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Report to the Subcommittee on Research and Technology, Committee on Science, Space, and Technology, House of Representatives

September 2018

SCIENCE AND TECHNOLOGY

Considerations for Maintaining U.S. Competitiveness in Quantum Computing, Synthetic Biology, and Other Potentially Transformational Research Areas

GAO-18-656

GAO

Highlights

Highlights of GAO-18-656, a report to the Subcommittee on Research and Technology, Committee on Science, Space, and Technology, House of Representatives

Why GAO Did This Study

Scientific and technological innovation contributes to U.S. economic competitiveness and prosperity. Federal agencies support transformational technological advances—those that result in new or significantly enhanced technologies—by, for example, funding research (nearly $70 billion in obligations in fiscal year 2017).

GAO was asked to examine support for research that could lead to transformational technological advances. This report (1) describes federal agencies' and nonfederal entities' support for such research in selected areas, (2) examines federal agencies' coordination on this research, and (3) describes experts' views on considerations for maintaining U.S. competitiveness through such advances. GAO selected quantum computing and synthetic biology as examples of research areas that could lead to transformational technological advances. GAO reviewed agency documents and interviewed federal officials, subject matter experts, and stakeholders. GAO also worked with the National Academies of Sciences, Engineering, and Medicine to convene a meeting to solicit views from 19 experts selected from government, academia, and industry, among others.

What GAO Recommends

GAO recommends that the agencies leading the interagency quantum computing and synthetic biology groups take steps to fully implement leading collaboration practices. The agencies agreed with GAO's recommendations.

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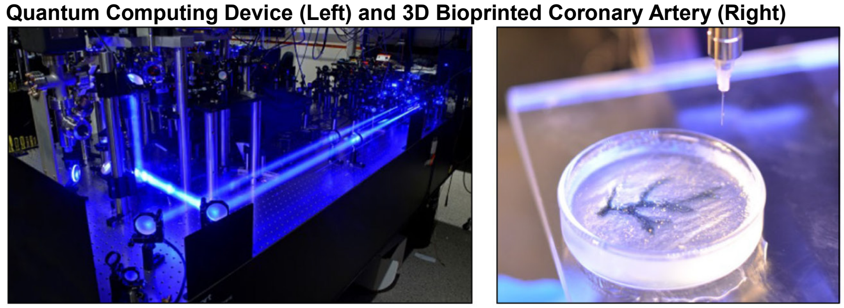
Considerations for Maintaining U.S. Competitiveness in Quantum Computing, Synthetic Biology, and Other Potentially Transformational Research Areas

What GAO Found

Multiple federal and nonfederal entities support research for transformational technological advances in the areas of quantum computing—the manipulation of bits of data using the behavior of individual atoms, molecules, or other quantum systems to potentially outperform supercomputers—and synthetic biology—the combination of biology and engineering to create or modify biological systems. GAO found that at least 6 agencies support quantum computing research; at least 10 agencies support synthetic biology research; and nonfederal entities, such as universities and businesses, support research in both areas.

Quantum Computing Device (Left) and 3D Bioprinted Coronary Artery (Right)



Sources: Massachusetts Institute of Technology Lincoln Laboratory (left) and Adam Feinberg, Carnegie Mellon University (right). | GAO-18-656

Agency officials said they coordinate on quantum computing and synthetic biology through efforts such as conferences and interagency groups, but GAO found that certain new efforts have not fully implemented selected leading collaboration practices. The quantum computing group, co-chaired by officials from 4 agencies, and the synthetic biology group, led by the National Science Foundation, have taken initial steps to implement some leading practices GAO identified that can enhance and sustain interagency collaboration. For example, both groups agreed to coordinate their research, and participating agencies documented agreement with the quantum computing group's purpose through a charter. However, the groups have not fully implemented other practices, such as agreeing on roles and responsibilities and identifying common outcomes, that could help ensure they effectively marshal agencies' efforts to maintain U.S. competitiveness in quantum computing and synthetic biology.

Experts identified considerations for maintaining U.S. competitiveness through transformational technological advances. The considerations broadly address federal and nonfederal entities' roles in supporting such advances and include:

- developing a strategic approach using consortia or other mechanisms to bring together potential partners;
- fostering an environment in which information is shared among researchers while also considering the risks of information sharing;
- focusing on technology development and commercialization, for example, by providing support across multiple stages of technology innovation; and
- strengthening the science and technology workforce through training, recruiting, and retaining talent.

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Abbreviations

ARPA-E	Advanced Research Projects Agency-Energy
BER	Biological and Environmental Research
BRAIN Initiative	Brain Research through Advancing Innovative Neurotechnologies Initiative
COMPETES 2007	America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science Act
CRISPR	clustered regularly interspaced short palindromic repeats
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DNA	deoxyribonucleic acid
DOD	Department of Defense
DOE	Department of Energy

Abbreviations Continued

EPA	Environmental Protection Agency
EPSCoR	Established Program to Stimulate Competitive Research
HHS	Department of Health and Human Services
IARPA	Intelligence Advanced Research Projects Activity
iGEM	International Genetically Engineered Machine
JQI	Joint Quantum Institute
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NSCI	National Strategic Computing Initiative
NSF	National Science Foundation
NSTC	National Science and Technology Council
ODNI	Office of the Director of National Intelligence
OSTP	Office of Science and Technology Policy
“qubits”	quantum bits
QIS	quantum information science
QIS Subcommittee	Subcommittee on Quantum Information Science
QIS working group	Interagency Working Group on Quantum Information Science
RNA	ribonucleic acid
SEMATECH	Semiconductor Manufacturing Technology consortium
STEM	science, technology, engineering and math
USDA	U.S. Department of Agriculture

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September 26, 2018

The Honorable Barbara Comstock
Chairwoman
The Honorable Daniel Lipinski
Ranking Member
Subcommittee on Research and Technology
Committee on Science, Space, and Technology
House of Representatives

Federal support for research and development can accelerate innovation, drive technological advances, and promote U.S. competitiveness in the global economy. For example, federally supported research led to the introduction of global positioning systems and touchscreen technologies that contributed to the development of smartphones, creating new industries and significant economic growth.[1] In fiscal year 2017, the federal government obligated nearly $70 billion for research, according to the National Science Foundation (NSF).[2] While some research leads to incremental changes in a scientific field, other research can yield disruptive or transformational advances. These advances are transformational because they result in new technologies or significantly enhanced capabilities in existing technologies.

The United States is considered a world leader in many science and technology areas, but other countries, such as China, are also making considerable investments in research. Increased competition from these countries has led some experts and others to express concern that the United States may be losing its competitive advantage. In January 2018, NSF's National Science Board reported that the United States' overall global share of research and development spending is declining relative

[1]Peter L. Singer, *Federally Supported Innovations: 22 Examples of Major Technology Advances That Stem From Federal Research Support*, (Washington, D.C.: The Information Technology and Innovation Foundation, February 2014).

[2]National Science Foundation, *Survey of Federal Funds for Research and Development Fiscal Years 2015-2017,* January 10, 2018, https://ncsesdata.nsf.gov/fedfunds/2015/index.html. An obligation is a definite commitment that creates a legal liability of the government for the payment of goods and services ordered or received, or a legal duty on the part of the United States that could mature into a legal liability by virtue of actions on the part of the other party beyond the control of the United States. GAO, *A Glossary of Terms Used in the Federal Budget Process*, GAO-05-734SP (Washington, D.C.: September 2005).

to other countries.[3] Moreover, other reports indicate that the United States is losing ground in certain technologies, such as intense ultrafast lasers, which may have applications in manufacturing, medicine, and national security.[4]

Since 2007, a series of laws has built on prior federal efforts to invest in innovation through research and development and to improve the United States' competitiveness.[5] In 2007, the America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science Act (COMPETES 2007) established the Advanced Research Projects Agency-Energy (ARPA-E) in the Department of Energy (DOE) to overcome long-term and high-risk technological barriers in the development of energy technologies.[6] It also, among other things, authorized programs in the Department of Education and NSF to train teachers in science, technology, engineering and math (STEM) fields. In 2011, the COMPETES Reauthorization Act of 2010 reauthorized parts of COMPETES 2007, established several new programs, and authorized additional funding for STEM education.[7] In 2017, the American Innovation and Competitiveness Act of 2017 reauthorized some parts of the COMPETES acts.[8] The three acts also provided direction to the Office of

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[3]The National Science Board also reported that the European Union's global share of research and development spending, overall, declined. National Science Foundation, National Science Board, *Science and Engineering Indicators 2018*, NSB-2018-1 (Alexandria, VA: 2018).

[4]Ultrafast lasers concentrate their energy in a very short-duration pulse (less than a trillionth of a second), which can be focused on a small area to reach the highest peak power and intensity. The National Academies of Science, Engineering, and Medicine, *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light* (Washington, D.C.: National Academies Press, 2017).

[5]Legislation prior to 2007 includes, for example, the Stevenson-Wydler Technology Innovation Act of 1980, which was enacted for the purpose of improving the economic, environmental, and social well-being of the United States by, among other things, stimulating improved utilization of federally funded technology developments by nonfederal entities. Pub. L. No. 96-480, 94 Stat. 2311 (1980) (codified as amended at 15 U.S.C. §§ 3701-3715, 3719-3723). Another law enacted in 1980, commonly referred to as the Bayh-Dole Act, allowed not-for-profit corporations, including universities, and small businesses to retain title to their federally funded inventions. Patent and Trademark Law Amendments Act, Pub. L. No. 96-517, 94 Stat. 3015 (1980) (codified as amended at 35 U.S.C. §§ 200-211).

[6]Pub. L. No. 110-69, § 5012(b), 121 Stat. 572, 621 (2007) (codified as amended at 42 U.S.C. § 16538(b)).

[7]Pub. L. No. 111-358, 124 Stat. 3982 (2011).

[8]Pub. L. No. 114-329, 130 Stat. 2969 (2017).

Science and Technology Policy (OSTP), whose responsibilities include coordinating federal research programs, advising the President on scientific and technological considerations with regard to federal budgets, and advising the President of scientific and technological considerations involved in areas of national concern.

However, continued concerns related to the federal debt and federal budget deficits are forcing difficult decisions about how much the federal government should spend on research, as well as what types of research it should fund. These concerns overlie a long-standing debate about the federal government's role in supporting science and technology research and which roles should be left to the private sector, academia, or other nonfederal entities. We have reported that the government often funds research at the early stages of technology development, whereas industry typically supports the final stages of technology development.[9] As a result, U.S. innovators may find it difficult to obtain public funding or private investment during the middle stages of innovation. We have also reported that substantial amounts of funding or investment are needed to support technology maturation through the middle stages of innovation and that high costs can be a barrier to technology commercialization, especially for small and medium-sized U.S. enterprises. Long-standing disagreements among stakeholders about the appropriateness of the federal government taking an active role in supporting technological advances with ambiguous applications has led to the creation, and sometimes the dissolution, of programs such as the Advanced Technology Program and the Technology Innovation Program. These two programs were established to help U.S. businesses and organizations support, promote, and accelerate innovation through high-risk, high-

[9]GAO, *Nanomanufacturing and U.S. Competitiveness: Challenges and Opportunities,* GAO-14-618T (Washington, D.C.: May 20, 2014).

reward research in areas of critical national need.[10] Different perspectives on the appropriate federal role may have also led to the proposals in the President's Budget for fiscal years 2018 and 2019 to eliminate ARPA-E.

You asked us to examine federal and nonfederal support for research that could accelerate innovation and advance U.S. competitiveness. This report (1) describes federal agencies' and nonfederal entities' support for research for transformational technological advances in selected areas, (2) examines federal agencies' coordination on this research, and (3) provides experts' views on considerations for maintaining U.S. competitiveness through transformational technological advances.

To address these objectives, we selected quantum computing (a sub-area of quantum information science) and synthetic biology as examples of areas of research that could lead to transformational technological advances. We selected these two areas based on several factors, including that they (1) represent enabling or platform technologies, (2) are supported by a mix of federal agencies and nonfederal entities, and (3) represent areas of congressional interest in which we have not recently conducted work.[11] For the purposes of our report, we defined quantum computing as computing in which bits of data are manipulated by using the behavior of atoms, molecules, or other quantum systems, with the potential to carry out extremely complicated calculations for specific

[10]The National Institute of Standards and Technology administered the Advanced Technology Program from fiscal year 1991 through fiscal year 2007 and the Technology Innovation Program from fiscal year 2008 through fiscal year 2010. The Advanced Technology Program was to address long-term, high-risk areas of technological research and development that were not otherwise being adequately developed by the private sector but were likely to yield important benefits to the nation. American Technology Preeminence Act of 1991, Pub. L. No. 102-245, § 201(b), 106 Stat. 7, 15 (1992). In 2007, the Advanced Technology Program was repealed and replaced with the Technology Innovation Program, which was established for the purpose of assisting U.S. businesses and institutions of higher education, as well as other organizations, to support, promote, and accelerate innovation in the United States through high-risk, high-reward research in areas of critical national need. COMPETES 2007, Pub. L. No. 110-69, § 3012, 121 Stat. 572, 593 (2007). The Technology Innovation Program was repealed in 2017 by the American Innovation and Competitiveness Act. Pub. L. No. 114-329, § 205(a)(1), 130 Stat. 2969, 3000 (2017).

[11]Enabling technology is equipment and/or methodology that, alone or in combination with associated technologies, provides the means to generate giant leaps in performance and user capabilities. A platform technology represents technologies that are used as a base on which other applications, processes, or techniques are developed. These technologies function as innovation catalysts and facilitate the development of follow-on technologies with applications for various industries.

problems that can outperform conventional supercomputers. We defined synthetic biology as the intersection of biology and engineering that focuses on the modification or creation of novel biological systems for useful purposes.

To describe federal agencies' and nonfederal entities' support for research that could lead to transformational technological advances in quantum computing or synthetic biology, we focused on federal and nonfederal efforts in fiscal year 2016 through the second quarter of fiscal year 2018. We reviewed agency documentation, relevant literature, and our prior work related to federal research efforts. We also interviewed officials from federal agencies that support quantum computing or synthetic biology research, as well as subject matter experts in the areas of quantum computing, synthetic biology, or federal research more broadly from industry, academia, nonprofit organizations, and professional associations. We included 10 agencies in our review: Department of Commerce, Department of Defense (DOD), Environmental Protection Agency (EPA), DOE, Department of Homeland Security (DHS), Department of Health and Human Services (HHS), National Aeronautics and Space Administration (NASA), NSF, Office of the Director of National Intelligence (ODNI), and the U.S. Department of Agriculture (USDA).[12] We did not seek to develop comprehensive information on federal agencies' and nonfederal entities' efforts to support research in quantum computing and synthetic biology. As a result, federal agencies and nonfederal entities could have efforts in these two areas that we do not discuss in our report.

To examine federal agencies' coordination on quantum computing and synthetic biology research, we identified coordination efforts that took place in fiscal year 2016 through the second quarter of fiscal year 2018 during our review of agency documentation and interviews with federal officials, including OSTP officials. We then compared these efforts with selected leading practices for enhancing and sustaining collaboration.[13] We selected six of the eight leading practices based on their relevance to

[12]We refer to departments and agencies, collectively, as agencies in our report. Also, as part of our efforts to collect information from DOE, we collected information from the National Nuclear Security Administration.

