by a team from the California Institute of Technology and collaborates extensively with its lead partner, Lawrence Berkeley National Laboratory. They are also partnered with several University of California campuses, including UC Irvine and UC San Diego, as well as the SLAC National Accelerator Laboratory. They were founded in 2010 and are currently the largest research program dedicated to the advancement of solar-fuels generation science and technology. Their leadership includes Director Harry A. Atwater, Deputy Director for Strategy and Project Management Xenia Amashukeli, and Deputy Director for Science and Research Integration Frances A. Houle.

JCAP's mission is to create the scientific foundation for a scalable technology that converts $CO_2$ into renewable transportation fuels, under mild conditions, with only sunlight to provide energy. JCAP is focused on four important thrusts of their renewable transportation mission: electrocatalysis; photocatalysis and light capture; materials integration; and test bed, prototyping, and benchmarking. The concentrations span from understanding the effect of molecular structure and surface composition on photocatalytic activity to understanding how ion transport through components affects the efficiency of integrated devices. These thrusts are representative of the TRL spectrum 1-4, with emphasis on applied research for engineering integrated devices.

The evidence of JCAP's impact lies in the accomplishments and capabilities that it has achieved over the lifetime of the center. This includes reduction of $CO_2$ and CO using bifunctional alloys, new electrocatalysts with benchmarked performance, and fully integrated and efficient prototypes for unassisted water splitting. Over the span of the center's lifetime, it has more than 250 publications, more than 40 intellectual property disclosures, and over 30 provisional patent applications. It has tours available for grades 10 and up, granting high school students a glimpse into cutting-edge work in solar fuels research.

JCAP has a Strategic Advisory Board and a Scientific Advisory Board that includes members from industry and academia.

Some of the unique competitive advantages of JCAP include streamlined access to DOE light sources and high-performance computational facilities; ultrahigh throughput experimentation capabilities; and suites of unique in situ instrumentation dedicated to research on solar fuels. JCAP also combines theory and experiment in a synergistic program to enable development of new catalysts and materials for solar fuels production with an emphasis on the reduction of $CO_2$ by heterogeneous catalysts.

## CLEMSON UNIVERSITY INTERNATIONAL CENTER FOR AUTOMOTIVE RESEARCH

The Clemson University International Center for Automotive Research (CU-ICAR; http://www.cuicar.com) is an innovation campus that focuses on research, education, and economic development related to the automotive industry. Founded in 2007, CU-ICAR is the culmination of a $250 million investment from private, federal, state, and local funds. The first of five technology neighborhoods have been completed on its 250-acre campus. Fred Cartwright is executive director for the CU-ICAR campus, while Zoran Filipi is the chair of the Department of Automotive Engineering.

CU-ICAR's missions include being a high seminary of learning in the field of automotive engineering;

leading translational research with an emphasis on industry relevance; contributing to high-value job creation in South Carolina; and leading global thinking on the sustainable development of the automotive sector. CU-ICAR is focused on seven strategic automotive research areas that are crucial to the advancement of the field: advanced powertrains, vehicular electronics, manufacturing and materials, vehicle-to-vehicle infrastructure, vehicle performance, human factors, and systems integration. It has accumulated approximately $23 million in sponsored research for its TRL spectrum of 4-6.

Their evidence of impact lies in the jobs and investments that CU-ICAR's efforts have brought—from the 789 on-campus jobs, to the $250 million that multiple organizations have invested, to the many attributed projects surrounding the CU-ICAR campus, the center has brought in significant development and aggregated good talent. Its educational impact is unique, with the nation's only graduate Department of Automotive Engineering, enrolling approximately 200 master's and Ph.D. students. CU-ICAR's Deep Orange program, an established framework in the Department of Automotive Engineering, is innovative in its intense collaboration with industry partners, with a unique educational experience for students as they experience industry's product development process and an emphasis on the link between engineering and design. It provides a hands-on and industrial perspective on research, and has been a crucial component of CU-ICAR's success story. CU-ICAR currently has a 95 percent gainful employment rate into the automotive industry, with students representing 18 countries, and 368 total M.S. and Ph.D. degrees awarded (332 and 36, respectively). The Automotive Engineering program has also accumulated approximately $23 million in its relatively short existence and is well positioned for revolution currently under way toward sustainable mobility and advanced manufacturing. Additionally, partnered with Greenville Technical College in the recently announced 100,000 square foot Center for Manufacturing Innovation, CU-ICAR and Clemson University have embarked on new models for education and research, all under one roof.

