Industries of the Future Institutes: A New Model for American Science and Technology Leadership

A Report to the President of the United States of America

The President's Council of Advisors on
Science and Technology

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Created by Executive Order in 2019, PCAST advises the President on matters involving science, technology, education, and innovation policy. The Council also provides the President with scientific and technical information that is needed to inform public policy relating to the American economy, the American worker, national and homeland security, and other topics. Members include distinguished individuals from sectors outside of the Federal Government having diverse perspectives and expertise in science, technology, education, and innovation.

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About this Document

This document follows up on a recommendation from PCAST's report, released June 30, 2020, involving the formation of a new type of multi-sector research and development organization: Industries of the Future Institutes (IotFIs). This document provides a framework to inform the design of IotFIs and thus should be used as preliminary guidance by funders and as a starting point for discussion among those considering participation. The features described here are not intended to be a comprehensive list, nor is it necessary that each IotFI have every feature detailed here.

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Abbreviations and Acronyms

AI	Artificial intelligence
DARPA	Defense Advanced Research Projects Agency
DOE	Department of Energy
IotF	Industries of the future
IotFI	Industry of the Future Institute
IP	Intellectual property
LLC	Limited Liability Corporation
NIH	National Institutes of Health
NSB	National Science Board
NSF	National Science Foundation
OSTP	Office of Science and Technology Policy
PCAST	President's Council of Advisors on Science and Technology
QIS	Quantum information science
RFI	Request for Information
R&D	Research and development
STEM	Science, technology, engineering, and mathematics
S&T	Science and technology
U.S.	United States

Executive Summary

America's global leadership in science and technology (S&T) reflects a pioneering spirit of forging headlong into the unknown, persevering in the face of the unexpected, and bringing to reality the unimaginable. Yet America's leadership position is being challenged as never before by rising international competition, particularly in artificial intelligence, quantum information science, advanced manufacturing, biotechnology, and advanced communications networks—collectively known as Industries of the Future (IotF). America also faces challenges of its own making, especially via certain superfluous administrative and regulatory barriers that stifle intellectual risk-taking, innovation, and the ability for the four sectors of its research ecosystem (industry, academia, non-profit organizations, and government) to interact productively.

The President's Council of Advisors on Science and Technology (PCAST) views these challenges as opportunities, and in that spirit **PCAST proposes a revolutionary new paradigm for multi-sector collaboration—Industries of the Future Institutes (IotFIs)—to address some of the greatest societal challenges of our time and to ensure American S&T leadership for decades to come**. By driving research and development (R&D) at the intersection of two or more IotF areas, these Institutes not only will advance knowledge in the individual IotF topics, but they also will spur new research questions and domains of inquiry at their confluence.

By engaging multiple disciplines and each sector of the U.S. R&D ecosystem—all within the same agile organizational framework—IotFIs will span the spectrum from discovery research to the development of new products and services at scale. Flexible intellectual property terms will incentivize participation of all sectors, and reduced administrative and regulatory burdens will optimize researcher time for creativity and productivity while maintaining appropriate safety, transparency, integrity, and accountability. IotFIs also will serve as a proving ground for new, creative approaches to organizational structure and function; broadening participation; workforce development; science, technology, engineering, and math education; and methods for engaging all sectors of the American research ecosystem. Ultimately, the fruits of IotFIs will sustain American global leadership in S&T, improve quality of life, and help ensure national and economic security for the future.

This document provides a framework to help inform the design of IotFIs. It is intended to serve as preliminary guidance for consideration by funders and as a starting point for discussion among those contemplating participation.

Introduction

Breakthroughs in advanced manufacturing, artificial intelligence (AI), quantum information science (QIS), biotechnology, and advanced communications networks—collectively known as Industries of the Future (IotF)—hold the potential to address some of society's greatest challenges and thereby improve quality of life for all as well as help to ensure national and economic security. They also will advance knowledge, create new industries and fields of study, and aid in developing the workforce needed for the United States to thrive in an increasingly competitive global science and technology (S&T) environment.

Indeed, that environment has changed markedly over the past two decades. Other nations are increasing their investments and leveraging resources across sectors[1,2,3] as a force multiplier, thus accelerating the rate of discovery and bringing new products to market. In order to continue advancing its position as a global leader in research and development (R&D), the United States must pioneer new approaches to S&T R&D, particularly in key areas of national interest.

Purpose of this Document

The President's Council of Advisors on Science and Technology (PCAST) **proposes a revolutionary new paradigm for multi-sector collaboration—Industries of the Future Institutes (IotFIs)—to address some of the greatest societal challenges of our time and ensure American S&T leadership for decades to come**. By integrating research efforts in multiple IotF areas as well as all sectors of the U.S. R&D ecosystem—academia, industry, government, and non-profit organizations (e.g., non-profit research foundations)—IotFIs will span the research spectrum from discovery to the development of new products and services at scale, all within the same organizational framework.

IotFIs will be unique not only in their research focus and their emphasis on multi-sector collaboration but also in their approach and support for scientific creativity; collaboration with all levels of science, technology, engineering, and math (STEM) education; community outreach; and reduced administrative burden, while flexible intellectual property (IP) terms will incentivize participation of all R&D sectors. IotFIs ultimately will serve as a proving ground for new, creative approaches to organizational structure and function, broadening participation, workforce development, and STEM education.

Achieving the IotFI goals of a multi-sector, multi-generational R&D organization with ample time and resources for research creativity will require overcoming some long-standing administrative and regulatory hurdles. In this document, we provide a framework to help inform the design of IotFIs. This document should be used as preliminary guidance for consideration by funders and as a starting point for those considering participation. Each IotFI can be crafted according to—and ultimately assessed on—the structure and attributes that best suit its research focus and needs more broadly. The features described here are not intended to be a comprehensive list, nor is it necessary that each IotFI have every feature detailed here.

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1 Sutter, Karen M. 2020. *"Made in China 2025" Industrial Policies: Issues for Congress.* CRS Report No. IF10964. Washington, DC: Congressional Research Service. https://crsreports.congress.gov/product/pdf/IF/IF10964.

2 Cabinet Office, Government of Japan. n.d. "Science, Technology and Innovation." Accessed December 16, 2020. https://www8.cao.go.jp/cstp/english/index.html.

3 European Commission. n.d. "Horizon 2020: Information and Communication Technologies." Accessed December 16, 2020. https://ec.europa.eu/programmes/horizon2020/en/h2020-section/information-and-communication-technologies.

The Current U.S. S&T Landscape

Businesses, academic institutions, government, and non-profit organizations play key roles in the U.S. S&T enterprise, with annual R&D expenditures totaling $548 billion in 2017.[4] Industry conducted more than 70 percent of all U.S. R&D in 2017, the majority of which was directed towards later stage R&D (i.e., applied research and experimental development).[5] The U.S. Federal Government is the largest funder of basic research (hereafter referred to as "foundational research") in the United States,[6] including intramural research conducted by Federal employees, extramural research funded through competitive grants to academia and the private sector, and other contracts and collaborations.

The outcomes of federally funded research—both new discoveries and human resources—are critical for future innovation. In particular, Federal investment contributes significantly to the training of the future STEM workforce by supporting aspiring and early career researchers and advancing understanding and capabilities in STEM education and workforce development. Academia is critical for educating future scientists, engineers, and technologists, and for serving as a home to inquiry across the spectrum of innovation—from foundational research to applied research and translation of discovery to practice. Non-profit organizations also play an important role in the U.S. S&T landscape by providing expertise, stakeholder and end user perspectives, and flexible research funding.

This strong foundation has helped the United States become a world leader in S&T. **In order to maintain a competitive edge and continue leading the global R&D enterprise, the United States must expand its portfolio to include *new administrative models for R&D*.**

Key Challenges and Opportunities

Multi-sector Engagement

Although the United States is a global leader in S&T research, the U.S. R&D ecosystem is not without challenges that can create gaps in continuity across the innovation continuum. For example, although Federal Government research laboratories lead the way on many scientific discoveries, their missions do not always include driving their research to at-scale economic impact. Meanwhile, establishing partnerships between industry and National Laboratories—a key vehicle for technology transfer—can be a lengthy process, which can delay results and disincentivize collaboration between these two sectors.[7]

Academic institutions continue to be at the forefront of research, but their efforts can be challenged by the high cost and steep learning curve for translating discoveries to at-scale impact, especially via partnerships with private companies.[8,9] At the same time, industry can be an attractive employer for

[4] National Center for Science and Engineering Statistics. 2019. *National Patterns of R&D Resources: 2017–18 Data Update*. NSF 20-307. Alexandria, VA: National Science Foundation. https://ncses.nsf.gov/pubs/nsf20307.

[5] Ibid.

[6] Ibid.

[7] National Institute of Standards and Technology (NIST). 2019. *Return on Investment Initiative for Unleashing American Innovation*. NIST Special Publication 1234. Gaithersburg, MD: NIST. https://doi.org/10.6028/NIST.SP.1234.

[8] Ibid.

[9] Wang, M., S. L. Pfleeger, D. M. Adamson, G. Bloom, W. Butz, D. Fossum, M. Gross, A. Kofner, H. Rippen, T. Kelly, and C. T. Kelley Jr. 2003. *Tech Transfer of Federally Funded R&D: Perspectives from a Forum*. Santa Monica, CA: RAND Corporation. https://www.rand.org/pubs/conf_proceedings/CF187.html.

many scientists owing to work environments that tend to be agile and fast-paced. Additionally, industry sometimes has the potential for making available significant resources without the need for researchers to spend time engaging in administrative tasks that often accompany academic and government-funded research. However, the majority of industry's focus is on later stage research. Combined, all of these factors indicate an opportunity to realize innovation potential with greater efficiency not only by enhancing connections across all sectors of the S&T enterprise, but doing so in ways that *overcome longstanding administrative barriers*.