[13]GAO, *Results-Oriented Government: Practices That Can Help Enhance and Sustain Collaboration among Federal Agencies*, GAO-06-15 (Washington, D.C.: Oct. 21, 2005).

the operations of the interagency coordination efforts we identified.[14] In this report, and in our past work, we define collaboration as any joint activity that is intended to produce more public value than could be produced when organizations act alone.[15]

To provide experts' views on considerations for maintaining U.S. competitiveness through transformational technological advances, we convened a meeting of 19 experts in October 2017, with the assistance of the National Academies of Sciences, Engineering, and Medicine.[16] The experts included current and former federal officials and subject matter experts from industry, academia, nonprofit organizations, and professional associations. About half of the experts were subject matter experts in quantum computing or synthetic biology, while the other half were experts with broader perspectives on the role of federal and nonfederal entities in supporting research for transformational technological advances. We worked with the National Academies to select experts with a range of viewpoints. We used a transcript of the meeting in analyzing information obtained from these experts. See appendix I for more detailed information on the scope and methods of our review and appendix II for a list of the experts who participated in the meeting we convened.

We conducted this performance audit from November 2016 to September 2018 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

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[14]We excluded from our review two leading practices related to reinforcing agency accountability and individual accountability for collaborative efforts.

[15]We also refer to coordination as collaboration in our work.

[16]We planned and convened this meeting of experts with the assistance of the National Academies to better ensure a breadth of expertise; however, we were responsible for all final decisions regarding meeting substance and expert participation. Any conclusions and recommendations in our reports are solely our own.

Background

This section provides information on translating research into new products or services, the federal government's role in supporting research, and OSTP's role in fostering collaboration among the various entities. It also provides information on the areas of quantum computing and synthetic biology.

Translating Research into New Products or Services

Technological innovation involves not only creating new ideas but also translating those ideas into a new product or service.[17] Innovation, and the research driving it, is inherently risky because the likelihood that research can be translated into a product or service and the ultimate value of that product or service are unknown. Because of this risk and the long time frames sometimes associated with technology development, there can be a gap in funding and investment support that makes it challenging to translate research into commercialized products or services. While government and universities often support early-stage research and industry tends to support later stages of development, there may be a gap during the middle stages of innovation during which innovators may have difficulty finding financial support, as illustrated in figure 1 (see app. III for a printable version).[18]

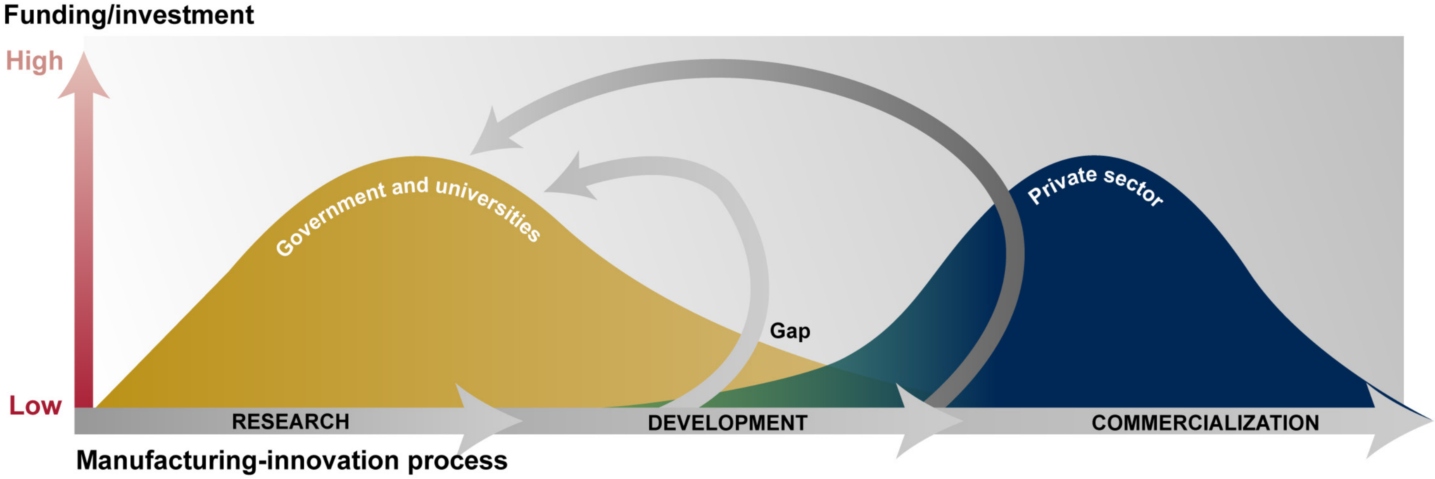
[17]National Research Council of the National Academies, *Building the Illinois Innovation Economy: Summary of a Symposium* (Washington, D.C.: National Academies Press, 2013).

[18]GAO, *Nanomanufacturing: Emergence and Implications for U.S. Competitiveness, the Environment, and Human Health*, GAO-14-181SP (Washington, D.C.: Jan. 31, 2014).

Interactive Graphic

Figure 1: Funding/Investment Gap in the Manufacturing-Innovation Process

Instructions: Online, roll your mouse over each arrow in the figure for more information.
For printable version, see Appendix III, page 75.



Source: GAO. | GAO-18-656

The linear, or pipeline, model of innovation presents innovation as a succession of outputs that transfer to the next level as inputs. The starting point in the pipeline model is basic research. Knowledge created through basic research transitions to the next stage of applied research then to development and, finally, commercialization. Under this model, innovation takes place in distinct and sequential phases.

Critics of the pipeline model have noted that innovation is actually cyclical because the development of knowledge involves feedback and interaction at these different stages of the cycle.[19] Alternative innovation models include the following:

- **Extended pipeline model.** Under this model certain research and development organizations support the entire technology development process, from basic research to initial commercialization.[20] Unlike the pipeline model, in which the government's support is disconnected from the rest of the innovation ecosystem, under the extended pipeline model the government's role is deeply connected to the rest of the system. Under this model, federal entities such as DOD support the evolution of technologies, including electronics, computing, and the internet, across all stages of innovation.
- **Induced innovation model.**[21] Innovation that follows this model is more industry-led because the parties involved have a market niche that the research needs to meet. Research under this model is more likely to lead to incremental advances because it is conducted in response to market demand.[22]

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[19]William B. Bonvillian and Charles Weiss, *Technological Innovation in Legacy Sectors* (New York: Oxford University Press, 2015), 23-30. Department of Commerce, *Between Invention and Innovation: An Analysis of Funding for Early-Stage Technology Development* (Gaithersburg, MD: Nov. 2002).

[20]William B. Bonvillian and Peter L. Singer, *Advanced Manufacturing: The New American Innovation Policies*, (Cambridge, MA: The MIT Press, 2017) 8.

[21]This model is also sometimes referred to as a technology demand or technology pull model. See Vernon Ruttan, *Technology Growth and Development: An Induced Innovation Perspective* (New York: Oxford University Press 2001) 7.

[22]Bonvillian and Singer, *Advanced Manufacturing: The New American Innovation Policies*, 7. Bonvillian and Weiss, *Technological Innovation in Legacy Sectors,* 25. Ruttan, *Technology Growth and Development*, 7.

- **Manufacturing-led model.** Under this model,[23] innovation is pursued with the main objective of manufacturing. This model describes innovations in production technologies, processes, and products that emerge from the manufacturing process. The production process is supplemented by applied research and development. It is typically industry-led but may have strong government support, particularly in countries such as Germany, Japan and China whose economies are organized around this model.

Federal Role in Supporting Research

While the different innovation models receive various levels of federal support, examining the organization of federal agencies in support of innovation is complex because of the decentralized nature of the federal research system. More than 25 federal agencies support intramural or extramural research, and these agencies may play different roles in supporting research that may lead to potentially transformational technologies. For example, NSF supports basic research that is in keeping with its mission of promoting the progress of science; advancing the national health, prosperity, and welfare; and securing the national defense. DOD supports research in line with its mission to provide the military forces needed to deter war and to protect the United States' security, while DOE supports research in line with its mission to ensure America's security and prosperity by addressing its energy, environmental, and nuclear challenges. Commerce's National Institute of Standards and Technology (NIST) supports research in measurement science, standards, and technology, in keeping with its mission to promote innovation and industrial competitiveness. Other agencies—such as EPA, and HHS's Food and Drug Administration—support research in their capacity as regulatory agencies.

Federal support for research is not only decentralized but also changes over time. Factors such as international conflict, budgetary pressures, and globalization may contribute to shifts in U.S. science and technology policy.[24] In times of war, federal support for research has increased in part because of the view that America's military survival might depend on science and technology leadership.[25] Budgetary pressures also affect the

[23]Bonvillian and Singer, *Advanced Manufacturing*, 8.

[24]Donald E. Stokes, *Pasteur's Quadrant: Basic Science and Technological Innovation* (Washington, D.C.: Brookings Institution Press, 1997), 90-95.

[25]Stokes, *Pasteur's Quadrant*, 91.

federal role in research when such pressures lead to reductions in federal funding for research. Globalization and the associated integration of the world economy may also affect federal science and technology policy. While the United States invests far more resources in research and development than any other country, its rank in research and development intensity has slowly fallen in recent years.[26]

Researchers have said that, in addition to globalization, domestic changes—such as the structure of U.S. companies—present new challenges to commercializing new products and services.[27] For example, in the last few decades, the amount of research produced by industrial laboratories has declined. Further, U.S. companies, particularly small and midsized firms, devote fewer resources to train employees compared to firms from the 1980s.[28] In recognition of the need for a more skilled workforce to enhance U.S. competitiveness, the federal government has increasingly shifted attention to preparing students for careers in STEM fields.[29]

The federal role also changes in response to differing policy views. One policy perspective maintains that the federal role should be to support innovation across the economy. This policy approach has underpinned innovation and economic growth since at least the end of World War II. As we reported previously, another perspective is that the federal role should be to support individual sectors.[30] Critics of the latter perspective argue that the government should not "pick winners and losers" in

[26]The National Science Board defines research and development intensity as the ratio of research and development expenditures to gross domestic product. In 2018, the National Science Board reported that the United States' rank by the "research and development intensity" indicator fell from 8th in 2009 to 10th in 2011 and to 11th in 2013 and 2015. National Science Board, *Science and Engineering Indicators 2018*.

[27]Suzanne Berger, *Making In America: From Innovation to Market* (Cambridge, MA: The MIT Press, 2013), 15-19.

[28]Berger, *Making In America,* 19. Bonvillian and Singer, *Advanced Manufacturing*, 221-222.

[29]GAO, *Science, Technology, Engineering, and Mathematics Education: Assessing the Relationship between Education and the Workforce*, GAO-14-374 (Washington, D.C.: May 8, 2014). As part of this effort, many federal agencies administer STEM education programs. In addition to the federal effort, state and local governments, universities and colleges, and the private sector have also developed programs that provide opportunities for students to pursue STEM education and occupations.

[30]GAO-14-181SP.

commercial contexts because it is unlikely that the government will have sufficient information or foresight about an individual firm's or a particular technology's growth potential to select it for special subsidy.[31] This view advocates allocating resources through market mechanisms because such mechanisms are anticipated to result in U.S. investments that are most efficient and best suited to the comparative advantages of the United States.[32] However, the federal government has supported individual sectors from research and development through implementation, most often because of the government's own needs in areas deemed important for national security (e.g., aerospace and defense).[33] In addition, findings of economic market failures have justified other interventions, such as for research, development, and demonstrations in various sectors, including agriculture and energy, and recently, advanced production technologies.[34]

The federal government has partnered with nonfederal entities to translate research into commercialized products to foster economic growth.[35] For example, DOD, through programs such as the Defense Advanced Research Projects Agency (DARPA), has partnered with nonfederal entities to support both early-stage research and later-stage production.[36] Some of these partnerships have led to development of transformational technologies. For example, in the 1970s DOD supported development of a communications network to facilitate information sharing, which is considered the foundation of the modern internet.[37]

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[31] GAO-14-181SP.

[32] GAO-14-181SP.

[33] GAO-14-181SP. Vernon W. Ruttan, *Is War Necessary for Economic Growth? Military Procurement and Technology Development* (New York: Oxford University Press, 2006) 3-9.

[34] President's Council of Advisors on Science and Technology, *Report to the President on Ensuring American Leadership in Advanced Manufacturing* (Washington, D.C.: June 2011).

[35] President's Council of Advisors on Science and Technology, *Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing* (Washington, D.C.: July 2012); and GAO, *Advanced Manufacturing: Commerce Could Strengthen Collaboration with Other Agencies on Innovation Institutes*, GAO-17-320 (Washington, D.C.: Apr. 6, 2017).

[36] GAO, *Military Acquisitions: DOD Is Taking Steps to Address Challenges Faced by Certain Companies*, GAO-17-644 (Washington, D.C.: July 20, 2017).

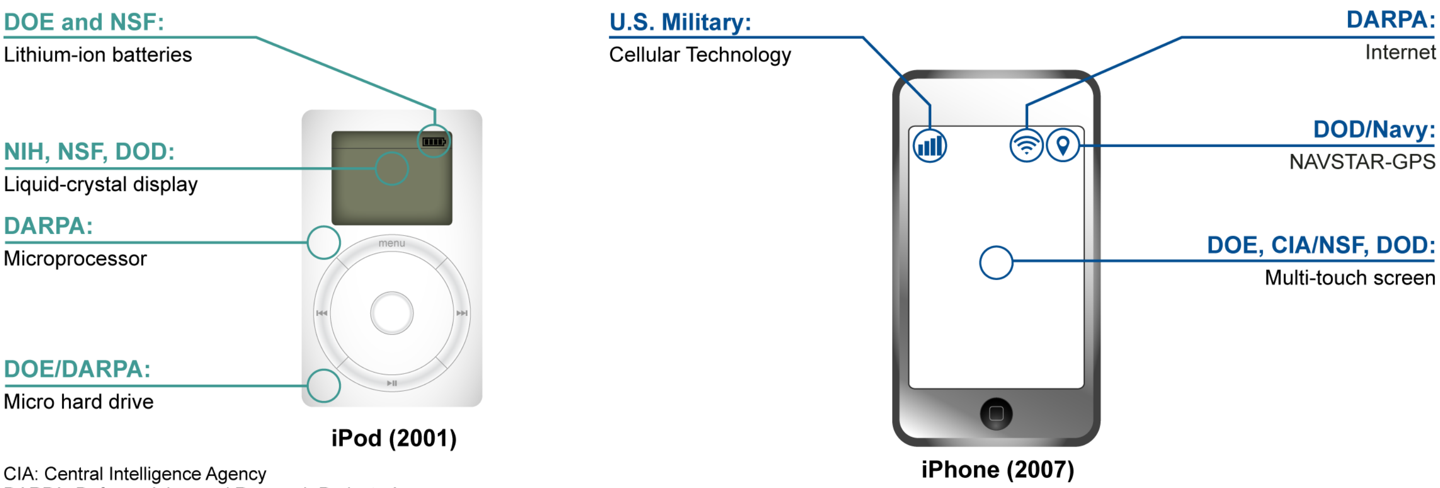
[37] GAO-17-644.