CU-ICAR has more than 130 industry partners, all fulfilling unique roles in the initiative. Its on-campus partners include BMW, Michelin, Koyo JTEKT, Sage Automotive Interiors, among others—these partners work closely with CU-ICAR faculty and students to foster innovation between industry and academia. Industry provides support with machinery and equipment, student fellowships and internships, as well as challenging projects in research. CU-ICAR also works closely with industry on the development of new curricula, providing adjunct professorships, and the formation of long-term strategic plans for the campus. Working with industry, CU-ICAR hosts many conferences throughout the year, utilizing multiple facilities designed for this purpose.

One of the distinct advantages of CU-ICAR includes its intimate relationship with industry, which enables a sustainable model for academic relevance and economic growth. The campus location, in the heart of the automotive cluster, in one of the fastest growing economies in the United States, makes CU-ICAR an attractive magnet for investment and talent. Campus design (currently six buildings in Technology Neighborhood I), with approximately 1,000 people, is such that creative "collisions" are frequent and encouraged. Further, with emphasis on the three pillars of research, education, and economic development, CU-ICAR is set apart from other more classic research campuses. There is a constant flow of new companies interested in CU-ICAR, Greenville, South Carolina, the state of South Carolina, and the southeastern United States. With the advent of many new technologies and business models, CU-ICAR is best positioned to lead academia and industry into the era of mobility.

## AMERICA MAKES

America Makes is the National Additive Manufacturing Innovation Institute (http://www.americamakes.us), an institute that is part of the National Network for Manufacturing Innovation Institutes (NNMI), also known as *Manufacturing USA*. It is a public-private partnership that has substantial investment from all sectors—private, federal, and academic. They currently have a portfolio of more than $96 million in public and private funds invested in advancing next-generation additive manufacturing in the United States. It was formally established in 2012 and is based in Youngstown, Ohio, and primarily driven by the National Center for Defense Manufacturing and Machining (NCDMM). The main leadership includes Ralph Resnick (founding director), Ed Morris (director), and Rob Gorham (operations director).

NNMI is geared toward bringing together industry, academia, and federal partners to increase U.S. manufacturing competitiveness and promote a robust and sustainable national manufacturing research and development infrastructure. America Makes is focused on increasing the nation's global manufacturing competitiveness through the following series of goals:

- Fostering a highly collaborative infrastructure for the open exchange of additive manufacturing information and research;
- Facilitating the development, evaluation, and deployment of efficient and flexible additive manufacturing technologies;
- Engaging with educational institutions and companies to supply education and training in additive manufacturing technologies to create an adaptive, leading workforce;
- Serving as a national institute with regional and national impact on additive manufacturing capabilities; and
- Linking and integrating U.S. companies with existing public, private, or not-for-profit industrial and economic development resources, and business incubators, with an emphasis on assisting small- and medium-sized enterprises and early-stage companies (start-ups).

This mission is supported by the collaboration of organizations that are cooperating to pool resources and connections to develop the standards, tools, education, and research required to accelerate the U.S. manufacturing industry into a dominant, global economic force. Its main focus area is the gap in manufacturing innovation that exists between TRL 4 and 7—this is the area where basic and feasibility research funded by the government and academia fails to cross into the systems integration and development region that is captained primarily by industry.

The evidence of impact for America Makes lies in their robust additive manufacturing technology roadmaps and how esteemed it is in the manufacturing industry, as well as 175 members that are a part of America Makes. These members include 109 industry partners, 62 of which are small businesses, 39 academic partners, 14 government partners, 10 nonprofit organizations, and 3 manufacturing extension partnerships. It also provides partner collaborations in projects that suit the capabilities and needs of its members. Its educational impact is leveraged through its combined knowledge and the intimate setting where industry can properly convey what they need to their academic partners, such that students can develop the best mindsets, talents, and experience at a young age.

## DIGITAL MANUFACTURING AND DESIGN INNOVATION INSTITUTE

The Digital Manufacturing and Design Innovation Institute (DMDII; http://www.dmdii.uilabs.org) is a public-private partnership managed by UI LABS. The mission of DMDII is to accelerate new technologies into the marketplace that enable manufacturing organizations across the United States to deploy digital manufacturing and design technologies so they can become more efficient and cost competitive. DMDII is a member-driven organization with companies, academic institutions, nonprofits, and governments that was launched in February of 2014 and has received $320 million over 5 years.

The institute's executive team includes Thomas McDermott (interim executive director) and Brench Boden (chief technology officer) and is supported by 5 directors and 12 staff members.