Education, Diversity, and Inclusion

The manner in which the United States prepares individuals to become the future STEM workforce has contributed significantly to the United States becoming a global leader in R&D. Going forward, an education and career in STEM may become less enticing, however, due to the combination of the high cost of higher education, decreasing state-level funding for public universities,[10] student debt, and low median family incomes. In 2018, the median incomes of Black, Hispanic, and White families were $41,511, $51,404, and $67,937, respectively.[11] These factors can severely challenge an individual's ability to afford college tuition and fees, which averaged $9,212 at public 4-year institutions and $3,313 at public 2-year institutions (in-state rates) for the 2018–2019 academic year.[12] For those who graduated from public 4-year institutions in 2018, 57 percent had student debt, with the debt averaging $27,200.[13] Community colleges are key educators and trainers of the STEM and skilled technical workforce while historically also being major entry points to higher education for the Nation's underrepresented youth and low-income and first-generation college students.[14,15,16] However, only approximately one-third of community college students graduate within 3 years, due in part to financial barriers.[17]

[10] Mitchell, Michael, Michael Leachman, Kathleen Masterson. 2017. *A Lost Decade in Higher Education Funding*. Washington, DC: Center on Budget and Policy Priorities. https://www.cbpp.org/research/state-budget-and-tax/a-lost-decade-in-higher-education-funding.

[11] Guzman, Gloria. 2019. "U.S. Median Household Income Up in 2018 from 2017." United States Census Bureau. September 26, 2019. https://www.census.gov/library/stories/2019/09/us-median-household-income-up-in-2018-from-2017.html.

[12] National Center for Education Statistics. n.d. "Table 330.10. Average Undergraduate Tuition and Fees and Room and Board Rates Charged for Full-Time Students in Degree-Granting Postsecondary Institutions, by Level and Control of Institution: Selected Years, 1963-64 through 2018-19." Accessed December 28, 2020. https://nces.ed.gov/programs/digest/d19/tables/dt19_330.10.asp.

[13] Baum, Sandy, Jennifer Ma, Matea Pender, and CJ Libassi. 2019. *Trends in Student Aid 2019*. 01469-066. New York: College Board. https://research.collegeboard.org/pdf/trends-student-aid-2019-full-report.pdf.

[14] National Science Board. 2019. *The Skilled Technical Workforce: Crafting America's Science and Engineering Enterprise*. NSB-2019-23. Alexandria, VA: National Science Board.

[15] National Academy of Engineering and National Research Council. 2012. *Community Colleges in the Evolving STEM Education Landscape: Summary of a Summit*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13399.

[16] Bragg, Debra, Brian Durham. 2012. "Perspectives on Access and Equity in the Era of (Community) College Completion" *Community College Review*. https://doi.org/10.1177/0091552112444724.

[17] Goldrick-Rab, Sarah. 2016. *Paying the Price: College Costs, Financial Aid, and the Betrayal of the American Dream*. University of Chicago Press. 219-220.

After 5 or 6 years of graduate study, those pursuing a post-doctoral fellowship in academia are likely to receive an annual stipend of less than $60,000 (as of 2016).[18] This is in contrast to the 2 years of full-time study required for a Master's in Business Administration degree, which yielded an average starting salary plus annual bonus totaling more than $105,000 in 2019.[19] These financial differences likely contributed to the fact that in 2018, fewer than 43,000 doctoral degrees in science and engineering fields were awarded in the United States,[20] while more than 192,000 masters degrees were awarded in business-related fields.[21] Unless changes are made to higher education in general and STEM education in particular, these financial barriers are likely to limit the Nation's ability to develop its STEM workforce and increase STEM participation, particularly among underserved and underrepresented groups.

It is vital that the United States draw individuals from diverse populations into STEM fields to maintain its global competitive edge and reach its full innovation potential. This need takes on greater importance since young working-age individuals are projected to compose a decreasing share of the U.S. population over the coming decades.[22] Fortunately, many opportunities exist to strengthen the STEM education system to broaden inclusion and better prepare future scientists for a variety of careers, which would strengthen the U.S. S&T enterprise for the long-term.[23,24,25,26]

Depending on the field within STEM education, wide variation exists in the participation of women, with 55 percent of biological sciences bachelor's degrees awarded to women in 2016, while only 19 percent of computer sciences bachelor's degrees were awarded to women that same year.[27] Meanwhile, Black and Latina/o students are 19 percent and 13 percent more likely to leave a STEM major and switch to a

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[18] Athanasiadou, Rodoniki, Adriana Bankston, McKenzie Carlisle, Carrie Niziolek, and Gary McDowell. 2017. "Assessing the Landscape of U.S. Postdoctoral Salaries." *Studies in Graduate and Postdoctoral Education* 9 (2): 213-242. https://doi.org/10.1108/SGPE-D-17-00048.

[19] Kowarski, Ilana. 2020. "Find MBAs that Lead to Employment, High Salaries" *U.S. News and World Report*. March 17, 2020. https://www.usnews.com/education/best-graduate-schools/top-business-schools/articles/mba-salary-jobs.

[20] National Center for Science and Engineering Statistics. 2019. *Survey of Earned Doctorates: U.S. Doctorate Awards*. NSF 20-301. Alexandria, VA: National Science Foundation. https://ncses.nsf.gov/pubs/nsf20301/report/u-s-doctorate-awards#overall-trends.

[21] National Center for Education Statistics. n.d. "Table 323.10. Master's Degrees Conferred by Postsecondary Institutions, by Field of Study: Selected Years, 1970-71 through 2017-18." Accessed December 16, 2020. https://nces.ed.gov/programs/digest/d19/tables/dt19_323.10.asp.

[22] Vespa, Jonathan, Lauren Medina, David Armstrong. 2020. *Demographic Turning Points for the United States: Population Projections for 2020 to 2060*. P25-1144. Washington, DC: United States Census Bureau. https://www.census.gov/content/dam/Census/library/publications/2020/demo/p25-1144.pdf.

[23] National Academies of Sciences, Engineering, and Medicine (NASEM). 2018. *Graduate STEM Education for the 21st Century*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25038.

[24] NASEM. 2016. *Barriers and Opportunities for 2-Year and 4-Year STEM Degrees: Systemic Change to Support Students' Diverse Pathways*. Washington, DC: The National Academies Press. https://doi.org/10.17226/21739.

[25] NASEM. 2017. *Undergraduate Research Experiences for STEM Students: Successes, Challenges, and Opportunities*. Washington, DC: The National Academies Press. https://doi.org/10.17226/24622.

[26] National Science Foundation. n.d. "Broadening Participation at NSF." Accessed December 16, 2020. https://www.nsf.gov/od/broadeningparticipation/bp.jsp.

[27] National Center for Science and Engineering Statistics. 2019. *Women, Minorities, and Persons with Disabilities in Science and Engineering: 2019*. NSF 19-304. Alexandria, VA: National Science Foundation. https://ncses.nsf.gov/pubs/nsf19304/digest/about-this-report.

non-STEM field, respectively, than White students.[28] Offering mentorship opportunities and reducing financial barriers are two clear paths toward reducing disparities in STEM education, making associated fields more attractive as a career while also strengthening the STEM workforce.[29] Undergraduate students from traditionally underrepresented and underserved groups, including women, are more likely to have positive experiences and remain in STEM fields when they have mentors with similar gender, racial, or cultural identities.[30,31] Research also has shown that mentorship is a key factor in retaining graduate students in STEM fields.[32]

The Importance of Foundational Research for Innovation

Foundational research expands the boundaries of human knowledge to reveal new frontiers and unanticipated discoveries that lay the groundwork for future innovations. Indeed, without foundational research into fundamental quantum theory and solid-state physics, there would be no transistor or integrated circuits that make modern computers possible, and the field of QIS would not exist.[33]

Dr. John L. Hall's curiosity-driven research in the 1960s explored whether the speed of light in a vacuum is a function of the direction in which the light travels.[34] To test this idea, he developed a new technique for stabilizing laser light, with which he later inadvertently discovered a way for the United States to detect underground nuclear weapons tests around the world.[35] His stabilized laser also turned out to become a core technology underlying the global positioning system (GPS),[36] upon which so much in modern society depends.[37]

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[28] Riegle-Crumb, Catherine, Barbara King, Yasmiyn Irizarry. 2019. "Does STEM Stand Out? Examining Racial/Ethnic Gaps in Persistence Across Postsecondary Fields." *Educational Researcher* 48 (3) (February): 133-44. https://doi.org/10.3102/0013189X19831006.

[29] NASEM. 2019. *The Science of Effective Mentorship in STEMM*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25568.

[30] Dennehy, Tara, Nilanjana Dasgupta. 2017. "Female Peer Mentors Early in College Increase Women's Positive Academic Experiences and Retention in Engineering." *Proceedings of the National Academy of Sciences* 114 (23) (Summer): 5964-5969. https://doi.org/10.1073/pnas.1613117114.

[31] Lisberg, Anneke, Brett Woods. 2018. "Mentorship, Mindset and Learning Strategies: An Integrative Approach to Increasing Underrepresented Minority Student Retention in a STEM Undergraduate Program." *Journal of STEM Education* 19(3) (Summer): 14-20. https://www.jstem.org/jstem/index.php/JSTEM/article/view/2280.

[32] NASEM. 2019. *The Science of Effective Mentorship in STEMM*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25568.

[33] Fermilab. 2014. "The Science of Matter, Space and Time." Last modified April 25, 2014. https://www.fnal.gov/pub/science/inquiring/matter/whysupport/index.html.

[34] Brillet, A., and J. L. Hall. 1979. "Improved Laser Test of the Isotropy of Space." *Physical Review Letters* 42 (9) (February): 549-552.

[35] Vali, Victor. 1969. "Measuring Earth Strains by Laser." *Scientific American* 221 (6) (December): 88-97. https://www.jstor.org/stable/24964394.

[36] Cundiff, Steven, Jun Ye, and John Hall. 2008. "Rulers of Light." *Scientific American* 298 (4) (April): 74-81. https://www.jstor.org/stable/26000561.

[37] Personal Communication from W. Carl Lineberger, National Science Board liaison to PCAST.

The world wide web was originally created to support high energy physics research,[38] and two common medical diagnostic tools—X-rays and magnetic resonance imaging—trace their origins to foundational physics research.[39,40]

More contemporarily, the COVID-19 pandemic demonstrates how foundational research, conducted over the past several decades (e.g., in rapid DNA sequencing, molecular biology, high-speed networking and high-performance computing, and an understanding of the immune system informed by research in HIV), has provided the basis for the rapid development of vaccines on time scales thought to be impossible. And Operation Warp Speed in the United States, which rapidly created and executed multi-sector partnerships for societal benefit, played a pivotal role in developing and supplying COVID-19 vaccines years faster than ever before.