DOD also funded research in the 1950s on speech recognition and artificial intelligence that commercial companies leveraged in the 1990s and 2000s to develop technologies such as the Speech Interpretation and Recognition Interface, the iPhone assistant.[38] NIST research, such as its critical technical evaluations of speech recognition technologies dating back to the 1980s, also contributed to the development of Speech Interpretation and Recognition Interface, according to NIST officials. Alongside DOE, HHS and NSF, DOD has funded research that led to technologies used to make the first iPod and later the iPhone (see fig. 2).[39] Many federal agencies also support other mechanisms, such as Small Business Innovation Research and Small Business Technology Transfer grants, to stimulate innovation by facilitating interactions among the federal government, private sector, and nonprofit research institutions.

[38]GAO-17-644.

[39]Singer, *Federally Supported Innovations*; Mariana Mazzucato, *The Entrepreneurial State: Debunking Public vs. Private Sector Myths*. (New York, NY: Anthem Press, 2013); and Office of Science and Technology Policy, *American Competitiveness Initiative: Leading the World in Innovation* (Washington, D.C.: 2006).

Figure 2: Federally Funded Research That Contributed to Development of Technologies Used to Create the iPod and iPhone



CIA: Central Intelligence Agency
DARPA: Defense Advanced Research Projects Agency
DHS: Department of Homeland Security
DOD: Department of Defense
DOE: Department of Energy
NASA: National Aeronautics and Space Administration
NIH: National Institutes of Health
NSF: National Science Foundation

Source: GAO graphic based on information from the Breakthrough Institute, Mariana Mazzucato, National Science Foundation and the Office of Science and Technology Policy. | GAO-18-656

Note: See Breakthrough Institute, *Where Good Technologies Come From* (Oakland, CA: 2010) and Mariana Mazzucato, *The Entrepreneurial State: Debunking Public vs. Private Sector Myths* (New York, NY: Anthem Press, 2013). According to NIST officials, NIST research in measurements and standards for networking, semiconductors, communications, materials, and cybersecurity contributed to technologies used to develop the iPod and iPhone. Other examples of NIST research contributions to smartphone technologies are in the areas of time and frequency, computing power, and radio communications.

Role of OSTP in Fostering Collaboration

OSTP was established in 1976 to provide advice on the scientific, engineering, and technological aspects of issues that require attention at the highest levels of government.[40] Advances in technology in areas such as quantum computing and synthetic biology have become increasingly interdisciplinary, and OSTP works with agencies across the decentralized federal research system to coordinate activities to support these advances. The National Science and Technology Council (NSTC) is a key component of these efforts and is charged with coordinating science and

[40]National Science and Technology Policy, Organization, and Priorities Act of 1976, Pub. L. No. 94-282, § 204, 90 Stat. 459, 463 (1976).

technology policy across the federal government.[41] One of the NSTC's primary objectives is to establish clear national goals for federal science and technology investments. NSTC organizes its work under six committees, such as the Committee on STEM Education, which is responsible for coordinating federal programs and activities in support of STEM education.[42] In addition to pulling together federal entities, OSTP also plays a role in pulling together nonfederal entities to help tackle technological issues of importance to the nation. For example, the National Strategic Computing Initiative, created in 2015, is a government collaboration with industry and academia to sustain and enhance U.S. leadership in high-performance computing.[43]

Quantum Computing

Quantum computing has the potential to revolutionize computing by introducing a fundamentally new approach to computing not available with classical computers, which constitute most computers in use today. Classical computers process two different states as 1s and 0s (binary digits) to form "bits" of information that the computer manipulates. Bits can exist in either a 1 or 0 state. These bits may be created using, for example, specific voltage or current levels in a circuit, and there is a limit as to how quickly transistors in classical computers can manipulate these bits to conduct calculations or how many circuit components can be included on a computer chip. While classical computers rely on bits,

[41]The NSTC was established by Executive Order 12881 on November 23, 1993. The council is chaired by the President, and its members include the Vice President, cabinet secretaries and agency heads with significant science and technology responsibilities, and other White House officials. The Assistant to the President for Science and Technology convenes meetings of the NSTC and, in the President's absence, presides over the meetings.

[42]The NSTC's six committees are the Committees on Environment, Homeland and National Security, Science, Science and Technology Enterprise, STEM Education, and Technology. NSTC sometimes organizes efforts on more specific topics under these committees. For example, the National Nanotechnology Initiative, which will be discussed in more detail later in this report, is an effort to bring federal agencies together to enhance understanding and control of nanoscale material and is coordinated by the NSTC Committee on Technology's Nanoscale Science, Engineering, and Technology Subcommittee.

[43]Executive Order 13702 established the National Strategic Computing Initiative (NSCI) on July 29, 2015. DOE, DOD, and NSF lead the NSCI effort, and OSTP and the Office of Management and Budget co-chair the NSCI Executive Council. The following agencies also participate in the NSCI: DHS, Federal Bureau of Investigation, Intelligence Advanced Research Projects Activity (IARPA), NASA, National Institutes of Health (NIH), NIST, National Oceanic and Atmospheric Administration, and National Security Agency.

quantum computers rely on quantum bits (“qubits”).[44] Unlike bits, qubits can be in combinations of both a 1 and a 0 at the same time due to quantum superposition. Phenomena such as quantum superposition and quantum entanglement (the ability of two particles to have correlated information, even at a distance) make quantum computers more powerful than even today’s most advanced classical supercomputers for solving some complex problems.[45] This ability to exist in combinations of both states simultaneously allows for the efficient implementation of certain algorithms, resulting in the ability to solve certain types of problems significantly faster than classical computers.[46]

To date, a universal quantum computer is not commercially available.[47] As of 2017, quantum computers contain at most 50 qubits and can perform some small calculations more slowly than classical computers. Among the challenges to building a quantum computer are developing software and hardware. Quantum hardware allows the computer to manipulate qubits by completely isolating quantum processors from outside forces. Quantum computing hardware is at the laboratory prototype stage and is progressing steadily, according to a 2016 federal report.[48] Hardware development efforts include the creation of logical qubits, which use error correction techniques to actively mitigate errors, thus stabilizing the quantum state of the qubit even in the presence of external factors (i.e., noise). Quantum information is extremely fragile and requires special techniques and equipment, such as extreme refrigeration, to maintain the qubit. Other challenges include creating qubits of high quality, packaging them together in a scalable form so they

[44]*American Leadership in Quantum Technology, Before the H. Comm. on Science, Space, and Technology,* 115th Cong. 31 (2017) (statement of Carl J. Williams, Acting Director, Physical Measurement Laboratory, National Institute of Standards and Technology Department of Commerce).

[45]*American Leadership in Quantum Technology* (2017).

[46]An algorithm is a step-by-step procedure for solving a problem or accomplishing some end especially by a computer, according to Merriam-Webster’s Collegiate Dictionary.

[47]A universal quantum computer would be able to solve any computational problem, as opposed to a more specialized quantum computer that would have more limited use. According to an industry research laboratory, the universal quantum computer is the most powerful and the hardest to build, posing a number of difficult technical challenges. Current estimates indicate that this machine would comprise more than 100,000 physical qubits.

[48]National Science and Technology Council, *Advancing Quantum Information Science: National Challenges and Opportunities* (Washington, D.C.: July 22, 2016).

can perform complex calculations in a controllable way, and limiting the errors that can result from heat and electromagnetic radiation. Addressing these challenges may require developing new materials. Stakeholders still consider developing a universal quantum computer a long-term goal. When available, these computers could provide new computational methods and powerful new tools for researchers. Quantum computing has the potential to support significant breakthroughs in medicine, manufacturing, artificial intelligence, defense, and improved cybersecurity. However, it may take a decade or more before such technology is ready to be demonstrated at scale.

Synthetic Biology

Synthetic biology represents an intersection of biology and engineering that focuses on the modification or creation of novel biological systems. The current state of synthetic biology is mostly the result of research in biology, engineering, computer science, and information technology dating back to the mid-1900s. Synthetic biology has drawn increasing attention as a potentially transformative platform technology. Whether found in nature or synthesized in a test tube, the building blocks of synthetic biology are assembled to create biological systems. Synthetic biological systems can function in cell-free environments, such as cell extracts, or may be placed into living cells, such as bacteria, which serve as a "chassis." In the short-term, synthetic biology is enhancing understanding of how living organisms work through progress in the ability to design and construct biological parts.

Synthetic biology is already being applied in a variety of fields. Through the creation of novel biological systems, synthetic biology offers potential solutions to many current challenges, such as climate change, energy needs, and global health. For example, synthetic biology may help address global warming through the development of artificial leaf technology, a synthetic version of the photosynthesis process.[49] In the energy sector, synthetic biology is being used to devise more efficient methods of producing biofuels,[50] and in the healthcare sector, synthetic

[49]The Royal Academy of Engineering, *Synthetic Biology: Scope Applications and Implications*, (London, United Kingdom: May 2009), 2. Julian David, Janna Olmos and Joanna Kargul, "A Quest for the Artificial Leaf," *The International Journal of Biochemistry and Cell Biology*, 66 (2015) 37-44.

[50]Current methods of producing biofuels result from the production of ethanol from sugars or biodiesel from vegetable oils. These methods have the disadvantage of not being particularly efficient processes that waste much of the organic matter or biomass. See The Royal Academy of Engineering, *Synthetic Biology*.

biology may lead to biosensors that can permanently reside in the body to detect and treat abnormalities such as cancer.[51] Synthetic biology has already resulted in biosensors that can detect arsenic in drinking water.[52] Factors that may support growth in synthetic biology applications include a decline in the cost of deoxyribonucleic acid (DNA) sequencing and increases in genetically engineered crop development, expenditures in research and development by biotechnology and pharmaceutical companies, and demand for synthetic genes.[53] On the other hand, bio-safety and bio-security concerns about the potential that synthetic biology could be used for nefarious purposes may restrict the short-term growth of synthetic biology.[54]

[51]The Royal Academy of Engineering, *Synthetic Biology*.

[52]Matthew Charles Edmundson and Louise Horsfall, "Construction of a modular arsenic-resistance operon in E. coli and the production of arsenic nanoparticles," *Frontiers in Bioengineering and Biotechnology, 3, 160* (2015).

[53]Crystal Market Research, *Synthetic Biology Market by Product and Application: Global Industry Analysis and Forecast to 2025* (New York, NY: NASDAQ OMX Corporate Solutions, Inc., November 2017).

[54]The National Academies of Sciences, Engineering, and Medicine, *Biodefense in the Age of Synthetic Biology*, (Washington, D.C.: The National Academies Press: 2018); and *Synthetic Biology Market*.

Multiple Federal Agencies and Nonfederal Entities Support Quantum Computing and Synthetic Biology Research for Transformational Technological Advances

Multiple federal agencies and nonfederal entities support quantum computing and synthetic biology research that could lead to transformational technological advances in many areas of the U.S. economy, including energy, medicine, and national security.[55] We identified 6 agencies that in fiscal year 2016 through the second quarter of fiscal year 2018 supported quantum computing research to advance foundational understanding of quantum computing or to develop related hardware and software. We found that 4 of the 6 agencies reported a combined total of at least $23.4 million in obligations to support quantum computing research in fiscal year 2017.[56] Similarly, we identified 10 agencies that, during the timeframe we reviewed, supported synthetic biology research to advance foundational understanding of synthetic biology or knowledge of how to apply it in bioengineering, national security, and biofuels development. We found that 6 of the 10 agencies reported a combined total of at least $211.2 million in obligations to support synthetic biology research in fiscal year 2017.[57] We also identified a variety of nonfederal entities, such as universities and private companies, that conduct research in quantum computing and synthetic biology.

Six Agencies Support Research in Quantum Computing

In fiscal year 2017, 6 agencies—DOD, DOE, ODNI, NASA, Commerce's NIST, and NSF—supported quantum computing research, and 4 of these 6 agencies reported a combined total of at least $23.4 million in obligations toward those efforts. Agency officials, stakeholders, and experts we interviewed told us they expect quantum computers could lead to transformational advances in national security technologies or in technology areas that rely heavily on simulation, such as machine learning for defense capabilities, pharmaceuticals, and materials science

[55] There may be additional federal agencies that conduct research in quantum computing and synthetic biology that we do not discuss in this report. Additionally the federal agencies we discuss in this report may have applications in areas outside of those we present in this report.

[56] DOD and ODNI did not provide data on obligations.

[57] DHS reported that it does not have any obligations related to synthetic biology research. We were not able to collect data on obligations from NIH because the system that NIH uses to track funding of specific scientific topics does not have a category for synthetic biology. Also, ODNI and USDA did not provide data on obligations.

for advanced manufacturing.[58] However, there is still uncertainty surrounding the specific applications of quantum computing. Agency officials, stakeholders, and experts told us that they anticipate that quantum computing applications may include large number factoring, optimization of certain tasks, and simulation of other quantum systems. Accordingly, agencies' quantum computing efforts included research to advance foundational understanding of quantum information science as well as research to develop the hardware and software needed to build a universal quantum computer.

Foundational Understanding of Quantum Information Science

Federally supported research in areas including the physical sciences, mathematics, and engineering can help advance foundational understanding of quantum information science needed to build a universal quantum computer. Among the 6 agencies that support quantum computing research, examples of agencies' efforts to support research to advance foundational understanding of quantum science include:

- NIST supports foundational quantum research at its laboratories and at several university-based research centers. At one of these centers, the Joint Quantum Institute (JQI) at the University of Maryland, researchers are investigating quantum computing architectures and developing methods to control quantum effects that can be exploited to process information in new ways.[59] Additionally, NIST supports JILA, an institute at the University of Colorado, where scientists explore fundamental questions related to quantum information and atomic and molecular physics.[60]
- NSF supports foundational quantum computing research as part of a broader portfolio of research on quantum phenomena in the Directorates for Mathematical and Physical Sciences, Engineering, and Computer and Information Science and Engineering. For example, under its Physics Division's Quantum Information Science

[58]We define advanced manufacturing as manufacturing that uses innovative technology to improve products or processes.

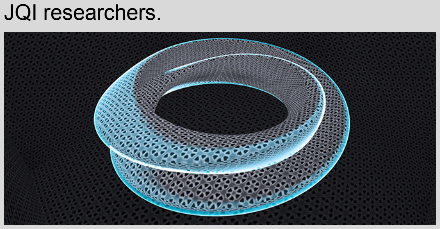
[59]The Joint Quantum Institute (JQI) was established in 2006 as a cooperative research institute between the University of Maryland and NIST to facilitate the interchange of ideas among scientists working in the fields of atomic physics, condensed matter, and quantum information. NIST also supports the Joint Center for Quantum Information and Computer Science, which was established in 2014 at the University of Maryland as a complement to the JQI.

[60]In 1995, the Joint Institute for Laboratory Astrophysics changed its name to JILA.

Joint Quantum Institute (JQI)

The JQI is a research partnership between the National Institute of Standards and Technology and the University of Maryland, with the support and participation of the Laboratory for Physical Sciences. JQI was created in 2006 to pursue theoretical and experimental studies of quantum physics in the context of information science and technology. Among other objectives, JQI conducts fundamental research on the engineering and control of systems based on quantum mechanics, which describes the behavior of matter and energy at the smallest physical scales. One attribute of quantum physics is that certain properties of a particle, such as its momentum and position, are not fixed; instead these properties follow probability distributions that describe the likelihood a property may be a particular value. Researchers have also discovered that the quantum states of two separate objects, like two atoms, can be entangled such that the state of one object is correlated with the other. This entanglement makes it possible to move quantum information from one place to another. The phenomena that occur at the quantum scale have the potential to affect disparate economic sectors and could lead to improvements in computing and materials science, among others. For example, researchers at JQI have devised a new chip that generates and steers single photons, which could allow researchers to systematically assemble pathways for single photons and enable new types of optical devices.