The technical focus of DMDII is digital manufacturing. The main idea in digital manufacturing is the digital thread, which is the seamless flow of information across the life cycle of a physical product. This life cycle includes all of the steps required to conceptualize, design, prototype, fabricate, assemble, and deliver a product to an end user. The institute is driving a portfolio of about 50 innovation projects, which are scoped to de-risk and demonstrate digital manufacturing technologies along the digital thread. The projects also show how these information flows can make products more quickly, more efficiently, and that better serve the end customer.

DMDII has a unique innovation system where projects are selected and managed against two criteria. First, each project within the institute must solve a business problem that is relevant for a majority of the industry members of the institute. Second, each project must have an innovative technology solution to this problem that represents a significant advance over the state of the art. Each project is conducted by a team of participants representing both industry and academic members of the institute. Normally, the industry members help to focus the project activities on meaningful project outcomes, while the academic members bring knowledge and new technologies to the project. However, in many cases, the industry members also contribute knowledge and technology and also, in many cases, the academic members bring relevant experiences that help to focus the project.

## POWERAMERICA

PowerAmerica, the Next Generation Power Electronics Manufacturing Innovation Institute (https://www.poweramericainstitute.org/), is helping to advance the development and adoption of cutting edge wide bandgap (WBG) semiconductor technology. The institute will receive $70 million from DOE over 5 years, which will be matched by an equal contribution from North Carolina State University and its industry and academic partners. The institute started operations in January 2015 and is led by North Carolina State University in Raleigh. The leadership team includes Nick Justice (executive director), Victor Veliadis (chief technology officer), and Dan Stancil (principal investigator).

PowerAmerica's mission is to accelerate the adoption of advanced semiconductor components made with silicon carbide (SiC) and gallium nitride (GaN) in a wide range of products and systems. WBG technology can improve energy efficiency, reduce the size and weight, and provide significant operational advantages in important industries such as energy production, passenger vehicles, data centers, industrial motors, telecommunications, and many defense applications. The institute advances this cause by making strategic investments in manufacturing facilities for the scale-up and high-volume production of WBG semiconductor devices. The institute also partners with packaging companies, system integrators, end users, and other stakeholders throughout the supply chain to conduct projects that demonstrate the benefits of SiC and GaN, as well as improve semiconductor device performance. PowerAmerica also works with 10 university partners that are helping to build a U.S. manufacturing workforce that possesses the necessary skill sets to "push the envelope" on wide bandgap technology and applications, as well as design, manufacture, install, and repair related production facilities, products, and the systems they enable. Its work places them in the TRL 4-7 categories.

PowerAmerica's technology advancement efforts have ranged from technology roadmapping, to specific projects that bring companies and universities together, to scale-up of emerging power electronics technologies for factory production, to the creation of the country's first "open-foundry" SiC-based semiconductor fabrication facility. Driving down the cost of WBG devices so they are competitive with conventional silicon-based semiconductors is an important goal of the institute. Another important contribution to the WBG community is the development of a "Device and Module Bank." This resource helps to address the continual challenge faced by researchers and system developers, which is the chronic shortage of WBG devices for testing and integration. The PowerAmerica Device Bank has made the devices widely available to its members through a simple online process that ensures confidentiality of the supplier's information and appropriate restrictions on use of the devices. The Device Bank is helping to provide a vehicle to connect device manufacturers with their potential customers and thereby accelerate product development and commercialization.

PowerAmerica is supported by a wide range of industry and academic partners, ranging from Lockheed Martin, Wolfspeed, and X-FAB to Virginia Tech, Florida State, and Ohio State University. These partners work together with the research staff to push technology into more integrated systems, as well as advising the institute on which scientific and technical challenges PowerAmerica is best suited to tackle (ones that are too risky or long-term for companies to handle). The institute is growing in membership each year and continues to engage with companies throughout the value chain to help develop the manufacturing capability, create high tech jobs, and produce the energy savings that are the promise of WBG power electronic systems.

## THE WYSS INSTITUTE

The mission of the Wyss Institute for Biologically Inspired Engineering (http://www.wyss.harvard.edu ) at Harvard University is to discover the biological principles that nature uses to build living things, and to harness these insights to create new engineering innovations to advance human health and create a more sustainable world. The institute is organized as a 501(c)3 within Harvard University and works as an alliance among the schools of Harvard University and its affiliated hospitals, in addition to neighboring academic institutions in the Greater

Boston area, including the Massachusetts Institute of Technology (MIT), Boston University, and Tufts University as well as select international institutions.