A commonly held view is that the spectrum of research is linear, beginning with foundational research that progresses to applied research and ultimately into practice; however, this pathway typically is anything but linear and contains many points of reentry and iteration. Indeed, another vital aspect of research exists that is sometimes referred to as "reverse translation." This occurs when research begins with the identification of a practical problem that raises new questions, thus requiring a return to a foundational research framework to unravel them. The newly gained foundational understanding already is placed in the context of its ability to solve the original practical problem. This both accelerates the translation of those findings into real-world impact and generates new foundational knowledge that might not have otherwise been sought.[41]

Cancer drug development is a real-world example of this approach.[42] When patients do not respond to existing anti-cancer therapies, a sample of their tumor or blood can be studied, which may generate new hypotheses and lines of foundational research inquiry to elucidate the biological mechanisms underlying the therapy resistance. The results of these reverse translation studies can generate new knowledge about biological pathways and may even result in the development of new anti-cancer therapies.

Foundational research underlies much of discovery and knowledge creation, both of which are critical for future innovation. However, foundational research can be considered risky because it requires investment of resources without necessarily knowing where the research will lead, whether it will have practical applications, or the time needed for associated benefits to be realized. Increasing opportunities for conducting foundational research, including directly and continuously alongside

[38] White, Bebo. 1998. “The World Wide Web and High-Energy Physics.” *American Institute of Physics* (November): 30-36. https://doi.org/10.1063/1.882070.

[39] Tretkoff, Ernie. 2006. “This Month in Physics History: July, 1977: MRI Uses Fundamental Physics for Clinical Diagnosis.” *American Physical Society News* 15(7) (July): 2. https://www.aps.org/publications/apsnews/200607/history.cfm.

[40] Chodos, Alan. 2001. “This Month in Physics History: November 8, 1895: Roentgen’s Discovery of X-Rays.” *American Physical Society News* 10(10) (November): 2. https://www.aps.org/publications/apsnews/200111/history.cfm.

[41] Shakhnovich, Valentina. 2018. “It's Time to Reverse our Thinking: The Reverse Translation Research Paradigm.” *Clinical and Translational Science* 11(2) (February): 98-99. https://doi.org/10.1111/cts.12538.

[42] Faucette, Stephanie, Santosh Wagh, Ashit Trivedi, Karthik Venkatakrishnan, Neerja Gupta. 2017. “Reverse Translation of US Food and Drug Administration Reviews of Oncology New Molecular Entities Approved in 2011-2017: Lessons Learned for Anticancer Drug Development.” *Clinical and Translational Science* 11(2) (December): 123-146. https://doi.org/10.1111/cts.12527.

efforts to develop new technologies and products, could help sustain U.S. leadership globally by accelerating breakthroughs and progress across the innovation continuum.

A New Collaborative Model for Innovation: IotF Institutes

The trends and challenges described in the preceding sections contributed to motivating PCAST to recommend, in a report issued June 30, 2020, actions designed to propel the U.S. S&T enterprise forward with respect to IotF. Specifically, the report recommended establishing IotFIs,[43] which will fuel innovation at the intersection of at least two of the five IotF topical areas, fostering a vibrant and dynamic research culture of convergence. A key feature of the IotFIs will be the greatest possible flexibility in administrative structure, staffing, IP rights, funding, and administrative processes and requirements. In combination, these and other factors will maximize potential benefits gained from multi-sector collaboration among industry, academia, National Laboratories and other government entities, and non-profit organizations. Tight coupling of multiple sectors will enhance innovation across the spectrum of foundational to applied R&D by enabling rapid feedback and providing a clear pathway to translate discoveries to practice and transfer technology from the laboratory bench to large-scale domestic production. This flexibility is essential for achieving a high return on investment for all participants and the Nation.[44]

Indeed, the COVID-19 pandemic has shown that scientific and technological progress can be accelerated when certain longstanding administrative hurdles are streamlined, without compromising integrity and safety. One such example is the COVID-19 High Performance Computing Consortium, which facilitated cross-sector sharing of data and computing capabilities to accelerate COVID-19 research.[45] IotFIs will reflect this streamlining philosophy to the extent allowable by law and policy as a means to help transform the American research enterprise to one of greater efficiency and fewer unnecessary regulations, while ensuring that adequate regulations to protect safety, integrity, transparency, and accountability remain intact.

Another integral feature of IotFIs will be their prioritization of cultivating a talented, diverse, and multi-generational workforce that is eager to work on the rapidly evolving fields of IotF in a way that is likely to yield significant societal benefits. The unique opportunity to craft an environment that combines multi-sector and interdisciplinary foundational and applied research and workforce development activities—including education and mentorship—within a single organizational construct is expected to attract talent that a single sector or entity with a more narrow, predefined mission likely will not, thus increasing the size and diversity of the talent pool working on S&T research. Additionally, the Institutes will be well-positioned to create training and reskilling programs in the technologies of the future and their scientific underpinnings to address the critical need to empower broad participation in

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[43] PCAST. 2020. *Recommendations for Strengthening American Leadership in Industries of the Future*. https://science.osti.gov/-/media/_/pdf/about/pcast/202006/PCAST_June_2020_Report.pdf.

[44] NIST. 2019. *Return on Investment Initiative for Unleashing American Innovation*. NIST Special Publication 1234. Gaithersburg, MD: NIST. https://doi.org/10.6028/NIST.SP.1234.

[45] COVID-19 High Performance Computing Consortium. n.d. "The COVID-19 High Performance Computing Consortium." Accessed December 15, 2020. https://covid19-hpc-consortium.org.

the knowledge economy across the U.S. workforce. These IotFI features will align well with the Federal strategy for STEM education outlined by the National Science and Technology Council in 2018.[46]

An IotFI can be formed around any major challenge and combination of IotF areas. IotFIs also may tackle critical and growing challenges regarding societal and ethical implications and responsible design and use of the technologies they study and create. Examples of pressing societal challenges upon which an IotFI could focus are shown in Table 1.

Table 1*. Examples of important societal challenges and the IotF areas that could be leveraged to address them at an IotFI.*

Societal Challenge	IotF Areas
New classes of therapeutics	Biotechnology and AI
Integrated and multimodal transportation	AI, QIS, and advanced communications networks
Generative design for factories of the future	Advanced manufacturing and AI
Home-grown advanced communications networks	QIS, advanced communications networks, and AI
Ensuring food security, biosphere safety, and sustainability	AI and biotechnology

Notably, IotFIs will *not*:

- Attempt to replicate existing models of R&D organizations such as National Laboratories or federally funded R&D centers—rather they will create a new multi-sectoral research paradigm;
- Be overly regulated or dependent on administrative processes that unnecessarily slow R&D progress;
- Focus on a single IotF field;
- Atomize budget and operations in a way that impedes agility;
- Require approval for researchers to shift their R&D focus as part of their efforts to innovate and work toward an IotFI's vision;
- Involve industry merely as an external partner;
- Be managed or operated by a single participating partner; or
- Rely predominantly on Federal funding.

Characteristics of some notable R&D organizations—past and present—are illustrated in Figure 1, including their funding sources (vertical axis) and the stages of innovation they address (horizontal axis). The vision for IotFIs also is shown. This figure illustrates that, unique to IotFIs are their engagement of all sectors of the R&D enterprise as core partners (with non-core partners as well), and that they span the spectrum from foundational research to product development and scale-up.

[46] Committee on STEM Education. 2018. *Charting a Course for Success: America's Strategy for STEM Education*. Washington, DC: National Science and Technology Council. https://www.whitehouse.gov/wp-content/uploads/2018/12/STEM-Education-Strategic-Plan-2018.pdf.