An illustration of a photonic chip created by JQI researchers.



Sources: JQI (text); and Emily Edwards, JQI (image). | GAO-18-656.

and Revolutionary Computing program, NSF supports theoretical and experimental research on quantum-based computing paradigms, information, transmission, and manipulation.[61] Also, the NSF Physics Division's Physics Frontiers Centers program supports university-based centers and institutes in enabling transformational advances through interdisciplinary research across different areas of focus. One of the Physics Frontier Centers that NSF supports is located at the JQI; this center supports research that focuses on studying the controlling and monitoring of quantum phenomena to support quantum engineering. A second Physics Frontier Center is at JILA. Both the JQI and JILA represent partnerships between the NSF and NIST.

- DOE's Office of Science supports foundational quantum computing research as part of its Advanced Scientific Computing Research program, which focuses on discovering, developing, and deploying computational and networking capabilities to analyze, model, simulate, and predict complex phenomena important to DOE and the advancement of science. The program's efforts include partnering with other Office of Science program offices to support research aimed at understanding how future computing technologies, including

[61]According to testimony by the NSF Assistant Director for Computer and Information Science and Engineering before the House Committee on Science, Space, and Technology's Subcommittees on Research and Technology and Energy in October 2017, this program was established in fiscal year 2005 as the Quantum Information Science and Revolutionary Computing program. *American Leadership in Quantum Technology*, Before the Subcommittee on Research and Technology and the Subcommittee on Energy, 115th Congress (2017) (statement of Dr. James Kurose, Assistant Director for Computer Science and Engineering, National Science Foundation).

those based on quantum information science, could impact DOE's mission.[62]

- NASA's Quantum Artificial Intelligence Laboratory—a collaborative effort with Google and the Universities Space Research Association—supports foundational research to maximize utilization of emerging quantum hardware. This work involves analytical and experimental research on the mechanisms underlying quantum computing, including, for example, researching quantum entanglement and measurement-based quantum computation. NASA also supports university-based quantum computing research through programs such as the Established Program to Stimulate Competitive Research (EPSCoR).[63]

Hardware Development

Agency officials and experts said that a number of unresolved technical challenges exist related to the hardware necessary to build a quantum computer, including the materials from which to build qubits. Among the 6 agencies that support quantum computing research, examples of efforts to support research to develop the hardware for building a quantum computer include the following:

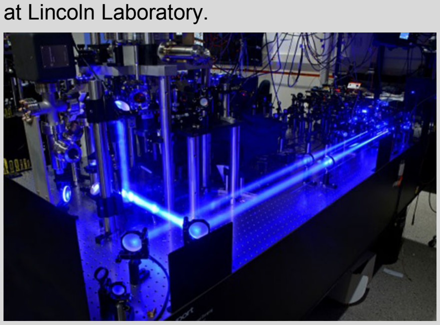
[62]The research supported by DOE's Advanced Scientific Computing Research program follows a report that summarized a February 2015 DOE-led workshop on quantum computing for science. According to the report, high-fidelity modeling and simulation of physical systems is critical for DOE to address some of the most challenging problems in energy, the environment, and national security, and DOE has a long history of advancing computation and increasing the capabilities for its high-performance computing systems to address these challenges. However, the report noted that constraints on increasing improvements to current computing approaches are leading to consideration of alternative computing approaches, including quantum computing. The February 2015 workshop was organized to assess the viability of quantum computing technologies to meet the computational requirements of DOE's science and energy mission, and to identify the potential impact of quantum technologies. The report found there is great potential for quantum computing to impact DOE's mission; however, additional research in the fundamentals of computer science and mathematics is needed to mature quantum computing technologies into viable solutions for DOE. See Department of Energy, *ASCR Report on Quantum Computing for Science,* (Washington, D.C.: February 17-18, 2015).

[63]According to a Congressional Research Service report, NSF established the EPSCoR program—originally named the Experimental Program to Stimulate Competitive Research—in 1978 to address congressional concerns about an "undue concentration" of federal research and development funding in certain states. The program is designed to help institutions in eligible states build infrastructure, research capabilities, and training and human resource capacities to enable them to compete more successfully for open federal research and development funding awards. In addition to NSF, DOE, NASA, NIH, and USDA support EPSCoR or similar programs. See Congressional Research Service, *Established Program to Stimulate Competitive Research (EPSCoR): Background and Selected Issues*, R44689 (Washington, D.C.: Jan. 12, 2017).

Lincoln Laboratory's Quantum Computing Laboratory

The Massachusetts Institute of Technology's Lincoln Laboratory is a federally funded research and development center sponsored by the Department of Defense that researches and develops a broad array of advanced technologies to meet critical national security needs. In the area of quantum information science, researchers with Lincoln Laboratory's Quantum Computing Laboratory are exploring the fundamentally different ways that information can be stored and manipulated through quantum physics. Specifically, Lincoln Laboratory researchers are working to develop and scale up two systems that could comprise the quantum bits, or "qubits" of a quantum computer. In one method, called Josephson junction-based superconducting circuits, Lincoln Laboratory researchers are using cryogenic dilution refrigerators and microwave test and measurement equipment to control and measure superconducting qubits at extremely cold temperatures. In another method, researchers are using cryogenically cooled vacuum systems to house micro-fabricated chips that trap individual strontium and calcium ions, which are manipulated using lasers and other electromagnetic fields. For both methods, researchers are working to scale up systems of qubits to a size large enough to address real computational problems.

Laser light manipulation of trapped ion qubits at Lincoln Laboratory.



Source: Massachusetts Institute of Technology's Lincoln Laboratory. | GAO-18-656

- DOD supports research related to quantum computing, as part of broader portfolios of research across the department. For example, as part of DOD's Applied Research for the Advancement of Science and Technology Priorities program, the Office of the Secretary of Defense administers the Quantum Science and Engineering Program—a cross-cutting effort that has supported research related to technologies for controlling qubit entanglement, among other things. Additionally, DOD supports a research program on Quantum System Sciences at Lincoln Laboratory, a federally funded research and development center operated by the Massachusetts Institute of Technology (MIT). This research encompasses, among other topics, development of quantum-based computation technologies.[64]
- DOE's quantum science research efforts, such as those supported by the Office of Science's Advanced Scientific Computing Research program, includes quantum computing hardware and architecture. After DOE issued its 2015 report on quantum computing for science, the agency held a February 2017 workshop to obtain information from stakeholders on the opportunities and challenges in establishing a quantum testbed to advance quantum computing hardware.[65] Subsequently, DOE issued solicitations in 2017 and 2018 for proposals to support developing quantum testbeds. According to an April 2018 announcement for one of these solicitations, a testbed laboratory will host experimental quantum computing platforms that are not yet ready for commercialization, and will function as a collaborative facility to provide internal and external researchers with access to novel, early-stage quantum computing resources.
- NIST's quantum science research efforts include projects within its Physical Measurement Laboratory that are looking at a spectrum of potential quantum computing hardware approaches, such as superconducting circuits or ion trap-based quantum computing, that could provide viable approaches for processing and manipulating quantum information. By working across multiple approaches, NIST

[64]Federally funded research and development centers are government-funded entities that have long-term relationships with one or more federal agencies to perform research and development and related tasks. These centers are typically entirely federally funded, or nearly so, but they are operated by contractors or other nongovernmental organizations. For past GAO work on these centers, see, for example, GAO, *Federally Funded Research Centers: Agency Reviews of Employee Compensation and Center Performance*, GAO-14-593 (Washington, D.C.: Aug. 11, 2014).

[65]DOE issued a report summarizing the input it received from stakeholders during its February 2017 workshop. See Department of Energy, *ASCR Report on a Quantum Computing Testbed* (Washington, D.C.: February 2017).

has been able to apply different quantum hardware platforms to address computing and metrology problems, including creating one of the most advanced ion trap-based quantum computing platforms. Furthermore, NIST is using its advanced microfabrication facilities to develop a broad array of components that will enable the scaling of different quantum computing hardware platforms.

- ODNI, through the Intelligence Advanced Research Projects Activity's (IARPA) Logical Qubits Program, is supporting research to overcome the limitations of current multi-qubit systems, whereby qubits are impacted by other qubits, environmental factors, and other forces, which can generate errors in quantum computing operations. IARPA's Logical Qubits Program is sponsoring research teams to build qubit structures with reduced susceptibility to these types of problems and has developed a quantum system with between 10 and 20 qubits.
- NSF supports research related to quantum computing hardware as part of a broader portfolio of research under its Computing and Communication Foundations Division, which supports research that explores the foundations of computing and communications devices and their usage, including advancing hardware designs for computers and computational sciences, among other focus areas. For example, under the division's Expeditions in Computing program, which provides financial assistance awards of up to $10 million over 5 years, NSF provided an award for the Enabling Practical-Scale Quantum Computation project in 2018. This project is a multi-institution, university-based effort to build a 100-qubit computer.

Software Development

Agency officials, stakeholders, and experts said one area in which a quantum computer could offer potential benefits over a classical computer is solving optimization problems. However, using a quantum computer for this or other applications requires developing software to, for example, translate algorithms into the steps to manipulate qubits to perform computing operations. Among the six agencies that support quantum computing research, examples of agencies' efforts to support research to develop software necessary to operate a quantum computer include the following:

- DOD's Air Force Research Laboratory issued a multi-year funding opportunity announcement for research on Quantum Computing Sciences with a focus on quantum computing algorithmic implementation and problem solving. Among other potential research topics, the Air Force is seeking research proposals to develop new algorithms to help solve optimization and machine learning problems.

- NASA's Advanced Supercomputing Division provides funding for the Quantum Artificial Intelligence Laboratory. Through this effort, NASA hosts a 2,031-qubit D-Wave 2000 quantum device. NASA researchers are using this system to explore the potential for quantum computers to tackle optimization problems that are difficult or impossible for traditional supercomputers to handle and to explore the software algorithms that would be needed to do so.

Ten Agencies Support Research in Synthetic Biology

In fiscal year 2017, 10 agencies—DOD, DHS, DOE, EPA, HHS, ODNI, NASA, NIST, NSF, and USDA—supported synthetic biology research, and 6 of these agencies reported a combined total of at least $211.2 million in obligations toward those efforts. According to one agency official and experts, although synthetic biology has advanced significantly, foundational understanding is still needed in some key areas, including measurement and tool development. Accordingly, synthetic biology research that federal agencies supported included research to advance foundational understanding of the science, and the application of synthetic biology in specific areas, such as bioengineering, genome editing, national security, and biofuels and bioproduct development.

Foundational Understanding of Synthetic Biology

One agency official and experts said that although synthetic biology research has made advances, additional foundational work is needed to move the area forward. For example, better measurements are needed in the area of synthetic biology and would be particularly useful for genome-editing methods. Among the 10 agencies that support synthetic biology research, officials from NASA, NIST, DOE, HHS (specifically, the National Institutes of Health (NIH)), and NSF said their agencies support research to advance foundational understanding of synthetic biology. Examples of federal efforts in this area include the following:

Genome in a Bottle

The Genome in a Bottle consortium is one of several ongoing collaborations among the National Institute of Standards and Technology, Stanford University, and other partners in the Joint Initiative for Metrology in Biology. The initiative focuses on measurements and standards supporting the newest developments in genomics and synthetic biology. The Genome in a Bottle consortium focuses on genome sequencing, which involves determining the chemical building blocks of deoxyribonucleic acid (DNA) or ribonucleic acid (RNA) and can give insights into the genes carried by an individual and how and when they are activated. Since the completion of the Human Genome Project in 2003 that first sequenced the whole genome of a human, scientists have worked to make whole human genome sequencing faster and less expensive. The consortium aims to develop the tools needed to ensure the accuracy of human genome sequencing. These tools include reference materials, standards, and data to enable the translation of whole human genome sequencing to clinical practice.

Illustration of a chromosome inside a bottle.

Sources: Joint Initiative for Metrology in Biology, the National Institutes of Health, and GAO (text); Genome in a Bottle consortium (image). | GAO-18-656

- NIST supports foundational synthetic biology research by developing measurement solutions, serving as a neutral ground for the discussion of underpinning measurements and other manufacturing needs, and leading and contributing to the development of standards. NIST measurement infrastructure includes the development of enabling tools, methods, and protocols; bioinformatics and modeling tools; and documentary standards and reference materials. NIST also leads several consortia to work with measurement stakeholders and partners to accelerate breakthroughs in genomics and synthetic biology. These include NIST's Genome in a Bottle consortium and the Joint Initiative for Metrology in Biology.[66]
- DOE supports foundational research related to synthetic biology as part of a broader portfolio of research under the Biological and Environmental Research (BER) Genomic Science program, which seeks to understand how genomic information is translated to functional capabilities, enabling more confident redesign of microbes and plants for sustainable biofuel production, improved carbon storage, or contaminant bioremediation. Within BER, DOE funds the Joint Genome Institute to produce high-throughput sequencing, a fast method of determining the order of bases of genetic material, synthesis and analysis in support of BER's bioenergy and environmental missions. Research enabled through this user facility includes developing renewable and sustainable sources of biofuels from plant biomass and exploring the biological processes controlling greenhouse gas accumulation in the atmosphere.
- Within HHS, multiple NIH institutes and centers support foundational research involving synthetic biology techniques, including NIH Common Fund support for research to understand and combat antibiotic resistance and National Cancer Institute support for research into new cancer immunotherapy methods. Additionally, the National Institute of Biomedical Imaging and Bioengineering has provided grants to researchers studying or using a multitude of synthetic biology techniques for applications, such as improving stem cell quality for biomedicine.
- NSF funds an estimated $60 million a year in foundational synthetic biology research across several directorates. For example, in 2013, NSF awarded a 5-year, $10 million Expeditions in Computing grant for

[66]The Joint Institute for Metrology in Biology is a collaboration among NIST, Stanford University, and industry partners to foster the innovation of standards-based measurement to facilitate translation of breakthroughs in genomics and synthetic biology.

a multi-university effort led by the California Institute of Technology to enable theoretical investigations in several synthetic biology-related topic areas. In 2016, NSF awarded a second 5-year, $10 million Expeditions in Computing grant for a multi-university effort led by Boston University to support synthetic biology research.