The Wyss Institute was launched on January 1, 2009, with the single largest philanthropic gift in Harvard's history at the time of $125 million from Hansjörg Wyss along with significant additional contributions from Harvard University. This gift was doubled in 2012. Additional funding is provided by government and industrial grants. The institute's executive team members including Donald E. Ingber, M.D., Ph.D. (founding director), Ayis Antoniou, Ph.D., M.B.A. (administrative director), and Mary Tolikas, Ph.D., M.B.A. (operations director). The institute currently has 18 core faculty and 15 associate faculty from Harvard and the institute's partner institutions who also hold academic positions at their home institutions. The institute organizes its research operations around the following eight major focus areas: adaptive materials technologies, living cellular devices, bioinspired robotics, biomimetic microsystems, immuno-materials, synthetic biology, molecular robotics, and 3D organ engineering.

Since its inception, the Wyss Institute has developed a unique model for innovation, collaboration, and technology translation that crosses institutional and disciplinary barriers. Institute faculty and staff engage in high-risk research that leads to transformative breakthroughs. The biological principles uncovered are harnessed to develop new engineering solutions in various sectors, including health care, energy, architecture, robotics, and manufacturing. These technologies are translated into commercial products and therapies through collaborations with clinical investigators, corporate alliances, and new start-ups that are led by a unique internal business development team that includes experienced entrepreneurs-in-residence. Also central to the institute's technology translation efforts is its Advanced Technology Team (ATT), which consists of expert technical staff with industrial experience in product development and team management who help build and lead integrated technology development teams focused on high-value applications. ATT members work closely with institute faculty and lead project development teams composed of students, fellows, and staff from multiple faculty laboratories that span across all of Harvard's schools and its collaborating institutions. These technical experts help to catalyze communications and interactions across the institute and to ensure that institute members remain at the leading edge of technology translation. In terms of TRL, the institute's technology maturity falls in the TRL 1-8 range.

During its brief history, and with only a relatively small number of faculty, the Wyss Institute has achieved a number of important milestones and successes, including more than 1,600 publications (with one article in *Science* or *Nature* every month on average) since the institute's inception in 2009; numerous major awards and recognition (e.g., National Academy elections) for faculty, staff, and technologies; submission of over 1,750 patents, including more than 70 awarded patents; and 17 new companies and 26 licensing deals.

Additional unique aspects of the Wyss Institute include the formation of multi-institutional consortium governed by a single agreement among all its collaborating institutions that governs ownership, management, and revenue sharing of intellectual property and lowers the barriers to the free flow of people and information. This enables the institute to bring together core and associate faculty and their staff from these institutions, so that they can work side-by-side at institute sites. The constant flow of core, associate, and collaborating faculty and staff between the institute and Harvard's various schools and partner institutions helps to maintain a two-way exchange of information, people, and resources, and to consolidate efforts in biologically inspired engineering across the entire region and beyond. This combination of novel attributes and organizational approaches allows the institute to harness the creative freedom of academia to generate a technology pipeline; enable its staff with product development experience to prototype, mature and de-risk these technologies; and leverage its internal business development team, intellectual property experts, and entrepreneurs-in-residence to drive their commercialization.

## INSTITUTE FOR SOLDIER NANOTECHNOLOGIES

The Institute for Soldier Nanotechnologies (ISN; https://www.isnweb.mit.edu), founded in 2002, is a team of engineers and scientists from MIT, the U.S. Army, and industry that works to discover and field technologies that dramatically advance soldier protection and survivability capabilities. The ultimate goal is to help the Army create integrated systems of nanotechnologies that combine high-tech protection and survivability capabilities with low weight, increased comfort, improved performance, and better compatibility with the end user. Army funding for ISN basic 6.1 research is approximately $135 million over 15 years, dispensed through renewable 5-year contracts administered by the U.S. Army Research Office (ARO). The main leadership includes John Joannopoulos (director), Raul Radovitzky (associate director), and William Peters (executive director).

The ISN's mission is to improve the protection and survivability of the warfighter by exploring the potential power of nanotechnology to enable advances in capabilities by working at and extending the frontiers of nanotechnology. Team-based innovation is a hallmark of ISN's intellectual course, with new ideas and collaborations emerging frequently. Research is primarily fundamental (6.1, $6 million per year), but there are 6.2 ($2 million per year) funds for transitioning basic MIT discoveries by Army and industry partners. The current research portfolio includes the following three strategic areas: (1) lightweight, multifunctional nanostructured materials; (2) soldier medicine—prevention, diagnostics, and far-forward care; and (3) blast and ballistic threats, materials damage, injury mechanisms, and lightweight protection. The research portfolio lies between TRL 1-3, with concept discovery, feasibility, and development. The Army and industry partners use the 6.2 funds to target selected activities for prototyping and scale-up for delivery to the warfighter.