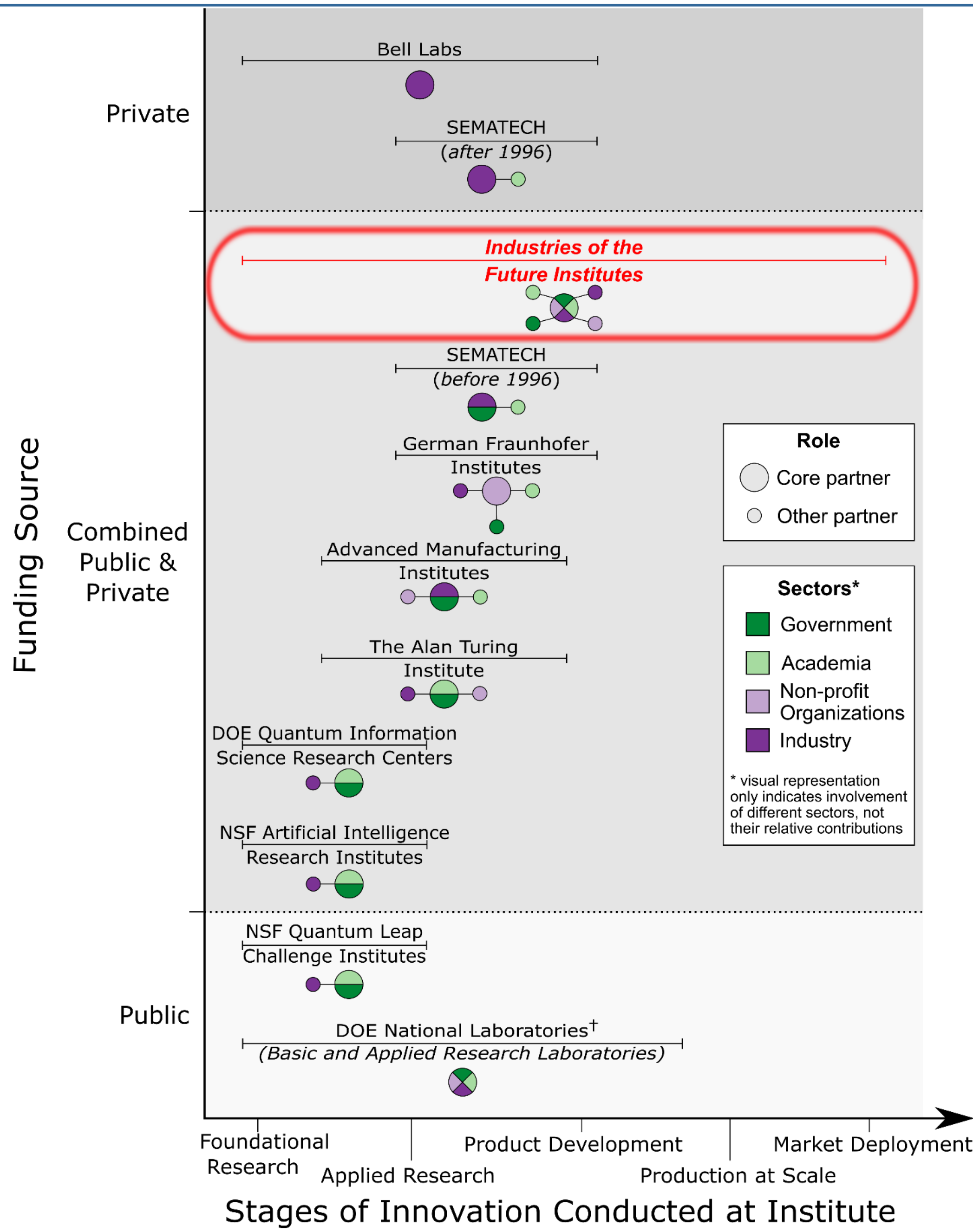

Figure 1. *Approximate depiction of several R&D organizations' research foci within the innovation landscape. The vertical axis, illustrating source of funding, is divided into three sections: solely public (i.e., government) funding, combined public and private funding, and solely private funding. The horizontal axis indicates the stages of the innovation spectrum that are core to that organization's mission and conducted by the organization itself (rather than by a partner or third party). Each organization also has an icon representing the nature of engagement among its partners of different sectors; these icons are not intended to capture all nuances of partners' roles (for more detailed descriptions, see Appendix A), but rather to illustrate the sectors represented by the "core partners" (those that manage, conduct, or oversee the organization's R&D operations on an ongoing basis and without whom the organization would not exist) and "other partners" (those that contribute to the organization intermittently or solely through financial or in-kind contributions). IotFIs are intended to be unique by virtue of having core partners from each sector and having activities that span the entire innovation spectrum.*
Notes: The horizontal axis is not intended to suggest that innovation is a linear process. †Due to the variation in management and activities at National Laboratories, one specific diagram could not be drawn to capture all. Instead, all four sectors are shown as core partners and no other partners are shown.

IotFI Mission, Vision, and Values

IotFIs' mission, vision, and values demonstrate their commitment to build a diverse, interdisciplinary, and multi-generational community of researchers and practitioners to address scientific, engineering, technological, translational, educational, and ethical challenges and opportunities within the IotF, for the benefit of all Americans.

Vision: Science, technology, engineering, and education advances in IotF transform American innovation, economic growth, and national security, yielding societal benefits that also ensure U.S. leadership in the technology-based global economy.

Mission: Advance IotF to uplift living standards and quality of life for all Americans, and ensure American economic prosperity and national security, by actively leveraging the full innovative power of the U.S. multi-sector R&D enterprise, including National Laboratories and other government organizations, academia, industry, and non-profit organizations. Specifically, IotFIs will:

- Accelerate the development of new knowledge in science, technology, engineering, mathematics, and related education through multi-disciplinary and multi-sector collaborations across the spectrum of foundational to translational and applied R&D;
- Cultivate an environment that promotes and facilitates free-flowing intellectual inquiry and bold thinking, and fosters creativity and technological innovation to address major societal challenges;
- Design and implement frameworks for the rapid development and deployment of technological innovations, aiming for efficient prototyping, scaling, and application of the technologies of the future while ensuring safety and security for the public and end users;
- Shape future scientists, engineers, technologists, and other STEM professionals by engaging students and STEM educators—locally and nationally—from K-12 education, community colleges, trade schools, and undergraduate and graduate programs through educational programming, work-based learning, mentorship, and research fellowships;
- Serve as a proving ground for new, creative approaches to organizational structure and function, broadening participation, workforce development, STEM education, and methods for engaging all sectors of the American research ecosystem;
- Design and offer in-person and virtual educational and experience-based learning programs to help build the STEM workforce of the future, with opportunities for individuals of all education levels and regardless of prior STEM experience; and
- Serve as a major contributor to frameworks, policies, and practices for the responsible, ethical, and equitable design and use of technologies of the future.

Values: IotFIs model the highest standards of ethical behavior, including integrity, honesty, openness, sharing, respect, vigorous and civil debate, transparency, accountability, safety, security, and diversity in all its forms.

Value Proposition for Participating Organizations

Participants from each sector of the American R&D enterprise will be included in every IotFI in order to collectively leverage their unique strengths and perspectives. These partners each stand to benefit from working together in an IotFI in ways that could otherwise be difficult or impossible to achieve. For example:

> *Academic Institutions* will gain new opportunities to translate their research to at-scale implementation within IotFIs via flexible staffing and funding arrangements with industry, government, and National Laboratory partners (see Personnel and Staffing section and Funding and Resources section). In addition, participation in IotFIs will provide opportunities for students to conduct research in multi-sector and cross-disciplinary settings, thus expanding their content knowledge, strengthening their critical thinking skills by addressing real-world problems from a variety of approaches, and developing their management and leadership skills. All of this will take place while ensuring researchers have a sustainable source of funding so they can focus their full energies on their R&D work.
>
> *National Laboratories* in particular, but also Federal Laboratories, will contribute and have access to IotFI-generated solutions to technical challenges linked to their mission objectives without having to realign their primary missions or alter their operational models. They also will collaborate with industry through a flexible but streamlined IP framework, thus shortening the time to initiate new projects. Furthermore, participating in IotFIs will continue National Laboratories' longstanding participation in advancing critical technologies for the Nation's sustained competitive advantage globally.
>
> *Private Companies* will benefit from more flexible and agile access to partnerships with the other participating sectors. The IotFI partnership model will help de-risk participation in foundational research and provide a competitive edge in the marketplace through IP generation and access. In addition, IotFIs will provide resources for product discovery, validation, and commercialization, which can be an insurmountable hurdle due to high costs, particularly for small businesses and start-up companies.[47] Companies also will benefit from access to spillover technologies and IP from any Manhattan Project-style challenge effort that an IotFI could undertake—that is, where the IP is of great interest to industry and could be easily licensed. (For more information on how IP will be addressed in IotFIs, see the Intellectual Property section.)
>
> To incentivize industry participation, it will be most productive to focus on areas of IotF research that are pre-competitive in nature to avoid anti-trust issues and where cooperation and the scale of companies working together is an advantage.
>
> *Non-Profit Organizations* will benefit by having direct engagement with and participation in an organization conducting cutting-edge technology R&D that can be harnessed to address pressing challenges that align with individual organizational and founder missions. IotFIs will provide non-profit organizations access to all points in the development pipeline (i.e., from foundational research to bringing a product to market

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[47] NIST. 2019. *Return on Investment Initiative for Unleashing American Innovation*. NIST Special Publication 1234. Gaithersburg, MD: NIST. https://doi.org/10.6028/NIST.SP.1234.

and public adoption). They will be able to invest in long-term efforts to improve the human condition by expanding opportunity and prosperity, and partnering with others to make inroads on the biggest challenges of our time. Importantly, IotFIs will facilitate the creation of trusted partnerships at the institutional leadership level, thereby allowing researchers and innovators to focus on their work.

*The Federal Governmen*t will participate as a key funder and reap the benefits accruing to society, the economy, and national security. In addition, R&D conducted at IotFIs will serve as a force multiplier for the national talent and knowledge base already produced through Federal R&D programs, and as strong support for Federal STEM education strategies and workforce development.

Furthermore, all IotFI partners will benefit from direct and continuous engagement with the students, postdoctoral fellows, and early career scientists working and training in this truly unique multi-disciplinary environment. We believe these individuals will—after completing their work at the IotFI—be uniquely suited to seek employment opportunities in any sector, particularly with those types of organizations involved in the IotFI. IotFI partners also will benefit from the diversity of expertise and experience that such an interdisciplinary and multi-generational collaboration will provide, along with other unique assets of partners, such as extensive or specialized datasets or facilities.

This discussion of benefits is not intended to be exhaustive, and many more benefits no doubt will be realized over time.

IotFI Governance and Operational Management

IotFIs will function in part as a network that shares best practices, and they will explore every potential opportunity for inter-IotFI collaboration to augment the efforts of individual IotFIs. Each Institute will establish its own leadership and organizational structure, within the context of leadership and governance elements described below, to reflect the specific objectives, strategies, goals, and metrics for success at that Institute, including activities at the main site, at remote partner locations, and through online collaboration networks or virtual environments. This flexibility is intended to avoid creating organizational stovepipes or prescribing administrative structures that are forced rather than naturally appropriate for the activities involved.

The leadership structure of each Institute will be lean to maximize resource allocation to project and program work and minimize administrative overhead; flexibility also will exist for an IotFI to adjust its structure and research focus over time. All participating sectors should have balanced, and ideally equal, partnership at the IotFI coordination and oversight levels to ensure shared responsibility and accountability, although the specific focus and overall goals of an IotFI may justify greater engagement of a particular sector. This also is possible at the project level within an IotFI if appropriately justified.

The aforementioned core leadership and governance elements are as follows:

National IotFI Office: A National IotFI Office should be established to enable and facilitate cross-fertilization, complementarity, collaboration, and synergy among the IotFIs; ensure the IotFI mission, vision, and values are upheld; and plan and administer national outreach activities related to IotF research, education, and workforce development.

Oversight and Guidance: Each IotFI should be governed by a separate Board of Directors consisting of non-conflicted external experts and representatives from the IotFI's participating organizations, with the specific representation tailored to each IotFI's focal area and resourcing model. The external members should be drawn from leading experts in IotF, business leaders, individuals from the local community, and experts in data security and dual use, program evaluation, and ethics. The Board should conduct periodic program reviews and financial oversight, determine metrics for success, and provide strategic guidance. Each Institute should report on its activities through a brief annual report that is approved by the Board of Directors and released to the public.