Bioengineering

Applications of synthetic biology in the field of bioengineering may lead to transformational technological advances in areas such as medicine and energy production, according to agency officials, experts, and literature.[67] Among the 10 agencies that support synthetic biology research, officials from DOD, NASA, EPA, NSF, and NIH said their agencies support synthetic biology research related to bioengineering applications. Examples of federal efforts in this area include the following:

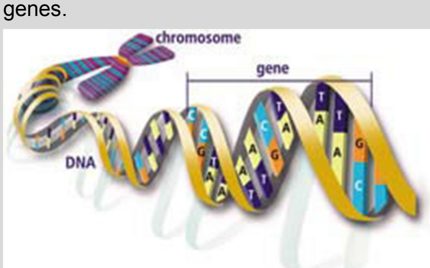
- DOD's DARPA is leveraging biotechnologies, such as synthetic biology, to develop new organisms with unprecedented behaviors and capabilities. DARPA's Living Foundries program funds researchers who are developing the techniques and tools to reprogram living organisms to produce chemicals that would be useful across DOD and to produce a wide variety of chemical compounds that are not easily produced through traditional chemicals. DARPA's goal for the program is to use organisms to make 1,000 molecules and material precursors spanning a wide range of defense-relevant applications. In addition, DOD's Applied Research for the Advancement of Science and Technology Priorities program on Synthetic Biology for Military Environments supports collaborative cross-service synthetic biology research to position DOD to meet unique defense needs and the specific challenges presented by military environments. A key focus of the program is developing several environmental "chassis" microbes that will provide robust performance outside the lab environment. Researchers are also developing applications such as living (self-healing) materials, rugged field-deployable sensors for chemicals and other threats, and microbiome regulation/manipulation for enhanced human performance.
- NASA supports synthetic biology research in the field of bioengineering to increase the capability and reduce the risk of space exploration, and as a tool to advance hypothesis driven investigation. NASA's Advanced Exploration Systems and Game Changing

[67]We define bioengineering as the application of principles and techniques from engineering to biological systems.

Gene Editing

The National Institutes of Health (NIH) describes gene editing as a group of technologies that give scientists the ability to add, remove, or alter genetic material at particular locations in the genome. One such technology is known as CRISPR-Cas9, which is short for clustered regularly interspaced short palindromic repeats and CRISPR-associated protein 9. According to NIH, the CRISPR-Cas9 system has generated excitement in the scientific community because it is faster, cheaper, more accurate, and more efficient than other existing gene editing methods. The system was adapted from a naturally occurring gene editing system that helps bacteria defend themselves against viruses by targeting the deoxyribonucleic acid (DNA) of the virus. In the lab, CRISPR-Cas9 allows researchers to cut out a specific sequence of DNA from cells. Once researchers cut out the targeted DNA sequence, they can use other techniques to add or delete genetic material. These genetic changes can cause the edited cells to express new physical traits, such as eye color, or change their disease risk. Gene editing is being applied to research on many diseases; however, according to NIH, there are still significant technical barriers to using gene editing therapies to treat human diseases. Further, the use of gene editing raises a number of ethical concerns.

An illustration of a chromosome unravelling to show the DNA that makes up individual genes.



Sources: NIH (text); U.S. Department of Energy (image). | GAO-18-656

Development programs are developing on-demand nutrients from microbes engineered to produce targeted nutrients for human consumption as well as examining how to manipulate certain types of bacteria to produce lightweight construction tools and materials.

- EPA employs synthetic biology approaches through its Chemical Safety for Sustainability Research Program, which seeks to develop new prediction techniques, pioneer the use of innovative technologies for chemical toxicity testing, and design tools to advance the management of chemical risks. For example, researchers are developing virtual tissues by building complex computer models for biological development. According to an EPA publication, the models will help reduce dependence on animal study data and provide faster chemical risk assessments.
- NSF's Science and Technology Center Program's Center for Cellular Construction seeks to develop tools to predict, design, and test the impact on cellular function of changes to cells' internal organization. The center will also develop living "bioreactors" that will generate products of commercial value. NSF has funded research into bacterial immunity, which led to the development of clustered regularly interspaced short palindromic repeats (CRISPR)-Cas9—a technology that allows researchers to precisely edit genes.[68]
- Several NIH institutes and centers support research related to bioengineering. For example, NIH's Synthetic Biology for Engineering Applications Funding Opportunity Announcement solicits applications to support research to advance the understanding and application of synthetic biology for human health. In addition, NIH institutes and centers have supported research across various areas, including engineering synthetic receptor systems and genetic controller circuits, engineering microbes as therapeutic platforms, and developing enabling technologies for human-machine hybrid tissues.

[68]NIH-funded research has also been instrumental to the discovery, understanding, and continued development and application to human health of technologies employed in synthetic biology research such as CRISPR-Cas9 and other gene editing tools.

National Security

Application of synthetic biology may support U.S. national security efforts by aiding with monitoring for biological or conventional threats, and strengthening the resilience of soldiers in combat. Among the 10 agencies that support synthetic biology research, officials from DOD, ODNI, and DHS said their agencies support synthetic biology research with potential national security applications. Examples of federal efforts in this area include the following:

- DOD's Office of Naval Research funds research to extend the natural capabilities of living organisms such as microbes and plants to create systems that will provide new naval capabilities, according to the office's website. Office of Naval Research officials told us the office is funding ongoing research related to engineering gut microbes in order to enhance the resilience of service members to deployment stressors, among other things. In addition, DARPA's Safe Genes Project supports force protection and military health and readiness by protecting service members from accidental or intentional misuse of genome-editing technologies. For example, researchers are developing the genetic circuitry and genome-editing machinery for robust, spatial, temporal, and reversible control of genome-editing activity in living systems.
- ODNI supports synthetic biology research through efforts including IARPA's Functional Genomic and Computational Assessment of Threats program, which supports research to protect against critical threats related to pathogens and other biological threats. Researchers aim to develop better approaches and tools for characterization and analysis of biological threats based on gene function.
- DHS's Biological Threat Characterization program and its Biodefense Knowledge Center program support synthetic biology research to understand the risks associated with the technologies useful for synthetic biology and the harmful pathogens that may be created by those who wish to do harm.[69]

Biofuels and Bioproducts

Synthetic biology is being used to develop cost-effective methods for producing biofuels and bioproducts according to agency officials, experts,

[69]The Biological Threat Characterization program conducts experiments and studies to better understand biological vulnerabilities and hazards. The Biodefense Knowledge Center is a DHS Science and Technology center that produces assessments and tools that help the homeland security community better understand scientific trends that may be exploited by adversaries bent on developing biological weapons or executing biological terrorism.

and DOE's website.[70] Among the 10 agencies that support synthetic biology research, officials from DOE and USDA said their agencies support synthetic biology research related to biofuels development applications. Examples of federal efforts in this area include the following:

- DOE officials told us that the Office of Energy Efficiency and Renewable Energy's Bioenergy Technologies Office manages the Conversion Program and the Advanced Algal Systems Program, both of which employ synthetic biology techniques to accomplish office goals. Within the Conversion Program, DOE funds the Agile BioFoundry to help develop and transition synthetic biology tools from the laboratory to the biofuels and bioproducts industry. The program accomplishes this through targeted research and development partnerships with industry and academia, as well as by developing integrated synthetic biology tools designed to speed up biomanufacturing. In addition, the office funds the Advanced Algal Systems Program, which supports early-stage applied research to apply synthetic biology approaches to alternative fuels that use algae as their source, among other things. According to a DOE website, this industry has the capability of producing billions of gallons per year of renewable diesel, gasoline, and jet fuel.
- USDA, through the Agricultural Research Service, led a collaborative project between federal, industry, and academic researchers to produce a commercial rubber-based tire using the guayule plant, a small shrub native to the United States that has been considered a possible alternative source of natural rubber.

Nonfederal Entities Support Research in Quantum Computing

Nonfederal research to advance quantum computing includes efforts to address existing hardware and software challenges. We identified a variety of nonfederal entities, such as universities and private companies, that have ongoing efforts aimed at building a quantum computer. Stakeholders we spoke to told us that private companies have been increasing their research in quantum computing.

[70]According to the Department of Energy, biofuels are liquid, solid, or gaseous fuel derived from renewable biomass. Biological materials can be used to produce such fuels as biodiesel, ethanol, methanol, methane, and hydrogen. Bioproducts are materials derived from renewable feedstocks. Examples include paper, ethanol, and palm oil.

Hardware Development

Academic and industry stakeholders we interviewed described various efforts to develop the hardware needed for a quantum computer. Examples of ongoing efforts include the following:

- Academic researchers at Purdue University partner with Microsoft at Station Q-Purdue to perform a variety of experiments and activities related to building a semiconductor-based quantum computer, including testing different hardware designs.[71]
- Academic researchers from Yale's Quantum Institute are working to develop scalable superconducting devices.
- Researchers at IonQ are working to develop general-purpose quantum information processors using a trapped-ion approach to create a quantum computer that is scalable and that could support a broad array of applications across a variety of industries.
- A Google official told us that the company has been working for several years to build a quantum computer through the Quantum Artificial Intelligence Lab. In a March 2018 press release, Google announced its newest 72-qubit quantum computer, called Bristlecone.

Software Development

Academic and industry stakeholders we interviewed described ongoing efforts related to software development. Examples of ongoing efforts include the following:

- An official from Microsoft said the company is working to develop quantum algorithms and software to run on a quantum computer for a given set of problems. Researchers are also currently developing an operating system and various applications that could be run on a quantum device.
- An IBM official told us that, in 2016, the company launched the Quantum Experience, a quantum computing system with five superconducting qubits on the cloud, encouraging students and researchers worldwide to explore quantum computing. Over the past two years, the system's software has been expanded and upgraded for greater functionality and exploration of quantum algorithms to allow researchers around the world to use the system to write more

[71]Microsoft's partners include the University of California, TU Delft, Niels Bohr Institute, University of Sydney, Purdue University, University of Maryland, ETH Zurich, and other institutions around the world.

than 80 research publications. MIT and many other universities now use the Quantum Experience in their curricula.

Nonfederal Entities Support Research in Synthetic Biology

We identified a variety of nonfederal entities, such as universities and private companies, that conduct research in synthetic biology to advance foundational understanding and develop new products.

Foundational Understanding of Synthetic Biology

The iGEM Foundation

The International Genetically Engineered Machine (iGEM) Foundation is an independent, non-profit organization dedicated to the advancement of synthetic biology, education and competition, and the development of an open community and collaboration. The foundation does these by fostering an open, cooperative community and friendly competition. The main iGEM program is the iGEM competition, which began in January 2003 as an independent study course at the Massachusetts Institute of Technology in which students developed biological devices to manipulate cells. This course became a summer competition with 5 teams in 2004, grew to 13 teams in 2005, and had expanded to 310 teams by 2017, reaching more than 40 countries. The competition was originally aimed at college students but has expanded to include high school students and others. The iGEM competition gives students the opportunity to push the boundaries of synthetic biology by tackling everyday issues facing the world. Multidisciplinary teams made up of primarily university students work together to design, build, test, and measure a system of their own design using interchangeable biological parts and standard molecular biology techniques. Every year nearly 6,000 people dedicate their summer to iGEM and then come together in the fall to present their work and compete at the annual Jamboree.

A picture of the iGEM logo.

Sources: iGem Foundation (text); iGem Foundation and Justin Knight (image). | GAO-18-656

Nonfederal stakeholders we interviewed described efforts to advance synthetic biology through activities they initiated as well as through efforts they led with support from federal and industry partners. These efforts include the following:

- The International Genetically Engineered Machine (iGEM) Foundation hosts an annual worldwide synthetic biology competition in Boston, the iGEM Giant Jamboree. The competition attracts teams from around the world (primarily university students) to use standardized genetic parts to address real-world problems in fields including health, medicine, manufacturing, and bioenergy.
- At MIT's Synthetic Biology Center, researchers work with federal and industry partners to advance understanding of synthetic biology for genetic programming, DNA synthesis, and genome design. Researchers at the Synthetic Biology Center seek to create a programming language for living cells that is similar to languages used to program computers and robots.

Development of New Products and Technologies

DNA Storage

To facilitate storing an ever-increasing amount of digital data, researchers from Microsoft, in collaboration with the University of Washington, are studying the use of synthetic deoxyribonucleic acid (DNA) as a means of storing data. According to a Microsoft researcher, this technology uses a process by which custom sequences of synthetic DNA are produced or manufactured to store information. The researcher described three main advantages of storing data in DNA as compared to the current means of storing data, generally magnetic and optical media:

Density. DNA may allow for the storage of up to 1 exabyte (one quintillion bytes) of data per cubic millimeter. In comparison, according to Microsoft, storing similarly large volumes of data in optical discs would occupy significant physical space.

Durability. Data could be stored in DNA for thousands of years, according to one Microsoft researcher.

Relevance. DNA would always remain a relevant storage mechanism, unlike other means of storing digital data (e.g., floppy discs), which becomes outdated as technology advances.

Source: Microsoft. | GAO-18-656

Industry stakeholders we interviewed described various efforts to develop new products and technologies based on synthetic biology, such as biosensors, new data storage technologies, and bioengineering techniques. These efforts include the following:

- IBM researchers are developing biosensors that may be used for the early detection of cancer. They are also working on understanding and analyzing cardiac, neurological, and mental health conditions.
- Researchers from Microsoft said the company is conducting research related to data storage using synthetic DNA as the information preservation medium. This storage technology uses a process by which custom sequences of synthetic DNA are manufactured to store information.
- Ginkgo Bioworks officials said the company is focused on trying to de-risk supply chains and improve supply chain management through synthetic biology approaches. To that end, the company designs custom enzymes for a variety of customers including companies in a wide range of industries such as food and fragrance companies.
- The Energy Biosciences Institute is a partnership among the University of California, DOE’s Lawrence Berkeley National Lab, and the University of Illinois. Researchers at the Energy Biosciences Institute carry out research in the areas of biofuels, carbon sequestration, and sustainable chemicals productions, among other things.

Agencies Coordinate Research through a Range of Efforts, but Interagency Groups Have Not Fully Implemented Selected Leading Practices

Agency officials we interviewed said they coordinate on quantum computing and synthetic biology research through a range of efforts, but we found that certain efforts are new and that agencies have not fully implemented selected leading practices for collaboration in these efforts. Agency officials told us they use means of coordination ranging from attending ad hoc meetings, such as conferences or workshops, to participating in ongoing interagency groups, such as interagency groups on quantum information science (QIS) and synthetic biology. However, we found that new interagency groups on QIS and synthetic biology have not fully implemented leading practices that can enhance and sustain collaborative efforts.

Agencies Coordinate on Quantum Computing and Synthetic Biology Research Using Efforts That Range from Ad Hoc Meetings to Ongoing Interagency Groups

Agency officials said that they coordinate on quantum computing and synthetic biology research by attending ad hoc meetings, as well as through ongoing efforts such as participating in interagency working groups. The means of coordinating that officials most frequently cited were participating in working groups or attending a conference or workshop. Meetings such as these bring together representatives of different agencies or departments to discuss common problems, exchange information, or develop agreements on issues of mutual interest, as we have reported in the past.[72] Specifically:

- Officials from 4 of the 6 agencies that support quantum computing research said they attended a conference or workshop related to quantum computing at some point from October 2015 through March 2018. For example, NASA and DOE officials participated in a 2017 NASA workshop that brought together experts from NASA research centers, DOE national laboratories, academia, and industry to discuss quantum information science and computation.[73]
- Officials from all 10 agencies that support synthetic biology research cited attendance at a conference, and officials from 7 of these 10 cited workshops as a way in which they coordinated on synthetic biology research from October 2015 through March 2018. For example, officials from DOD, DOE, NIST, and national laboratories attended a

[72]GAO, *Managing for Results: Key Considerations for Implementing Interagency Collaborative Mechanisms*, GAO-12-1022 (Washington, D.C.: Sept. 27, 2012).

[73]NASA hosted the Quantum Computing for Aerospace and Engineering workshop on Nov. 7-8, 2017, in Suffolk, Virginia.