The ISN has many industry partners—for example, FLIR Systems, JEOL USA, Lockheed Martin, Nano-C, Raytheon, Total American Services, Triton Systems, VF Corporation, Xtalic, and the Center for Integration of Medicine and Innovative Technology. Industry and Army partners work together with ISN researchers to push technology from basic research into real products and help with transition scaling advising the ISN on which scientific and technical challenges are priorities (too risky and/or long-term for companies to handle, or well-aligned with Army science and technology objectives). The ISN places a strong emphasis on basic research. However, the transitioning of promising outcomes of that research is also a crucial component of the mission. To this end, the ISN works with the Army, industry partners, startups and other companies, and with the MIT Technology Licensing Office to help assure that promising ISN innovations leave the laboratory and make it into the hands of soldiers and first responders as rapidly and efficiently as possible. The Army Research Laboratory's Army Research Office Technology Transfer Officer (TTO) provides an onsite full-time specialist for transitions. It is the TTO's charge to help maximize the effectiveness and efficiency with which ISN technologies progress from the laboratory bench to more advanced stages of development.

One of the key unique competitive advantages of the ISN is its intimate relationship with the Army. Many high-ranking officials and officers visit MIT/ISN to be briefed on the latest research, and also offer key insight into the current issues the warfighter faces both on and off the field, allowing ISN to identify and redirect resources to critical areas that require the most attention. The MIT/ISN faculty also visits Army installations, such as Fort Bragg, West Point, and Special Operations Command, where direct interactions with warfighters and their equipment are inspirational. Finally, the 6.2 funding is only available to Army researchers and industry researchers (MIT/ISN industrial partners), and those are only for transitioning the basic discoveries from the laboratory to the field. Subcontracts back to MIT can be made to have the transition team include the Army, industry partners, and MIT faculty.

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# Acronyms and Definitions

| | |
|---|---|
| AI | artificial intelligence |
| ARPA-E | Advanced Research Projects Agency-Energy, a U.S. DOE program |
| CERC | Convergent Engineering Research Center |
| CRISPR | clustered regularly interspaced short palindromic repeats |
| DARPA | Defense Advanced Research Projects Agency |
| DOE | U.S. Department of Energy |
| ERC | Engineering Research Center |
| EU | European Union |
| GCSP | Grand Challenges Scholars Program |
| GRA | Georgia Research Alliance |
| I-ARPA | Intelligence Advanced Research Projects Activity |
| I-CORPS | Innovation-Corps, a U.S. National Science Foundation program |
| IP | intellectual property |
| IT | information technology |
| NAE | National Academy of Engineering |
| NGA | National Governors Association |
| NRC | National Research Council |
| NSF | National Science Foundation |
| PI | principal investigator |
| R&D | research and development |
| RD&I | research, development, and innovation |

RFP request for proposal

TRL technology readiness level

**Convergence**
An approach to problem solving that integrates knowledge, tools, and ways of thinking from life and health sciences, physical, mathematical, and computational sciences, social sciences, and engineering disciplines.

**Convergent engineering**
A deeply collaborative, team-based engineering approach for defining and solving important and complex societal problems. All necessary technical and social science disciplines, skills, and capabilities are brought together to address a specific research opportunity. It is distinguished by resolutely using best team-research and value-creation practices to rapidly and efficiently integrate the unique contributions of individual members and develop valuable and innovative solutions for society.

**Deep collaboration**
Intense intellectual interaction of research team members to continuously refine common research goals and strategies.

**Interdisciplinary**
Involves the integration of perspectives, concepts, theories, and methods from two or more disciplines or fields to address the problem.

**Multidisciplinary**
The sequential or additive combination of ideas or methods drawn from two or more disciplines or fields to address the focal problem.

**Team research**
Research conducted by more than one individual in an interdependent fashion, including research conducted by small teams and larger groups. Includes all traditional natural and social science fields, as well as engineering.

**Transdisciplinary**
Entails not only the integration of discipline-specific approaches, but also the extension of these approaches to generate fundamentally new conceptual frameworks, hypotheses, theories, models, and methodological applications that transcend their disciplinary origins.

**Value creation**
The learning and creating activity whose goal is the development of new, sustainable value for society, whether as notable new research results or as marketplace innovations.

**Value proposition**
A review and analysis of the needs, competition, and value (i.e., benefits per costs) that an organization can deliver to its prospective customers and other stakeholders within and outside the organization.