Executive Leadership: Each IotFI's in-house leadership should consist of a Director and Deputy Director, or Co-Directors, who are core staff dedicated full-time to the IotFI and appointed by the Board of Directors. Each Institute's leadership team should have a strong record of excellence in foundational or translational research, exceptional leadership and communication skills and experience, and other qualifications deemed necessary by the Board. Additional diversity of experience could be achieved by each IotFI Board selecting the Director and Deputy Director from different R&D sectors to ensure that representatives from each sector serve in the IotFI's Executive leadership over time.

Technical Management: IotFIs could have a combination of technical units, each with its own Director that reports to the Executive Leadership. In addition to research units, IotFIs could consider other programs, such as education and training labs and workforce development, fellowship, and scholar-in-residence programs (see later sections on Personnel and Staffing and New Foundations for Building the Workforce of the Future).

Research Programs: Agility and flexibility will be key features of IotFI research programs. Care should be taken when defining an IotFI's scope of programs so as not to preclude promising research directions that are not originally envisioned. Scope should be established to guide, not restrict. IotFI research portfolios should maintain a mix of short-, medium-, and long-term projects that hold the potential for commercialization of innovation at scale.

Programs at IotFIs could be proposed by teams consisting of participants from academia, National and Federal Laboratories, non-profit organizations, and industry; programs could be selected upon recommendation of a review committee. Once a research program is initiated, it should be evaluated periodically to determine whether it is making progress, needs to be redirected given the rapid evolution of technology, and remains an appropriate fit for the IotFI. Reviews should be streamlined and conducted only as frequently as necessary to ensure accountability and progress toward goals.

IotFI Personnel and Staffing

The ability to share ideas and work across R&D sectors is critical to bringing a variety of perspectives and solutions to bear on societal challenges IotFIs will address. Establishing a multi-sector R&D workplace with staffing from multiple organizations, however, is easier said than done owing to policies involving data sharing, IP, workspace organization, conflict of interest considerations, and the administrative agreements needed to allow staff to work across multiple organizations. Early in the process of establishing IotFIs, all R&D sectors will need to be engaged to determine how to overcome these barriers most effectively so that IotFIs will be able to seamlessly team individuals from multiple disciplines, sectors, and backgrounds across all career stages to ensure cross-fertilization of ideas, skillsets, and experiences in tackling research questions and accelerating innovation. In some cases, depending on the source of funding, temporary waivers of policies and regulations may be needed to achieve some of the desired goals (recall IotFIs are envisioned as an environment for testing new administrative and regulatory constructs).

Several staffing elements will be critical for IotFIs to achieve their mission of free-flowing intellectual inquiry, fostering creativity and technological innovation, and engaging students and STEM educators. Each IotFI should prioritize having diversity—in all of its forms—in every element of the organization. All personnel within IotFIs will benefit from education, training, and development opportunities, and likewise be afforded opportunities to contribute to IotFI education, training, upskilling, and outreach activities (as described in the section New Foundations for Building the Workforce of the Future).

In addition to having core leadership, research, and administrative staff, a substantial number of IotFI positions should be dedicated to student trainees and interns spanning all education levels. IotFIs should form flexible personnel structures to allow the seamless flow of researchers, faculty, technologists, and others between their home institution and the IotFI to meet its mission of multi-sector engagement. Clear and simple administrative policies should enable researcher transitions between the IotFI and their home organizations to avoid the potential disruptive implications of non-compete agreements. Examples of policies include dual and joint appointments with conflict of interest management plans, split appoints, and regular and reverse sabbaticals. Individuals within an IotFI should not need to be solely dedicated to a given sector of the R&D enterprise.

Ethicists should be employed at each IotFI to address questions that may arise, and to conduct research, in the responsible and ethical use of technology. In addition, a designated IotFI community liaison could be employed to conduct outreach activities and community engagement (see section on Community Outreach and Engagement).

Meeting the IotFI mission and vision will rely on the ability to recruit domestic and international talent. In both cases, it is important that participants in the U.S. research enterprise—irrespective of nationality, country of origin, or other characteristics—adhere to the ethical principles of research described earlier in this document and codified by Federal policies.

Compensation of IotFI staff will require special consideration for multiple reasons. First, differences among compensation models used by IotFI partner organizations could be a source of tension if researchers retain the salaries provided by their home institution. Compensation strategies will need to be developed and deployed by each IotFI's administration for fairness and to assure a balance of talent with a range of experience. Second, as described in the Introduction, the cost of education is a particular barrier to broadening participation in STEM fields nationally. IotFIs should compensate their interns, students, and fellows sufficiently to enable participation regardless of socioeconomic status. This may require IotFIs to provide additional compensation and benefits—such as health insurance, retirement plans, undergraduate and graduate student loan forgiveness, or tax waivers for student stipends—that go beyond what is provided in typical funding sources such as Pell Grants or National Institutes of Health (NIH) and National Science Foundation (NSF) doctoral and post-doctoral fellowships. In this regard, IotFIs can serve as a testbed for new staffing models that, if successful, could be applied more broadly across the R&D enterprise.

New Foundations for Building the Workforce of the Future

IotFIs have a tremendous opportunity to increase the size, skill spectrum, and diversity of the U.S. STEM workforce while also modeling the research environment of the future—an inclusive environment that empowers individuals of diverse backgrounds to participate in the science, engineering, and skilled technical workforce of the future from foundational research to product development and scale-up. Achieving this goal requires a commitment to broadening participation within IotFIs of traditionally underrepresented and underserved groups and the individuals whose education and training IotFIs will support. IotFIs must foster a culture that enthusiastically supports and protects staff time for providing (for others) and obtaining (for oneself) mentorship, training, community outreach, educational resource development, and opportunities for work-based learning experience.

IotFIs can play an important role in creating and supporting science and engineering career pathways across the Nation (locally and virtually) for individuals from communities that have been underrepresented—a critical objective for ensuring a strong and competitive U.S. R&D ecosystem for the long term.

IotFI Personnel Education, Training, and Professional Development

Opportunities for professional development and mentorship must be intrinsic to each Institute's design and be available for all members of the IotFI community, at every career stage and organizational level. This includes education and training opportunities in STEM, cultural competence and implicit bias awareness, ethical principles for responsible conduct of research and design and use of technology, and leadership, management, and communication, among other areas. Such investment in the development of human capital intramurally will provide a model and the expertise and authority necessary to lead outreach efforts and bring members of the local community into the IotFI enterprise for education, training, and skills development.

IotFIs will be well-situated to provide a truly unique mentorship experience because they are cross-disciplinary, multi-sector, and multi-generational organizations. Early-career professionals and students at any stage in their education may not have access to mentors who have experience outside of academia to inform them of, or help them prepare for, the myriad career options available to someone with their expertise. IotFIs should ensure their researchers have the option to choose their mentors—rather than having them assigned— and to have multiple mentors from across participating sectors and scientific disciplines. These interactions will help inform mentees about and prepare them for STEM careers that best fit their interests, strengths, and expertise.

This mentorship will benefit not only mentees but also mentors and IotFIs as a whole. For example, evidence suggests that mentorship may be linked to increased job satisfaction, career success, organizational commitment, and higher job performance for the mentor, and that these reciprocal benefits should be considered in establishing mentorship arrangements.[48] Cross-disciplinary and cross-sector mentorship in IotFIs should strengthen the interconnectedness within each IotFI, increasing opportunities for exchange of information and ideas among sectors and disciplines. Mentorships should be informed to the extent possible by best practices for inclusion and to facilitate positive and productive interactions that support a diverse and respectful research environment.[49]

[48] Ghosh, Rajashi, and Thomas G. Reio Jr. 2013. "Career Benefits Associated with Mentoring for Mentors: A Meta-Analysis." *Journal of Vocational Behavior* 83(1) (August): 106-116. https://doi.org/10.1016/j.jvb.2013.03.011.

[49] NASEM. 2019. *The Science of Effective Mentorship in STEMM*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25568.

Community Outreach and Inclusion

IotFIs should support and give back to their local and regional communities by engaging individuals with little previous experience or opportunity in STEM as a means to help promote excitement, enthusiasm, education, and skills development in IotF-related areas. In contrast to many existing, large-scale research programs (e.g., federally funded centers and institutes)—in which such activities are mandated but sometimes not fully integrated into the fabric of the organization—this engagement will be designed from the outset as an integral component of IotFIs.

The Institutes should begin their outreach through partnerships with educational institutions and any other relevant groups such as non-profit workforce training programs, science centers, etc. They can hold open houses to enable community members to experience an R&D and innovation environment, provide educational programs for the public, partner with local educational institutions to develop and offer formal IotF-related experiences and curricula, and train and empower local workers to become part of the STEM workforce or specifically the IotFI team. Below are examples of opportunities IotFIs could consider creating in their local and regional communities, with IotFI staff at all levels (both core staff and those "on rotation" from partner organizations) engaging as part of their core research activities:

- Opportunities to volunteer at local K-12 schools for regular teaching, mentoring, and extracurricular activities. This would be supported with protected time to participate in these activities;
- Programs for local K-12 teachers to participate in externships and research opportunities throughout the year. Onsite summer professional learning programs also should be offered for teachers who are not local and do not have an IotFI in their community;
- Project-based learning and work-based learning opportunities for local high school students—including students who have special needs—such as job shadowing, mentoring, internships, and apprenticeships. IotFIs should actively engage with local schools so that students are aware that these opportunities are available to them;
- On-site programs, such as Family Days and special lectures on hot topics of interest to the local community, with both in-person and virtual participation options;
- Internships and mentorship programs that partner with local community colleges and Minority Serving Institutions;
- Networking events for internships and training experience at IotFIs to help local individuals identify opportunities for permanent positions at the IotFI and its partner organizations;
- Lectures offered for in-person and online attendance for local, regional, and national audiences to learn about the research conducted at the IotFIs; and
- Online opportunities for the public to contribute to research, such as crowdsourcing and citizen science.

As part of each IotFI's commitment to strengthening the STEM workforce in its local and regional community, each IotFI could create an in-house program to provide upskilling and reskilling training and job placement assistance for local and regional workers. Engaging stakeholders representing the IotFI, local government, local and regional industry partners in need of STEM-enabled workers, and economic development boards/Opportunity Zone representatives will be key to tailoring these programs to community needs.