4-day conference in June 2017 to discuss synthetic biology applications in genetic engineering.[74]

- Officials from 7 of the 10 agencies that support synthetic biology research also said they coordinated research with other selected agencies through communities of practice or consortia that meet on an ad hoc basis. For example, NASA officials said they support synthetic biology work through the Space Technology Research Institute in Biomanufacturing, a University of California Berkeley-led consortium of universities.

Officials we interviewed also said they coordinate with one another through ongoing efforts, such as interagency groups. For example, on June 21, 2018, NSTC established the Subcommittee on Quantum Information Science (QIS Subcommittee) to coordinate quantum computing research.[75] According to its June 2018 charter, the QIS Subcommittee's purpose is to establish and maintain a national agenda in quantum information science and technology, expand U.S. economic and national security, and coordinate federal quantum information science and technology policy and programs. The functions of the QIS Subcommittee include to

- issue and update plan(s) that coordinate(s) federal policy to expand U.S. leadership in quantum information science and technology;
- enable stakeholders to invest effectively in quantum information science and technology and post-quantum application spaces through data gathering, analysis, consultation, planning, convening, and reporting; and
- provide a forum for research and development coordination and collaboration, including sharing expertise and best practices for program management and conducting joint workshops and program reviews.

[74]The Synthetic Biology: Engineering, Evolution and Design conference was held in Vancouver, British Columbia, in June 2017.

[75]The Subcommittee on Quantum Information Science is under NSTC's Committee on Science.

The QIS Subcommittee is led by co-chairs from NIST, DOE, NSF, and OSTP and includes 9 additional agencies.[76] The QIS Subcommittee met for the first time as an official chartered group on June 28, 2018. The OSTP official serving as a co-chair for the QIS Subcommittee said that the group's first priority will likely be to develop a national approach to QIS research and development.

Officials from 5 of the 6 agencies that support quantum computing research said that prior to the formation of the QIS Subcommittee, they coordinated through the NSTC Interagency Working Group on Quantum Information Science (QIS working group), which was formed in 2014.[77] In July 2016, the QIS working group produced a report, which the agency officials serving as the group's co-chairs told us included its strategic plan for federal QIS research.[78] The July 2016 report identified QIS as a priority for federal coordination and investment as a component of U.S. scientific leadership, national security, and economic competitiveness. The QIS Subcommittee co-chair from OSTP said that the shift from a working group to a subcommittee is a significant elevation that communicates the importance of QIS to the administration.

Agencies also coordinated synthetic biology research through interagency working groups. Officials from NSF and USDA told us that, in December 2017, they formed a new synthetic biology working group that had 7

[76]The QIS Subcommittee's member agencies include DOD, DOE, DHS, Department of the Interior, HHS, NASA, NIST, NSF, National Security Agency, ODNI, Department of State, and USDA. Members also include the Office of Management and Budget and OSTP from the Executive Office of the President.

[77]The following agencies were members in the QIS working group: DOD, DOE, DHS, NIST, NSF, National Security Agency, and ODNI. The Office of Management and Budget, OSTP, and National Security Staff from the Executive Office of the President were also members. NASA was not a member until 2018, according to agency officials. The QIS working group was preceded by the NSTC Committee on Technology's Subcommittee on Quantum Information Science, which was tasked with developing a vision for federal QIS research. This committee produced the report, *A Federal Vision for Quantum Information Science* (Washington, D.C.: Jan. 5, 2009).

[78]National Science and Technology Council, *Advancing Quantum Information Science*.

member agencies as of February 2018.[79] These officials said that the participating agencies saw a need for continued communication and information sharing, and the officials said the group's efforts will increase coordination. Prior to the formation of this new group, 7 of the 10 agencies that support synthetic biology research participated in an NSTC Synthetic Biology Working Group that NSF officials said existed from 2012 to 2013 and was co-chaired by DOD and DOE,[80] according to a 2013 DOE report to Congress that the group produced.[81] According to some officials, the working group ended after it produced this report, which described synthetic biology research and development needs at the time and identified which federal agencies were planning synthetic biology research. The report also discussed the need for communication and coordination among federal agencies that support basic and applied synthetic biology research to build synergies, consider new research and development needs, and evaluate issues as they emerge. According to a senior NSF official we interviewed who was helping lead efforts to establish the new group, one of its first undertakings will be to update the 2013 report to provide a roadmap for agencies' synthetic biology research. However, the official also stated that the participating agencies were still considering the new group's activities.

[79]Officials from USDA and NSF said that, in addition to their agencies, the working group includes representatives from DOD, DHS, DOE, ODNI, NASA, and OSTP. According to DOD and NSF officials, some member agencies first met in September 2017 to discuss the group. Officials from DHS and EPA also cited the Technical Working Group on Security Risks Associated with Applications Enabled by Advances in Genome Editing and Synthesis Technologies and Other Related Enabling Technologies, chaired by DHS, HHS and OSTP, as a working group through which synthetic biology was discussed in the context of security risks.

[80]According to a DOD official, after the synthetic biology working group ended, officials from several agencies participated in quarterly phone calls from 2014 through 2015 to discuss synthetic biology programs.

[81]Department of Energy, *Synthetic Biology Report to Congress* (Washington, D.C.: July 2013). The interagency Synthetic Biology Working Group was created in response to a Congressional directive to develop a comprehensive plan for federally supported synthetic biology research and development activities. The 7 agencies involved in this working group were USDA, Commerce, DOD, DOE, HHS, NASA, and NSF.

Agencies Are Coordinating on Quantum Computing and Synthetic Biology through New Interagency Groups, But Have Not Fully Implemented Leading Collaboration Practices

By recently establishing the QIS Subcommittee and a synthetic biology working group, NSTC and federal agencies, respectively, took steps to further coordination on quantum computing and synthetic biology research. However, the new subcommittee and working group have not fully implemented leading practices for collaboration.[82]

We have reported that effective collaboration can help reduce or better manage fragmentation, overlap, and duplication of federal programs.[83] As described above, a number of federal agencies support research related to quantum computing and synthetic biology. In our April 2015 guide to evaluating and managing fragmentation, overlap, and duplication, we define fragmentation as those circumstances in which more than one federal agency, or organization within an agency, is involved in the same broad area of national need, and opportunities exist to improve service delivery.[84] This definition applies concerning federal agencies' quantum computing and synthetic biology research, with more than one agency involved in the same broad area of national need. However, as shown in our description above of the agencies' support for research in these two areas, agencies' activities sometimes differ in meaningful ways or leverage the efforts of other agencies.

We examined agencies' efforts to coordinate through interagency groups by selecting six leading practices that we have previously identified can enhance and sustain interagency collaboration:[85]

- **Define and articulate a common outcome.** Effective collaboration requires agencies to define and articulate common outcomes or

[82]GAO-06-15 defines collaboration broadly as any joint activity that is intended to produce more public value than could be produced when the agencies act alone.

[83]GAO, *Fragmentation, Overlap, and Duplication: An Evaluation and Management Guide*, GAO-15-49SP (Washington, D.C.: Apr. 14, 2015). GAO-15-49SP defines overlap as when multiple agencies or programs have similar goals, engage in similar activities or strategies to achieve them, or target similar beneficiaries. GAO-15-49SP defines duplication as instances when 2 or more agencies or programs are engaged in the same activities or provide the same services to the same beneficiaries.

[84]GAO-15-49SP.

[85]GAO-06-15. Because we focused our review on activities of the interagency groups and not on the individual agencies, we excluded from our review two key practices related to reinforcing agency accountability and individual accountability for collaborative efforts.

purposes they are seeking to achieve that are consistent with their respective agencies' goals and missions.

- **Establish mutually reinforcing or joint strategies.** Having mutually reinforcing or joint strategies enables agencies to align activities, core processes, and resources to achieve a common outcome.
- **Identify and address needs by leveraging resources.** Agencies can sustain their collaborative efforts by identifying the human, information technology, physical, and financial resources necessary to achieve identified outcomes.
- **Agree on roles and responsibilities.** By defining and agreeing on roles and responsibilities, including leadership, collaborating agencies can better clarify who will do what, organize their joint and individual efforts, and facilitate decision making.
- **Establish compatible policies, procedures, and other means to operate across agency boundaries.** Agencies can facilitate collaboration by addressing the compatibility of standards, policies, procedures, and data systems that will be used in the collaborative effort.
- **Develop mechanisms to monitor, evaluate, and report on results.** Creating the means to monitor and evaluate collaborative efforts enables agencies to identify areas for improvement.

We identified limitations in agencies' past efforts to coordinate quantum computing and synthetic biology research. In the area of quantum computing, the QIS working group—which preceded the subcommittee—took steps to implement selected leading practices for collaboration, but the group did not fully implement these practices. For example, the QIS working group's July 2016 report broadly identified quantum computing research needs but did not identify common outcomes for agencies' collaborative efforts to advance QIS, including quantum computing. The three senior officials who served as co-chairs of the QIS working group said they were not aware of any federal goals or outcomes for quantum computing research, and DOE officials said that clarifying common goals could help interagency collaboration on quantum computing research. Officials from some agencies cited challenges with collaborating on joint quantum computing projects—for instance, because of variations among agencies on time frames for providing financial assistance.

OSTP officials described the establishment of the QIS Subcommittee as an effort to further previous coordination conducted through the QIS working group. While the QIS Subcommittee has taken initial steps to implement certain leading practices for collaboration, it has not fully implemented the relevant leading collaboration practices we identified. For example, by developing a charter that identifies its high-level purpose and functions and that identifies co-chairs for the group, the QIS Subcommittee has taken initial steps to identify some agencies' roles and to establish means for operating across agency boundaries. Moreover, by having a charter signed by senior officials, the QIS Subcommittee has taken steps to document agencies' agreement to collaborate, which is a key feature of collaborative mechanisms we have identified in our prior work.[86] However, the working group has not defined roles and responsibilities for agencies other than the co-chairs. OSTP officials said that efforts to date have focused on ensuring that all relevant agencies are included in the QIS Subcommittee; the officials also said that agencies' roles and responsibilities for contributing to the subcommittee will evolve.[87] Table 1 provides additional information on the extent to which the QIS Subcommittee has implemented leading practices for collaboration.

[86]GAO-12-1022.

[87]Ensuring that all relevant agencies are included is another key feature of collaborative mechanisms we identified in GAO-12-1022.

Table 1: Extent of Implementation of Selected Leading Practices for Collaboration by the Quantum Information Science (QIS) Subcommittee, as of June 2018

Leading collaboration practice	Status of QIS Subcommittee efforts
Define and articulate a common outcome	• QIS Subcommittee charter identifies the subcommittee's high-level purpose and functions. • Office of Science and Technology Policy (OSTP) officials said the subcommittee has not yet determined whether it will define and articulate common outcomes as part of an effort to develop a long-term plan to address QIS challenges.
Establish mutually reinforcing or joint strategies	• OSTP officials said a first step will be to develop a national approach and plan for QIS research and development.
Identify and address needs by leveraging resources	• OSTP officials said a main goal is to coordinate the agencies' efforts and work through the agencies to achieve goals.
Agree on roles and responsibilities	• QIS Subcommittee charter identifies certain agencies as co-chairs for the group. • Other member agencies' roles and responsibilities have not been identified, as of June 2018. • OSTP officials said that agencies' roles and responsibilities are still evolving.
Establish compatible policies, procedures, and other means to operate across agency boundaries	• QIS Subcommittee charter outlines the purpose and scope of the subcommittee, its functions and membership, the potential for seeking private sector advice as needed, and the subcommittee's termination date. • Specific policies and procedures for collaborating across agency boundaries have not been established, as of June 2018.
Develop mechanisms to monitor, evaluate, and report on results	• QIS Subcommittee charter states that one function of the group includes reporting.[a] • OSTP officials said that no particular mechanism has been identified, as of June 2018.

Source: GAO analysis of information provided by OSTP officials. | GAO-18-656

[a]According to the QIS Subcommittee charter, this function is: Enable stakeholders to invest effectively in quantum information science and technology and post-quantum application spaces through data gathering, analysis, consultation, planning, convening, and reporting.

With regard to interagency coordination on synthetic biology research, NSF and USDA officials noted that the new synthetic biology working group hoped to, through continued communication and information sharing, address limitations in agencies' coordination that existed prior to its formation. Officials from NSF said the group was needed for communication, information sharing and to leverage resources and DOD officials agreed that the working group was needed. Additionally, one DOD official and one expert said that limited interagency coordination had resulted in lost opportunities to further develop the area of synthetic biology. They also noted that having a national strategy for synthetic biology would be beneficial. Other officials noted that, as in the area of quantum computing, differences in funding timeframes across agencies hinder their ability to coordinate their synthetic biology research. Some of these officials also said such differences make it difficult to develop an integrative roadmap for their research.

Like the QIS Subcommittee, the new synthetic biology working group has taken initial steps to implement some leading practices for interagency collaboration but has not fully implemented the relevant leading collaboration practices we have identified. For example, the group has taken initial steps to identify member agencies' roles by having NSF serve as the lead agency for the first 2 years. However, the group has not identified other member agencies' roles and responsibilities. An NSF official said the new working group had also considered developing a document, such as a charter, to guide its efforts but, as of June 2018, it had not yet decided whether to do so. Table 2 provides additional information on the extent to which the Synthetic Biology Working Group has implemented leading practices for collaboration.

Table 2: Extent of Implementation of Selected Leading Practices for Collaboration by the Synthetic Biology Working Group, as of June 2018

Leading collaboration practice	Status of Synthetic Biology Working Group efforts
Define and articulate a common outcome	• National Science Foundation (NSF) officials said the working group will include a roadmap for agencies' synthetic biology research in an update of a 2013 report to Congress on synthetic biology. • NSF officials said there is no time frame for producing the update to the 2013 report.
Establish mutually reinforcing or joint strategies	• NSF officials said the group will update a 2013 report to Congress on synthetic biology that will provide visibility into what is in each agency's portfolio and look for opportunities to collaborate.
Identify and address needs by leveraging resources	• NSF officials said the group will update a 2013 report to Congress on synthetic biology, which will enable agencies to identify where they can collaborate to advance the field.
Agree on roles and responsibilities	• NSF identified as the lead agency for the first 2 years. • Roles of member agencies other than NSF have not been identified, as of June 2018. • Some member agencies have taken responsibility for drafting sections of a report that will update a 2013 report to Congress on synthetic biology. • Other responsibilities have not been identified, as of June 2018.
Establish compatible policies, procedures, and other means to operate across agency boundaries	• No steps taken to establish policies, procedures, or means to operate across agency boundaries, as of June 2018.
Develop mechanisms to monitor, evaluate, and report on results	• No steps taken to develop mechanisms to monitor, evaluate, and report on results, as of June 2018.

Source: GAO analysis of information provided by NSF officials. | GAO-18-656

As we previously reported, interagency collaborative mechanisms can take many different forms, such as working groups or subcommittees, and the leading practices we identified that help enhance and sustain interagency collaboration can be adapted to help address the specific challenges agencies face.[88] For example, incorporating the leading practices into agencies' collaborative efforts can help address issues associated with potential fragmentation, overlap, and duplication in instances where multiple agencies have activities in a similar area. The QIS Subcommittee and the synthetic biology working group are mechanisms through which agencies can address limitations in past interagency coordination on quantum computing and synthetic biology. However, as of July 2018, the subcommittee and working group were still new and have had limited time to fully implement the leading practices we have identified. As the subcommittee and the working group move

[88] GAO-06-15.

forward, by taking steps to fully implement these leading practices, member agencies could better marshal their collective efforts to support research in the areas of quantum computing and synthetic biology and help maintain U.S. competitiveness through transformational technological advances.

Experts Identified Key Considerations for Maintaining U.S. Competitiveness through Transformational Technological Advances

Experts who participated in the meeting we convened with the assistance of the National Academies identified four key considerations for maintaining U.S. competitiveness through transformational technological advances. These considerations extend beyond quantum computing and synthetic biology, and more broadly address the role of federal and nonfederal entities in supporting research for such advances. The key considerations experts identified were (1) developing a strategic approach for transformational technology, (2) fostering information sharing, (3) focusing on technology development and commercialization, and (4) strengthening the science and technology workforce.[89]

Developing a Strategic Approach for Transformational Technology

Experts emphasized the importance of developing a strategic approach for advancing potentially transformational technologies for maintaining U.S. competitiveness.

Experts explained that there are multiple methods for strategic approaches and one of these experts explained that different methods can be effective for different research areas. However, experts described two key aspects of a strategic approach: (1) mechanisms to bring

[89]The evidence presented in this section is primarily based on GAO's analysis of a transcript of this meeting. During the meeting, experts provided presentations, which were followed by open discussion among all meeting participants. After the end of each session, an expert summarized what was conveyed and other experts were afforded an opportunity to agree or disagree with the characterization of what was discussed. In addition, we conveyed to experts our interpretation of their statements for their input and correction. For purposes of quantifying expert remarks, we refer to a statement from an individual expert as being from one expert, and unless there is significant disagreement in the transcript of the meeting, we refer to statements from two or more experts as being from experts. In cases of significant disagreement in the transcript, we refer to statements from two to three experts as being from a few experts, and statements from four to six experts as being from some experts. We did not ask experts to come to a consensus or agreement on the topics discussed. This section also includes information from interviews with stakeholders and agency officials and other written documentation.

together potential partners such as through partnerships or consortia and (2) future-oriented technology planning such as through roadmaps or grand challenges. We further describe these aspects below:

- **Partnerships and consortia.** Experts described how partnerships and consortia provide a means of bringing together stakeholders from across different sectors—including the public, private, or academic sectors—to support development of transformational technologies. According to experts, partnerships and consortia can provide a means of strategically organizing the shared resources of different stakeholders and identifying what is needed, such as pre-competitive research to develop a technology, and how that technology might be used.[90] Experts noted examples of partnerships and consortia to support technology development:
    - **Manufacturing USA institutes.** One expert described the 14 Manufacturing USA institutes as a model for coordination and as the largest recent U.S. technology development project.[91] As we reported in April 2017, each institute is a public-private partnership between a sponsoring federal agency (DOD, DOE, or Commerce) and a nonfederal entity (generally a nonprofit organization or university) in charge of the institute's operations.[92] Each institute

[90]Pre-competitive research represents research and development activities up to the stage at which technical uncertainties are sufficiently reduced to permit preliminary assessment of a technology's commercial potential. This stage of research occurs prior to the development of application-specific technology prototypes.

[91]The Manufacturing USA institutes were established after a series of reports by the President's Council of Advisors on Science and Technology. The reports' recommendations included that the federal government establish a national network of manufacturing innovation institutes as public-private partnerships to create a manufacturing research infrastructure to help bridge the gap between research and development activities and domestic production. See, for example, President's Council of Advisors on Science and Technology, *Report to the President on Ensuring American Leadership in Advanced Manufacturing*, and President's Council of Advisors on Science and Technology, *Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing*. In 2012, at the request of the President and using existing statutory authorities, DOD, with co-funding and participation from DOE and other agencies, established a pilot manufacturing innovation institute focused on additive manufacturing. Subsequently, DOD and DOE established additional institutes using their existing statutory authorities. The Revitalize American Manufacturing and Innovation Act of 2014 called for the Secretary of Commerce to establish a Network for Manufacturing Innovation program. Pub. L. No. 113-235, § 703(2), 128 Stat. 2220, 2221 (2014) (codified at 15 U.S.C. § 278s). In September 2016, the Secretary of Commerce announced a new public name for the program, Manufacturing USA.

[92]See GAO-17-320.

Lessons Learned from the SEMATECH Consortium

In the face of international competition during the 1980s, the U.S. semiconductor industry took steps to strengthen its domestic capabilities. In one such step, U.S. semiconductor companies formed the Semiconductor Manufacturing Technology (SEMATECH) consortium in 1987 to further semiconductor manufacturing technology. SEMATECH received federal financial assistance through 1996, after which its leadership chose not to solicit continued federal support because of improvement in the U.S. semiconductor industry's competitiveness. In a September 1992 report, GAO provided lessons learned from the federal government's participation in SEMATECH and identified several considerations for future consortia, including that they:

- are industry-led and industry provides at least half of the annual funding because industry can best design a research program to meet its needs;
- develop a comprehensive industry assessment and prepare an operating plan that identifies realistic objectives and milestones as a basis for receiving federal funds;
- include active participation by member companies' senior executives in establishing research priorities and overseeing technological progress;
- have a program to improve long-term working relationships between manufacturers and key suppliers, unless inappropriate for the industry's structure;
- emphasize research projects that improve an industry's overall efficiency and that have industrywide applications;
- consider ways to provide access for smaller industry members that might not have the resources to participate; and
- establish criteria for determining how or when government should end its funding.

Sources: GAO and National Research Council of the National Academies. | GAO-18-656

has a technological focus, such as additive manufacturing, advanced flexible electronics, or regenerative medicine, and includes members such as companies, nonprofit organizations, academic institutions, and federal agencies.

- **Semiconductor Manufacturing Technology consortium (SEMATECH).** Experts described SEMATECH, a nonprofit consortium that supported research and development on advanced semiconductor manufacturing, as a successful, industry-led, public-private collaboration that helped government and industry stakeholders take a strategic approach to challenges facing the U.S. semiconductor industry in the late 1980s.[93] However, Commerce's NIST officials noted that after federal support ended, SEMATECH began accepting memberships from companies from competitor countries, which led to a transfer of technology through the consortium's work outside the United States.[94]

[93]In prior reports, we and the National Research Council found that SEMATECH helped improve the U.S. semiconductor industry's competitive position. See GAO, *Federal Research: Lessons Learned from SEMATECH*, GAO/RCED-92-283 (Washington, D.C.: Sept. 28, 1992) and Charles W. Wessner, Editor, Board on Science, Technology, and Economic Policy, Policy and Global Affairs, National Research Council of the National Academies, *Government-Industry Partnerships for the Development of New Technologies* (Washington, D.C.: National Academies Press, 2002).

[94]NIST officials cautioned that the Manufacturing USA Institutes could face similar challenges after the initial period of federal support for the institutes ends.

- **Grand challenges, strategies, and roadmaps.** Experts described the importance of grand challenges, strategies, and roadmaps in supporting a strategic approach to developing transformational technologies.[95] In particular, experts described how these mechanisms help stakeholders coalesce around technology goals and organize efforts toward reaching them. Examples experts noted included the following[96]:
    - **Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative.** Experts described the BRAIN Initiative, which was launched in 2013 to build neuroscience measurement tools, as a key example of a grand challenge. The BRAIN Initiative—led by HHS (specifically NIH), NSF, and DARPA, with the participation of other federal agencies as well as foundations,[97] universities, and industry—seeks to deepen understanding of the human mind and to improve how brain disorders are treated, prevented, and cured.[98]
    - **National Nanotechnology Initiative.** Experts described the National Nanotechnology Initiative as a key example of a federal government strategic effort. The National Nanotechnology Initiative began in 2000 and is an interagency effort to bring together the nanotechnology-related activities of 28 federal agencies in an effort to enhance understanding and control of nanoscale material. The National Nanotechnology Initiative maintains a strategic plan describing the initiative's vision and goals and the strategies to achieve these goals. In discussing this

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[95]According to a 2015 report from the National Economic Council and OSTP, grand challenges are ambitious but achievable goals that harness science, technology, and innovation to solve important problems. See National Economic Council and Office of Science and Technology Policy, *A Strategy for American Innovation* (Washington, D.C.: October 2015).

[96]In addition to the examples provided, other initiatives, such as the Human Genome Initiative and NIH's Precision Medicine Initiative, among others, may also provide illustrative examples.

[97]One expert noted that foundations played a key role in promoting, convening, and creating consensus within the BRAIN Initiative.

[98]The BRAIN Initiative is working to develop new technologies to explore how the brain's cells and circuits interact at the speed of thought, ultimately uncovering complex links between brain function and behavior, through the following goals: (1) accelerating the development and application of new neurotechnologies, (2) enabling researchers to produce a dynamic picture of the functioning brain, (3) exploring brain functionality, (4) linking brain function and behavior, and (5) advancing consumer applications.

initiative, experts described how it could enable federal agencies to share information on their research and ensure that key research areas are advanced in pursuit of a long-term national nanotechnology strategy.

Grand challenges may be articulated through strategy documents and, according to experts, involve getting stakeholders to think about potentially transformational technologies in a future-oriented way. Roadmaps, according to experts, represent detailed plans to guide progress toward a technology goal. Federal agencies, industry, or others may lead roadmapping efforts, according to experts. Additionally, one expert stated that roadmaps can help accelerate technology development. Another expert noted that for some fields, such as quantum computing and synthetic biology, a technology development strategy is needed in addition to a research and development strategy because the former outlines how a technology would move forward beyond the research and development phase.

Across both of these aspects of a strategic approach, experts emphasized the importance of a sustained commitment of resources to support technology development. One expert also emphasized the importance of setting tough performance objectives without specifying how innovators will solve a problem. Experts acknowledged that developing shared national strategies is challenging in the United States, in part because of the decentralized nature of research support across multiple federal agencies.[99] However, experts also cited as strengths of the federal research system the ability of federal agencies to support multiple approaches to developing transformational technologies in accordance with their missions and the ability to evolve and try new approaches.[100]

Experts identified several indicators of when developing a strategic approach might be important to support U.S. competitiveness through transformational technological advances in a particular area. Specifically:

[99]One expert stated that establishing priorities as policy mandates—such as through OSTP-led initiatives or legislation—will cause federal agencies to prioritize these efforts and coordinate relevant activities.

[100]The National Research Council also cited the decentralized nature of the federal research system as a strength in a 2012 report. See Committee on Cooperative National Innovation Policies: Best Practice for the 21st Century; Board on Science, Technology and Economic Policy; Policy and Global Affairs, National Research Council of the National Academies, *Rising to the Challenge: U.S. Innovation Policy for the Global Economy* (Washington, D.C.: National Academies Press, 2012).

- **Convergence of advances across different technology areas.** Experts described how transformational technologies often occur as a result of different technologies that have advanced incrementally over time.[101] One expert noted the development of the Global Positioning System as an example of a technology that required the convergence of advances in computing power, satellite technology, geospatial imaging, and timekeeping.[102] Because of the strength and role of the federal government in convening and fostering engagement among non-traditional collaborators on interdisciplinary issues, experts identified technology convergence as a potential indicator of the need to take a strategic approach.
- **Progress from discovery to real-world application.** Experts described how progress from discovery in an area of science to the appearance of niche applications for a technology can be an indicator of the need to take a strategic approach. According to one expert, one challenge in technology development is how to push the technology forward as quickly as possible to develop it into something useful. Experts explained that by taking a strategic approach that extends beyond early-stage research, the federal government can support the development of potentially transformational technologies.
- **Existence of barriers to technology development.** Experts identified several barriers to the development of transformational technologies that could indicate the need to take a strategic approach to developing a technology. Examples of barriers experts identified included high capital costs for research, prototyping, demonstration, or other aspects of a technology development life cycle; regulatory barriers; lack of consensus on standards; and technology measurement challenges, such as limitations in the availability of tools with which to measure products or processes.[103] Experts described

[101]Incremental technology improvements refer to updates or improvements to existing products and technologies.

[102]According to one expert, cross-agency mechanisms that enable cross-disciplinary research and development—which is often called convergence—are an important way to bring together a mix of relevant scientific fields.

[103]Experts described how regulations could present barriers to the development of potential transformational technologies in different ways. For example, some experts described how regulations, particularly when not updated, may hinder technology innovation. Experts also described how gaps in regulatory science—which has been defined as the development and use of new tools, standards, and approaches to more efficiently develop products and effectively evaluate product safety, efficacy, and quality—may present a barrier.

multiple ways in which the federal government can play an important role in addressing such barriers through helping efforts to de-risk technologies, establishing or revising regulations, supporting standards development, and developing measurement tools.[104]

- **Increasing involvement across multiple stakeholders or competitors.** Experts described aspects of how increasing involvement across multiple stakeholders in a particular technology area can indicate the need to take a strategic approach to developing a transformational technology. For example, when multiple federal agencies are working in a technology area or industrial participants increase involvement in a particular technology, experts said such involvement could signal that a strategic approach is needed to work across boundaries and engage the research community in a coordinated way. Similarly, according to one expert, increasing international competition in a technology area could serve as an indicator of the need for the federal government to exercise leadership through a strategic approach to organize domestic public and private efforts in order for the United States to remain competitive.
- **Need for sustained, long-term investment in areas of national interest.** Experts identified the need for sustained, long-term investment in areas of national interest as a potential indicator of the need for a strategic approach to transformational technologies. Experts described how the short-term cycles of many federal programs and disincentives for the private sector to sustain long-term investments can present challenges to developing transformational technologies, which one expert noted can take years or even decades to develop. Experts also cited a need for a strategic approach to advancing a technology when it has the potential to be transformational and presents enormous societal benefits.

In the areas of quantum computing and synthetic biology, experts cited a need to develop a strategic approach to maintain U.S. competitiveness. Within the area of quantum computing, experts cited all of the indicators identified above in stating that U.S. competiveness in quantum computing could benefit from a national strategy. For example, experts described the need to foster interdisciplinary engagement across the fields of physics, engineering, and computer science to support convergence of advances in these areas to further quantum computing technology. Experts also

[104]However, one expert cautioned that standards should not be developed too early because they can deter the growth of alternative technology pathways or lock development into existing pathways.

indicated that real-world applications are beginning to become apparent in the area of quantum computing. However, they noted that significant barriers to development exist and discussed a need for sustained long-term investment in this area, which has significant implications for national security, and according to one expert, economic competitiveness. Moreover, experts expressed concern over the significant and increasing international competition from China, the European Union, and other countries. One expert noted that given the security implications of quantum computing technology, the United States needs to find a way to counter the significant investment that China is making. Stakeholders and one agency official we interviewed cited similar concerns, such as the European Union's plans to launch a flagship initiative on quantum technology, which includes quantum computing; therefore, the United States needs a national quantum computing strategy, the experts said.