Individuals already participating in the STEM workforce, and those seeking a career change, would benefit. Activities could include workshops on specific skills that are applicable to IotF; certificate programs (see next section); year-long and part-time projects allowing workers to maintain current jobs while enhancing skills; opportunities for trainees to interact with IotFI permanent staff and visiting scientists; and online courses.

Cross-talk among the programs at each IotFI would provide for identification of best practices and lessons learned. Support for program activities would derive in part from Federal funds, for example, through a new grant program at NSF (as proposed in PCAST's June 2020 report), and complemented by private sector funding, economic development funds, and in-kind support. Funds from an IotFI's parallel 501(c)(3) charitable foundation (described in Business Structure section) also may be an appropriate means of supplementary funding.

Metrics for success in outreach and inclusion could include: numbers of workers who receive new skills relevant to their existing jobs; retention and advancement in STEM careers; corporate reviews of technical skills of workers; and economic indicators (see section on Program Evaluation and Defining Success for more detail).

Certificate Programs

As further commitment to supporting the STEM workforce of the future and reducing barriers to entry, the National IotFI Office should offer certificate programs, with assistance in development and course teaching from staff at the individual IotFIs. The National IotFI Office could have a Certifications Board with representatives from all sectors. This Board would oversee the creation of a framework for IotF-specific credentials that include certifications as well as informing curriculum and credits for secondary and post-secondary education. The Board also could offer actionable recommendations to make such certifications more accessible via remote learning opportunities at a reasonable cost.

During development, the Board should consult with trade associations and Pledge to America's Workers[50] signatories, among others, on how to prioritize certification development and how they can bring more talent into STEM careers and translate that to filling IotF jobs quickly. Broad endorsement and adoption by all sectors relying on the STEM workforce is key to program success. The certificate program should include several key features to ensure an effective program and reduce barriers to participation, such as the following:

- Certifications should be offered for each IotF field and sub-component skill;
- Certifications should be skills-based and not tied to vendor products to ensure freedom from conflict of interest among members of the Certifications Board and to allow the certificate programs to adapt over time with changes in technology;
- Courses should be accessible online to increase accessibility to those who do not live near an IotFI. Offering courses that are archived online and do not have to be watched in real-time would facilitate participation by enabling individuals to tailor their coursework to their work schedules and personal responsibilities. This would also enable self-directed learning that can be tailored to an individual's own learning pace;
- Multiple certificate levels should be offered, from basic to advanced, with basic being achievable within a short timeframe (e.g., less than 6 months);

[50] The White House. n.d. "Pledge to America's Workers." Accessed January 5, 2021. https://www.whitehouse.gov/pledge-to-americas-workers.

- A scholarship program should be offered so that cost is not a barrier to participation in the certificate programs. This might be funded through the IotFI charitable foundation described in the Business Structure section;
- Design of the program should leverage existing, successful frameworks for certifications in other industries such as financial services (e.g., certified public accountant, financial advisor, and Series 7 exams). The work underway in public and private sectors on IotF-related certifications should also be considered. Examples include:
    - Quantum Engineering and Technology certificate programs at The University of Chicago[51]
    - The Artificial Intelligence Board of America (ARTiBA™) Artificial Intelligence Engineer (AiE™) certification[52]
    - Nokia Bell 5G Certification Program[53]
    - Machine Learning AI Certificate at Stanford University[54]
    - Internal reskilling and rebadging frameworks in place such as the Bank of America GT&O University[55] and IBM Badging Program[56]
- Measures of success should include Key Performance Indicators that measure and track
    - Number of certifications awarded
    - Completion rate and timeframe
    - Reskilling rate
    - Job fill rate
    - Retention rate
    - Student demographics (e.g., gender, age, education background, geographic location, race/ethnicity, career field at time of enrollment, prior STEM experience)

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[51] Chicago Quantum Exchange. n.d. “Certificates Program in Quantum Engineering and Technology.” Accessed December 15, 2020. https://quantum.uchicago.edu/certificates.

[52] Artificial Intelligence Board of America. n.d. “Artificial Intelligence Engineer.” Accessed December 16, 2020. https://www.artiba.org/certification/artificial-intelligence-certification.

[53] Nokia. n.d. “Nokia Bell Labs 5G Certification Program.” Accessed December 16, 2020. https://www.nokia.com/networks/training/5g/bell-labs.

[54] Stanford University. n.d. “Artificial Intelligence Graduate Certificate.” Accessed December 16, 2020. https://online.stanford.edu/programs/artificial-intelligence-graduate-certificate.

[55] Bank of America. n.d. “Global Technology & Operations Development Program.” Accessed December 16, 2020. https://campus.bankofamerica.com/careers/global_technology_operations_development_program.html.

[56] IBM. n.d. “IBM Credentials: Badges and Certifications.” Accessed December 18, 2020. https://www.ibm.com/training/credentials.

IotFI Business Structure

Structuring IotFI operating partnerships as Limited Liability Corporations (LLCs)—similar to the structure of several of the organizations that operate National Laboratories—is likely the most appropriate framework given IotFI goals and activities. An IotFI LLC would provide the flexibility needed to best determine how to manage financial support from participating organizations, business income from licensing fees for commercialized products, and benefits from the IotFI inuring back to the IotFI participant.

IotFIs also may choose to set up separate but parallel 501(c)(3) charitable foundations. This would allow IotFIs to accept donations for specific tax-exempt purposes such as supporting scholarships for the education (tuition, conference travel, etc.) of students who work at the IotFI, STEM-related community engagement activities, or work-based learning opportunities for domestic and international students, scholars, and educators. Such foundations also would facilitate interaction with non-profit research organizations, many of which only fund non-profit entities.

IotFI Funding and Resources

Federal research funding is a critical component of the U.S. S&T R&D ecosystem, but obtaining and sustaining that funding can be challenging for researchers due to the often time-consuming administrative requirements of writing grant proposals, progress reports, time and effort reporting, and compiling the required supporting documentation (financial, regulatory, etc.). Sharing funding among sectors also can be challenging, for example, due to regulations governing the tax-exempt status of many academic research institutions and the nature of bonds used to fund academic research facilities. IotFIs will need to address these challenges to meet their goals. For example, temporary waivers or exemptions could be sought, directly from Federal agencies or more broadly from the Executive Office of the President, to address certain regulations directly or indirectly affecting the challenges described above. If found to be successful in the proving ground of IotFIs, they could be extended more broadly.

Initially, IotFI seed funding is envisioned to come from multiple Federal agencies, each contributing a nominal amount that would sum to a meaningful base. This funding will be critical for launching each Institute and bringing in non-Federal partners as participants and co-funders. However, as the Institutes mature and their business models become more self-sustaining, the preponderance of core funding will shift to non-Federal sources to facilitate multi-sector participation and reduce administrative burden that can accompany Federal funding. In order to stand up an Institute quickly, it may be advantageous for an IotFI to launch as a “virtual” Institute, with brick-and-mortar facilities to follow.

An IotFI’s core funding and direction should be defined for a set period of time—for example, 10 years—after which funding levels and agreements could pivot in response to changing opportunities and needs. Although some IotFI participants may contribute funding, others may be better positioned to provide in-kind support, such as expertise, facilities, data and computational resources, or fabrication and manufacturing capabilities. For example, academic institutions offer a vast constituency of talented foundational and applied researchers and students poised to be the science leaders of the future. Industry brings a substantive IP portfolio, capital assets base, massive and rich data sets, and engineering and manufacturing experience and facilities to commercialize at scale. Non-profit organizations can offer financial support and nimble administrative structures that provide flexibility and potential longevity, which can have an outsized positive impact on research. National Laboratories can offer access to facilities and other outside collaborations.

Institutes may develop other creative funding and resourcing models, rather than limiting themselves to what has come before. Funding models are expected to vary from IotFI to IotFI and should be tailored to an Institute’s specific mission, with partner roles articulated in partnership agreements. IotFIs can innovate new resourcing models that provide the financial stability necessary to support foundational research while incentivizing deep engagement from all sectors. IotFIs should aim to become mostly or completely self-sustaining, independent of Federal funding, for the reasons stated above.

State and local governments also can provide support to attract IotFIs to their region, such as through tax incentives, public–private partnerships, and space on university campuses. IotFIs could be located in Opportunity Zones that are in close proximity to a National or Federal Laboratory to enable access to unique and world-leading research capabilities, as well as engineering and fabrication capabilities. Opportunity Zones are intended to attract investment in underdeveloped communities, creating education and training opportunities, and attracting new businesses to the region for positive impact on the local economy.

Long-term funding for IotFIs will depend strongly on their success and value-creation, and whether their mission changes over time. The exact mix of in-kind and direct investment by partners likely will vary among IotFIs. In addition, specific partners will vary among IotFIs based on their location, areas of research, training opportunities and workforce needs, and anticipated translational and external engagement activities. The longer-term need for Federal funding likely will depend on how the mission and technological focus of the Institutes evolve and how industrial partners view the value of participation. If Federal funding is maintained at an IotFI for the long-term, perhaps an exemption from some Federal regulations will be needed (as described earlier) provided the Federal funding remains below an established threshold.

Intellectual Property

IP protections are an important mechanism for both safeguarding the intellectual outcomes of researchers as well as incentivizing investment to transition those outcomes into products and services for the benefit of society. However, IP provisions and associated policies also can create challenges to multi-sector R&D collaboration.[57]

For example, as discussed in the Introduction, creation and adoption of IP and financial agreements for R&D, conducted in partnership with National Laboratories or other organizations subject to Federal policies and practices, can be lengthy and burdensome. In some cases, a new IP agreement must be negotiated for each new project. In addition, under existing frameworks, universities may incur costs with little operational flexibility and uncertain return, especially in multi-sector collaborations.

To avoid these pitfalls, early in their development, IotFIs must establish a simple, customizable, flexible, and reasonable IP master agreement framework to create favorable conditions across the innovation spectrum for participation and contribution from IotFI partners. This framework should be comprehensive enough to avoid the arduous task of renegotiating IP terms for every project. Flexibility and breadth are essential to encourage, incentivize, and enable participation from all sectors of the Nation's S&T enterprise and for all players along relevant value chains.

IotFI IP terms will aim to prevent "spillage" of IP generated through Institute projects to external parties. In particular, IP generated within an IotFI project, going beyond project participants, will need to be carefully managed in a manner that channels long-term rewards to those contributing financial and intellectual resources to the IotFI while promoting commercialization and dissemination of the benefits from research and related results from IotFI projects participants' efforts. Examples of how IP has been handled by other organizations can be found in Appendix B.

IotFI partners should address key terms for IP management and define a flexible, simple, and comprehensive framework in the IotFI's partnership agreement. Topics that will need to be addressed include:

- Enhancing IP protection for AI-related assets (such as software, data sets, etc.) while ensuring ease of sharing information and capabilities for the benefit of IotFI research;
- How patent, license, and royalty assignment will be determined among partners;
- How partners will manage IP preparation, filing, and prosecution, including cost-sharing of costs and fees;
- Availability and sharing of pre-existing partner-held IP (i.e., "background IP") among IotFI partners;
- License and sub-license guarantees for partners, structured to enable translation of innovation to products that ensures return on investment for funders and in-kind contributors;
- Clear standards of authorship, acknowledgment, and conditions for partner review for publications resulting from IotFI research;
- How participating academic institutions will be compensated for IP management; and
- Opportunities for non-competitive (across a range of industries), precompetitive, and competitive (within a narrow set of applications) partnerships.

Some examples of flexibility and incentives to participate could include:

[57] NIST. 2019. *Return on Investment Initiative for Unleashing American Innovation*. NIST Special Publication 1234. Gaithersburg, MD: NIST. https://doi.org/10.6028/NIST.SP.1234.

- IP rights in each IotFI project could be negotiable but weighted to favor those providing major funding (direct as well as in-kind, of not only subject matter expertise but also manufacturing and other assets that are leveraged and/or used for the project or for scale up and ultimately manufacturing, as applicable) by granting them ownership and/or exclusive IP rights for an IotFI area and/or their respective field of industry or business (including sub-licensing rights). All other participants in a given project could receive a royalty-free non-exclusive IP license (without any sub-licensing rights) limited to their respective field of industry, business, or academia for use in the scope of their existing research, work, or activities.
- Creation of a temporary waiver or dispensation, applied solely to IotFI activities and partners, related to Internal Revenue Service revenue proclamations regarding safe harbor provisions for certain types of research conducted in buildings financed with tax exempt bonds.
- If a participant (or participants) covers all costs of a given project, then that participant (or participants) could dictate terms for the IP developed out of that project (i.e., "foreground IP").
- The cost of patenting activities could be equally split amongst the participants or as mutually agreed to by participants.
- Publication of findings could be joint publications.
- Multi-party projects in which participants occupy distinct positions in the value chain and do not compete may be used to avoid overlapping interests among multiple participants.
- To address challenges with sharing data assets, a trusted, independent, neutral party could be involved to manage complex data sets for the common good of the IotFI without divulging competitive secrets.[58]

[58] King, Gary and Nathaniel Persily. 2019. "A new model for industry-academic partnerships." *Political Science and Politics* 53(4): 1-7. https://gking.harvard.edu/files/gking/files/partnerships.pdf.

Program Evaluation and Defining Success

IotFIs will be successful if they contribute to the generation of new knowledge and practical deployment of technology that advances areas of national need (e.g., empowers the economy, creates high-paying jobs, supports national security, and improves the health and well-being of all Americans). Measuring progress on these broad goals will be necessary to determine effectiveness and identify needed adjustments. It is crucial that evaluation be infrequent and minimally intrusive on research activities, but that progress be measured continually in terms of output and impact. Evaluation metrics may need to be tailored to individual IotFIs.

For example, each IotFI could develop a 10-year strategic plan (updated biannually) and a biannual business plan stating annual goals, objectives, and metrics for success. An internal light-touch annual evaluation could be used to assess progress, with a major 5-year review designed to determine whether adjustments in scope are needed. Federal agencies could conduct periodic reviews of any element of performance associated with their funding (technical, financial, environment safety and health, partnerships, IP capture and licensing, etc.) to assure progress and responsible use of taxpayer funds. However, such reviews should be coordinated and minimally burden researcher time.

Metrics and measures that should be considered include the following:

- Organizational performance
  - Number of patents (filed, awarded, licensed)
  - Number of technologies transferred and successfully deployed
  - Number of participating organizations
  - Reduction in time for transition from innovation to deployment
  - Creation of startup companies and other translational activities led by IotFI participants
  - Increased diversity and inclusion within the IotFI ecosystem

- STEM education and workforce
  - Facilitating the design and offering of new educational programs
  - Increasing the size of the STEM-enabled workforce
  - Showing clear evidence of increasing engagement of traditionally underrepresented and underserved groups in STEM
  - Evaluation of mentorship experience from former trainees

- Policy impact
  - Reduction of administrative burden on researchers, with this demonstration driving changes in policy nationally
  - Demonstration of whether new IP strategies empower innovation and drive changes in policy nationally
  - New models for collaboration and coordination among the R&D sectors

Implementation Plan

Implementing a concept as bold as IotFIs will involve many steps and actions over varying periods of time. PCAST believes the best approach going forward is to focus on creating a single inaugural Institute as a means for testing the concepts described herein prior to scaling the program to multiple Institutes. The following course of action is recommended to assure the inaugural Institute is launched in an expedient and effective manner.

The White House Office of Science and Technology Policy (OSTP) should continue to serve as the primary coordinator of Federal and non-Federal stakeholders for IotFIs, particularly in the early stages of implementation. Consistent with the value brought to PCAST and this report by the Students, Post-Doctoral Scholars, and Early Career Professionals Subcommittee, PCAST suggests strong engagement not only of senior professionals but also graduate and undergraduate students, post-doctoral scholars, and early career non-academic and academic professionals, as appropriate.

Months 1–3: Upon issuance of the current document, PCAST recommends that OSTP initiate discussions with the Office of Management and Budget—and continue current discussions with agencies—regarding the provision of nominal seed funding to establish the inaugural IotFI. At an appropriate time thereafter, an announcement should be made by OSTP, in coordination with other agencies as appropriate, regarding the *intention* to launch the inaugural Institute. This announcement should highlight the primary goals and objectives of the IotFI program, as well as several of the key attributes anticipated to attract participation. The goal of this action is to broadly raise awareness of the IotFI program and prepare the community to provide input via a Request for Information (RFI), which should be issued shortly thereafter by OSTP to solicit comments from the broad community. Potential areas of inquiry and questions for the RFI are as follows:

IotFI Structure

- Is an existing organizational construct (e.g., LLC) most appropriate for IotFIs, or is a new approach needed?
- For what new and creative constructs and approaches to organizational structure, administration, research, policy, and human capital (broadening participation, education) can IotFIs serve most effectively as a proving ground?

IotFI Administrative and Regulatory Framework

- What actions can the Federal Government take to minimize administrative workload for participants to conduct R&D?
- How can IotFIs best serve as a framework for overcoming IP conditions that inhibit collaboration across sectors?
- What specific actions can the Federal Government take to streamline IP negotiations to incentivize multi-sector participation?

IotFI Human Capital

- How can IotFIs most effectively accommodate personnel whose home organization is in academia, for-profit companies, non-profit organizations, and government entities?
- What incentives and/or strategies (e.g., mentoring) would be most effective in engaging students and early career researchers to participate and achieve success in IotFIs?

IotFI Research and Commercialization

- What projects of significant scope, scale, duration, and potential societal impact are most appropriate for being addressed by IotFIs, and which of the five IotF would be most important for inclusion?
- Are potential linkages missing or are there roadblocks along the path from foundational research through applied research and ultimately to commercialization at scale, and how can IotFIs most effectively address them?

Additionally, OSTP should, in coordination with relevant agencies, initiate engagements with private sector Chief Executive Officers, Chief Technology Officers, and other leaders as soon as possible following the release of the current report given that participation of industry, start-up companies, and non-profit organizations is essential for success of the IotFI concept. Representatives from academia, Federal and National Laboratories, and policy leaders familiar with the detailed administration and benefits of Opportunity Zones also should participate.

Four distinct sessions should be held with the following stakeholders:

1. Chief Executive Officers from Fortune 500 companies and large technology companies
2. Chief Technology Officers from Fortune 500 companies industrial research corporations
3. Chief Technology Officers and Chief Executive Officers of start-up companies
4. Technical leaders from non-profit science and technology entities including Vice Presidents of Research from science and technology-oriented U.S. philanthropic foundations and academic institutions

Months 4-6: Based upon input from the RFI, OSTP should coordinate the design of the administrative aspects of the IotFI (e.g., options including the LLC model) with the goal of refining the operational structure of the framework that will enable the desired IotFI attributes to be readily implemented. Furthermore, the operational framework should include detailed plans for soliciting and evaluating proposals for the inaugural and subsequent IotFIs (see below). For example, rather than a typical lengthy written proposal, the initial competitive process might consist of a one-page vision paper accompanied by a 5-minute video. Promising submissions could then be invited to provide an in-person presentation.

Working with other agencies, particularly the National Institute of Standards and Technology, OSTP should establish IP terms with all stakeholders (academia, industry, National and Federal Laboratories, and non-profit organizations) through targeted discussions and feedback from the RFI. It is anticipated that stakeholders may provide useful insights and recommendations to complement the initial guidance put forward by PCAST that can be incorporated to assure a flexible IP framework is established for IotFIs that incentivizes participation and overcomes longstanding challenges that have hampered multi-sector partnerships in the past.

Months 7-9: OSTP should coordinate with relevant agencies to establish a competitive process for proposing the inaugural IotFI and ensure the solicitation is open for a period of 6–8 weeks. Requirements for proposals and their review should be established.

Months 10–12: Review proposals, negotiate terms and conditions, and finalize administrative and operational structure.

Month 12: Announce inaugural IotFI.

Conclusion

This document provides guidance for creating a system of new, transformative R&D Institutes—IotFIs—that span the entire innovation spectrum from foundational research through product deployment. PCAST believes IotFIs have unprecedented potential to fill important gaps in the U.S. R&D landscape by bringing together experts from all stages of the innovation spectrum, across all sectors of the R&D enterprise, to work at the intersection of two or more IotF areas. Most importantly, these Institutes are designed to spur innovation by serving as a proving ground for new approaches to governance, IP management, and innovative research. The recommendations provided in this report are not intended to be prescriptive but rather to provide broad contours and inspiration to the scientists, engineers, and innovators across all sectors who will come together to implement the IotFI concept.

Appendix A

Additional information on partners' roles in organizations shown in Figure 1. "Core partners" are those that manage, conduct, or oversee the organization's R&D operations on an ongoing basis and without whom the organization would not exist. "Other partners" are those that contribute to the organization intermittently or solely through financial or in-kind contributions.

R&D Organization	Academia	Industry	Government	Non-profit Organizations
Bell Labs	Not applicable	Core partner – Bell Labs was subsidiary of both Western Electric and AT&T.	Not applicable	Not applicable
SEMATECH	Other partner – Universities engaged with SEMATECH through its Centers of Excellence, separate organizations that conducted longer-term research, and also received funding from SEMATECH.	Core partner – Private industrial partners in the semiconductor field each had input over the direction of the R&D consortium.	Core partner after 1996 (not applicable before 1996) – DARPA initially contributed half of the funding to SEMATECH and had voting power on the board. DARPA left in 1996 after being voted out by member industries in 1994.	Not applicable
German Fraunhofer Institutes	Other partner – Fraunhofer Academy and high-performance centers engage universities in R&D process. Neither are core to the central Fraunhofer mission.	Other partner – Institutes work with small-and medium-sized enterprises to develop new technologies that meet their needs on a project-by-project basis.	Other partner – Government does not hold sway over Fraunhofer operations but does contribute roughly 1/3 of funding through grants.	Core partner – The non-profit Fraunhofer Society, which governs the Institutes, is a non-profit organization.
Advanced Manufacturing Institutes	Other partner – Universities contribute staff and personnel.	Core partner – Commercial partners contribute funding. Aim is for innovations to propel small, medium, and large industry products to market.	Core partner – The Institutes were created by government and are managed by nine Federal agencies (Departments of Agriculture, Commerce, Defense, Education, Energy, Health and Human Services, Labor, NASA, and NSF).	Other partner – Non-profit members work to facilitate collaboration across communities.
The Alan Turing Institute	Core partner – The Institute was created by five universities (Cambridge, Edinburgh, Oxford, Warwick, and UCL), all of which are represented in the organization's governance.	Other partner – Several private companies are listed as strategic partners. They primarily contribute funding and engage in some research projects.	Core partner – Public research councils are the principal funders of the Institute, which was created partially to inform AI policy in the United Kingdom.	Other partner – Many non-profits contribute to the Institute, and the Institute itself is a registered non-profit charity.
DOE National Quantum Information Science	Core partner – Contributes staff and personnel.	Other partner – Some companies contribute funding and resources.	Core partner – Institutes are operated by National Laboratories, owned by DOE.	Not applicable

R&D Organization	Academia	Industry	Government	Non-profit Organizations
Research Centers				
NSF National Artificial Intelligence Research Institutes	Core partner – Institutes are managed by U.S. universities.	Other partner – Mechanisms are available for industry partnerships.	Core partner – NSF governs high-level mission of program.	Not applicable
NSF Quantum Leap Challenge Institutes	Core partner – Institutes are managed by U.S. universities.	Other partner – 22 industry partners contribute to research.	Core partner – NSF governs high-level mission of program.	Not applicable
DOE National Laboratories	Core partner – Some National Laboratories are managed and operated by universities.	Core partner – Some National Laboratories are managed and operated by private companies.	Core partner – The National Laboratories are owned and overseen by the Federal Government, with one also managed and operated by the Federal Government.	Core partner – Some National Laboratories are managed and operated by non-profit companies.

Notes: AI = artificial intelligence; DARPA = Defense Advanced Research Projects Agency; DOE = Department of Energy; NSF = National Science Foundation; R&D = research and development

Appendix B

Highlights of IP practices at example R&D organizations shown in Figure 1.

R&D Organization	Funding Source	Partners	IP Owners/Licensers	Licensees	Royalty Recipients
Bell Labs (1925–1984)	Private	AT&T and Western Electric (under the Bell System monopoly).	AT&T (parent company) owned IP.	Per 1956 consent decree, any third party could license a patent for free or a nominal fee.	None
SEMATECH	Private (since 1996); public & private (pre-1996)	Semiconductor industry companies (and DARPA, pre-1996). Some engagement with academia.	SEMATECH (since 1996); SEMATECH and Federal Government per Bayh-Dole Act provisions (pre-1996).	SEMATECH industry partners exclusively for 2 years; others after 2 years.	SEMATECH (since 1996); SEMATECH, inventors per Bayh-Dole Act provisions (pre-1996).
German Fraunhofer Institutes	Public & private	Federal and regional governments, academic institutions, small and medium-sized companies.	The Fraunhofer Society, sometimes industry partners.	Industry partners; other organizations for a fee.	The Fraunhofer Society
The Alan Turing Institute	Public & private	Universities, other research organizations. Some industry partners.	The Alan Turing Institute/researchers hold copyright on at least some code produced and share under open-source license.	Unknown	Unknown
NSF National Artificial Intelligence Research Institutes	Federal; private possible for some projects	National Laboratories, universities, companies.	Home R&D institution owns and licenses IP; Federal Government (and industry co-sponsor, if any) may sub-license IP (*Bayh-Dole Act provisions*).	Federal Government (and industry co-sponsor, if any) receives non-exclusive royalty-free license; other organizations may obtain licenses from the Federal Government or R&D institution (*Bayh-Dole Act provisions*).	Research institution and inventors (*Bayh-Dole Act provisions*).
NSF Quantum Leap Challenge Institutes	Federal	Universities; National Laboratories, companies are engaged at some.	Home R&D institution owns and licenses IP; Federal Government may sub-license IP (*Bayh-Dole Act provisions*).	Federal Government receives non-exclusive royalty-free license; other organizations may obtain licenses from the Federal Government or R&D institution (*Bayh-Dole Act provisions*).	Research institution and inventors (*Bayh-Dole Act provisions*).

R&D Organization	Funding Source	Partners	IP Owners/Licensers	Licensees	Royalty Recipients
DOE National Quantum Information Science Research Centers	Public & private	National Laboratories, universities, companies.	Presumably subject to Bayh-Dole Act provisions.	Presumably subject to Bayh-Dole Act provisions.	Presumably subject to Bayh-Dole Act provisions.

Notes: DARPA = Defense Advanced Research Projects Agency; DOE = Department of Energy; IP = intellectual property; NSF = National Science Foundation; R&D = research and development;

Appendix References

AT&T Bell Laboratories. 1930. *Bell Telephone Laboratories: A Description of the Laboratory Research Organization of the Bell System*. New York, NY: Bell Telephone Laboratories. https://babel.hathitrust.org/cgi/pt?id=mdp.39015067864820&view=1up&seq=1.

Battelle. n.d. "Laboratory Management." Accessed January 5, 2021. https://www.battelle.org/laboratory-management.

Byron, Robert M. 1993. "SEMATECH, A Case Study: Analysis of a Government-Industry Partnership." Thesis, Naval Postgraduate School. https://apps.dtic.mil/dtic/tr/fulltext/u2/a273166.pdf.

Department of Energy. 2020. "White House Office of Technology Policy, National Science Foundation and Department of Energy Announce Over $1 Billion in Awards for Artificial Intelligence and Quantum Information Science Research Institutes." August 26, 2020. https://www.energy.gov/articles/white-house-office-technology-policy-national-science-foundation-and-department-energy.

Department of Energy. n.d. "National Laboratories." Accessed January 5, 2021. https://www.energy.gov/national-laboratories.

Fraunhofer Society. 2019. *Annual Report 2019*. Munich, Germany: Fraunhofer Society. https://www.fraunhofer.de/content/dam/zv/en/Publications/Annual-Report/2019/Fraunhofer-Annual-Report-2019.pdf.

Fraunhofer Society. n.d. "Patents/Licenses." Accessed December 17, 2020. https://www.fraunhofer.de/en/about-fraunhofer/profile-structure/facts-and-figures/patents-licenses.html.

Gertner, Jon. 2012. *The Idea Factory: Bell Labs and the Great Age of American Innovation*. United Kingdom: Penguin Press.

Github. n.d. "The Alan Turing Institute." Accessed December 15, 2020. https://github.com/alan-turing-institute.

Hof, Robert D. 2011. "Lessons from Sematech." *MIT Technology Review*. July 25, 2011. https://www.technologyreview.com/2011/07/25/192832/lessons-from-sematech.

Irwin, Douglas and Peter Klenow. 1996. "High-tech R&D Subsidies Estimating the Effects of Sematech." *Journal of International Economics* 40(3-4) (May): 323-344. https://doi.org/10.1016/0022-1996(95)01408-X.

Manufacturing USA. n.d. "How to Engage with Manufacturing USA Institutes." Accessed January 6, 2021. https://www.manufacturingusa.com/pages/how-engage-manufacturing-usa-institutes.

National Science Foundation. 2020. *National Artificial Intelligence (AI) Research Institutes: Program Solicitation*. NSF 20-604. Alexandria, VA: National Science Foundation. https://www.nsf.gov/pubs/2020/nsf20604/nsf20604.htm.

National Science Foundation. 2020. "NSF establishes 3 New Institutes to Address Critical Challenges in Quantum Information Science." July 21, 2020. https://www.nsf.gov/news/special_reports/announcements/072120.jsp.

National Science Foundation. 2020. *Quantum Leap Challenge Institutes: Program Solicitation*. NSF 19-559. Alexandria, VA: National Science Foundation. https://www.nsf.gov/pubs/2019/nsf19559/nsf19559.htm.

Noll, A. Michael. 2015. *Memories: A Personal History of Bell Telephone Laboratories*. Lansing, Michigan: Michigan State University. https://quello.msu.edu/wp-content/uploads/2015/08/Memories-Noll.pdf.

Stanford University. n.d. "SLAC Overview." Accessed January 5, 2021. https://www6.slac.stanford.edu/about/slac-overview.

The Alan Turing Institute. 2020. *Annual Report*. London, UK: The Alan Turing Institute. https://www.turing.ac.uk/sites/default/files/2020-07/the_alan_turing_institute_annual_report_2020_final.pdf.

35 U.S. Code Chapter 18 – Patent Rights in Inventions Made with Federal Assistance. P.L. 96-517, as amended. 1980.