Similarly, with regard to synthetic biology, experts cited several of the indicators described above in stating that the United States could benefit from a strategic approach to maintain competitiveness. For example, experts discussed barriers to technology development, including a lack of measurement tools and regulatory barriers. According to one expert, before the 2017 update to the Coordinated Framework for the Regulation of Biotechnology, the system was last updated in 1992.[105] The expert said that it was not yet clear if the updated framework would help advance synthetic biology research. Experts also noted the need to engage across multiple stakeholders in this area; in particular, one expert noted the need for leadership to advance a dialogue about how synthetic biology could

[105]The Coordinated Framework for the Regulation of Biotechnology, a policy originally announced in 1986, outlined a comprehensive federal regulatory policy for ensuring the safety of biotechnology research and products. 51 Fed. Reg. 23,302 (June 26, 1986). In 2015, the Executive Office of the President issued a memorandum directing the primary agencies that regulate the products of biotechnology—EPA, the U.S. Food and Drug Administration, and USDA—to update the Coordinated Framework for the Regulation of Biotechnology by clarifying roles and responsibilities, to develop a long-term strategy to ensure that the federal biotechnology regulatory system is prepared for future biotechnology products, and to commission an expert analysis of the future landscape of biotechnology products to support these efforts. The agencies issued the updated framework in 2017.

help address issues of national concern.[106] Experts described significant foreign competition in synthetic biology. One expert said that there are more than 40 countries that have a unified strategy for synthetic biology.[107] While one expert stated that NSF has initiated a synthetic biology roadmapping effort, a few experts stated that the United States does not have a similar unified synthetic biology strategy.[108] One expert said that in the absence of such a strategy, the United States faces economic and physical security risks. Stakeholders we interviewed raised similar concerns.

Fostering Information Sharing

Experts also suggested considering how to foster information sharing to help maintain U.S. competitiveness through transformational technological advances. Experts discussed the role the federal government can play in bringing together stakeholders to discuss emerging technologies and collaborate on pre-competitive research. For example, according to one expert, in 2015, 2 years after the BRAIN initiative was launched, the White House convened a meeting that brought together industry partners, academic researchers, and government scientists to share information and discuss research plans.[109] This expert highlighted the importance of communication among representatives of organizations that would not normally work together, and how these conversations about where they saw research going over

[106]As part of a November 2016 workshop on Making the Living World Engineerable: Science, Practice, and Policy, participants discussed current trends in synthetic biology and implications for federal policy. Participants described similar challenges in terms of the barriers to advancing the technology and the need to increase engagement across multiple federal agencies and stakeholders in a strategic approach to how synthetic biology could be developed to address U.S. needs. Forum on Synthetic Biology; Committee on Science, Technology, and Law; Policy and Global Affairs; National Academies of Sciences, Engineering, and Medicine, *Making the Living World Engineerable: Science, Practice, and Policy: Proceedings of a Workshop in Brief* (Washington, D.C.: National Academies Press, December 2016).

[107]Many countries have developed strategies to commercialize and industrialize technological advances, according to a 2012 National Research Council report. See National Research Council of the National Academies, *Rising to the Challenge*.

[108]This is consistent with the findings of a 2012 report by the National Research Council, see National Research Council of the National Academies, *Rising to the Challenge.*

[109]We have previously reported that in-person interactions help to build trust—an essential element to collaborative relationships—and strengthen professional networks. See, GAO, *Managing for Results: Implementation Approaches Used to Enhance Collaboration in Interagency Groups*, GAO-14-220 (Washington, D.C.: Feb. 14, 2014).

the next 5 years led to greater understanding and collaboration to support the research under this initiative.

Experts identified three key reasons for sharing information to facilitate transformational technological advances in supporting U.S. competitiveness:

- **Convergence of different disciplines.** Experts generally agreed that information sharing can facilitate an interdisciplinary approach to study a problem, which they said is important to the nation's ability to conduct research for transformational technological advances. The federal government's ability to convene groups, according to one expert, is particularly important for interdisciplinary areas of study because it can help bring stakeholders together to discuss how research could help address an area of national need. Another expert explained that agencies' research is increasingly interdisciplinary, which increases the importance of coordinating across agencies.[110] Agency officials and stakeholders we interviewed also discussed the importance of sharing information across fields of study. One stakeholder said that without government funding for interdisciplinary efforts in quantum computing, it will be challenging to solve problems, such as creating some of the computer programming needed to operate a quantum computer, that need to be solved in order to make quantum computing viable.
- **Overcoming barriers to innovation.** Experts discussed how information sharing can facilitate the identification of barriers to innovation and help overcome them. For example, one expert noted the importance of information sharing in trying to address the challenges the U.S. semiconductor industry faced in the 1980s. The expert emphasized the recognition that individual companies could not address the barriers to innovation on their own and that they needed information sharing, such as cross-licensing of intellectual property and communication about roadmapping to overcome barriers that they faced. Another expert explained that information sharing

[110]This view is consistent with a National Research Council study that stated that the scientific opportunities facilitated by the convergence or coming together of insights and approaches from originally distinct fields of study can make fundamental contributions to solve society's most difficult problems. See Committee on Key Challenge Areas for Convergence and Health; Board on Life Sciences; Division on Earth and Life Studies; National Research Council of the National Academies, *Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond* (Washington, D.C.: 2014).

across federal agencies led to the identification of the U.S. biotechnology regulatory system as a significant barrier to innovation and that, based on this, the Coordinated Framework for the Regulation of Biotechnology was updated.[111] This expert further said that information sharing is the first step in coordination—by sharing information, agencies can determine where there might be overlapping research efforts or gaps in ongoing research.

- **Leveraging international research.** Experts explained that bringing technologies to the United States that were developed elsewhere is not something that has been central to U.S. science and technology policy, but they stressed that the United States needs to consider how to take advantage of research that other countries are conducting and effectively utilize that information to maintain U.S. competitiveness. For example, one expert described the importance of the iGEM competition as an opportunity for information exchange among researchers from around the world who are working in synthetic biology-related fields. In describing this example, the expert noted that most bioengineers will not be U.S.-based and that, to remain competitive in synthetic biology, the United States needs to better understand discoveries being made by researchers from around the world.

Experts said that while information sharing is important, there are tradeoffs, particularly with regard to sharing and protecting pre-competitive intellectual property. The experts said that the benefits of sharing pre-competitive intellectual property include the opportunity to speed innovation by allowing multiple researchers to work with the intellectual property concurrently and by preventing foreign competitors from restricting use of the intellectual property through obtaining a patent. Economically valuable knowledge can spread through publicly and freely available records such as scientific publications and open source software. Such knowledge can be used repeatedly, can quickly spread to users outside the institutions where it was created, and can lead to the creation of new products. For example, one expert stated that, as of

[111]As noted previously, the 2015 Executive Office of the President memorandum that led to the 2017 Update to the Coordinated Framework for the Regulation of Biotechnology stated that the update should clarify roles and responsibilities of the primary agencies involved in regulating biotechnology products. Specifically, the memorandum provided that the update should, among other things, clarify the mechanism and timeline for regularly reviewing, and updating as appropriate, the Coordinated Framework to minimize delays, support innovation, protect health and the environment, and promote public trust in the regulatory systems for biotechnology products.

Human Genome Project

A deoxyribonucleic acid (DNA) strand around the outline of a person.

The Human Genome Project, which formally began in 1990, was a 13-year international collaborative research project coordinated by the Department of Energy and the National Institutes of Health. The Human Genome Project's goals were to (1) identify all the genes in human DNA, (2) determine the chemical base pair sequences of human DNA, (3) store this information in databases, (4) improve data analysis tools, (5) conduct technology transfer, and (6) address the ethical, legal, and social issues that may arise from the project. The full sequence of the human genome was completed and published in April 2003.

Through its policy of open data release, the Human Genome Project facilitated the research of others. The Human Genome Project also anticipated and promoted commercializing genomic resources and applications by establishing an infrastructure and supporting private-sector technology development. Consequently, the project led to new tools to support biological research. Further, the data and technologies generated by the project and related research present a broad array of commercial opportunities across many areas of the economy. These include more individualized diagnostics, prognostics, drugs, and other therapies as well as hardier, more nutritious, and healthier crops and animals, among other applications.

Sources: Department of Energy and the National Institutes of Health (text); Department of Energy (image). | GAO-18-656

October 2017, a quantum computer we described earlier in this report had been available over the Internet for public use for about a year and had 50,000 users. Having a larger number of users working with this resource could lead to more rapid discovery of ways in which a quantum computer might be used than if it had not been shared. The expert said that because this technology exists, it should be developed as quickly as possible to determine what its first useful application will be and to find the first problem that only a quantum computer can solve. Doing so, the expert said, would create opportunities in which a U.S. company could profit from the technology while also developing it. In addition, information sharing was cited as instrumental to the success of the Human Genome Project, according to NIH officials we interviewed, because the project made the genome's sequencing available as a resource for researchers to use.[112]

At the same time, experts said that while information sharing is important, there are risks, such as foreign commercialization of U.S. intellectual property. Experts noted that the world is increasingly competing with the United States in research for transformational technological advances. One expert cautioned that while information sharing is important for transformational technologies, it must be done carefully so that other companies do not exploit a technology or it is not leaked to a foreign competitor. Similarly, one stakeholder said that while information sharing is beneficial at the early stages of technology development, a balanced approach to information sharing—an approach that allows for trade secrets and that guards some research results—is needed once a technology is no longer in the early stages of development.

In light of these tradeoffs, experts emphasized the importance of ensuring that intellectual property protections support U.S. competitiveness; however, they also described challenges with how intellectual property is managed in the United States. For example, experts said it can be challenging to bring industry and academic researchers into partnerships that support transformational technological advances. Experts explained that some collaborators are willing to openly share their intellectual property, while other experts noted that some collaborators may be less inclined to do so because they view intellectual property as a profitable

[112]The Human Genome Project, coordinated by DOE and NIH, was an international, collaborative research project with a goal of completely mapping and understanding all the genes of human beings, collectively known as the genome. The project completed and published the full human genome sequence in 2003.

commodity. Additionally, one expert cited differences between potential industry and academic collaborators' knowledge of, and attention paid to, developing technologies into commercial products as a potential barrier. One expert said that foreign countries generally allow university-developed intellectual property to be owned and licensed by the inventors or third-party companies (instead of the university). This can create a foundation for a startup company or make it easier to get the interest of companies who would like to acquire a university-based technology or process. The expert noted that in one circumstance, this has given an advantage to a foreign university in recruiting top researchers, helping it to become a leader in quantum computing. However, another expert stated that most major research universities have moved to a model of developing partnerships with firms, especially startups, which has minimal upfront licensing costs, and shared gains over time if the project is successful—according to that expert, such universities typically share research intellectual property rights with faculty inventors.

Focusing on Technology Development and Commercialization

Focusing on technology development and commercialization is another policy consideration that experts identified for maintaining U.S. competitiveness through transformational technological advances. According to experts, the United States' "innovation ecosystem"—the network of public and private institutions within a country whose activities and interactions initiate, develop, commercialize, and diffuse new technology innovations—has either lost or needs better mechanisms for commercializing technologies to maintain U.S. competitiveness. To address this issue, experts discussed how the federal government could focus on technology development and commercialization by providing support across multiple stages of innovation and support for the development of tools to enhance innovation.

Providing Longer-Term Assistance to Support Technology Development

Experts discussed a need to improve technology development and commercialization by providing support across multiple stages of innovation. Experts described how sustained federal research investments have led to key scientific discoveries, including, for example, NIST and IARPA's decade-long support for quantum computing research and NSF's investment in synthetic biology. However, while experts said federal agencies' ability to support new discoveries is a strength, they explained that the United States is losing the ability to commercialize technologies that are invented here. For example, according to one expert, while the technology might soon be available to build small (100 qubit) quantum computers, the United States does not have the necessary enterprise in place to manufacture those systems. Experts stated that it may take decades or more from the time research is funded until it is commercialized. During this intervening period, significant investment is needed to support the innovation cycle in terms of research in the design, building, and testing of new product prototypes and production processes.

Experts described an increasing reliance, over time, on venture capital funding to support investments in the innovation cycle. They said that while this is generally working well in some areas such as software and biotechnology, venture capital investors have become less willing to support other technologies that require higher levels of capital investment, longer-term returns, and greater risk. For example, one expert stated that while the U.S. venture capital system spends $70 billion annually on technology commercialization activities, in 2015, the expert estimated that 5 percent of venture capital funding went to hard technologies.[113] Multiple reports in recent years have documented the challenges associated with how the innovation cycle is supported in the United States and its implications for the domestic commercialization and production of new technologies.[114] For example, in a 2012 report, the National Research Council stated that discoveries and inventions originating from research conducted at U.S. universities, corporations, and national laboratories no longer naturally led to products that are commercialized and manufactured within the United States. According to this report, manufacturing is important in developing new products because in many high-technology industries, design cannot easily be separated from manufacturing, and a lack of sustained investment in research and

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[113]According to NSF's *Science and Engineering Indicators 2018*, in the United States, venture capital early- and later-stage investment reached $65 billion between 2013 and 2016. National Science Board, *Science and Engineering Indicators 2018.* Also, a recent report by MForesight—a national consortium that engages advanced manufacturing stakeholders—showed that the majority of venture capital investment in 2017 (57.4 percent) went to software while a relatively smaller proportion (1.5 percent) went to industrial and energy technologies. See Sridhar Kota and Thomas C. Mahoney, *Manufacturing Prosperity: A Bold Strategy for National Wealth and Security,* MF-TR-2018-0302 (Alliance for Manufacturing Foresight, June 2018). Hard technologies are physical products obtained from scientific breakthroughs that must be translated from science into commercially viable products and require time and resources to develop. Examples of hard technology breakthroughs include technologies that increase the efficiency of power systems and production processes, and sustainably produced chemicals.

[114]See, for example, Peter L. Singer and William B. Bonvillian, *"Innovation Orchards": Helping Tech Start-Ups Scale* (Information Technology and Innovation Foundation, March 2017); Bonvillian and Singer, *Advanced Manufacturing*; Kota and Mahoney, *Manufacturing Prosperity*; and Berger, *Making in America.*

infrastructure threatens to damage the U.S. innovation ecosystem, economy, and security.[115]

To address this issue, experts discussed a need to provide longer-term federal financial assistance to better support technology development across multiple stages of innovation. Experts stated that federal agencies often support research on short-term funding cycles (e.g., 3 years or less) that may not be conducive to the long-term support sometimes needed to effectively de-risk potentially transformational technologies. A 2017 National Academies report cited short-term funding as one factor that has resulted in U.S. science losing its flexibility and nimbleness, elements that feed new discovery.[116] Additionally, experts said that federal agencies' support may not extend to the later stages of technology development but providing longer-term support for research is an important part of the federal government's role in advancing transformational technologies. For example, one expert said that long-term federal support facilitates creating a research infrastructure that can support a technology's development.

Experts cited several examples of how federal agencies' programs provide different models for supporting technology development across multiple stages of innovation.

- **Advanced Technology Program.** Experts cited NIST's Advanced Technology Program—which COMPETES 2007 repealed—as a success in terms of its efforts to support transformational research.[117] Experts cited several aspects of the program in discussing its success, including its support for (1) research that accelerated the development of high-risk technologies with the potential for broad-based economic benefits to the nation; (2) information sharing across

[115]See National Research Council of the National Academies, *Rising to the Challenge.*

[116]National Academies of Sciences, Engineering, and Medicine, *Opportunities in Intense Ultrafast Lasers.*

[117]The program's purpose was to help U.S. businesses create and apply the generic technology and research results necessary to (1) commercialize significant new scientific discoveries and technologies rapidly and (2) refine manufacturing technologies. The Advanced Technology Program was established by the Omnibus Trade and Competitiveness Act of 1988, Pub. L. No. 100-418, § 5131(a), 102 Stat. 1107, 1439 (1988), and was repealed by COMPETES 2007, Pub. L. No. 110-69, § 3012(a), 121 Stat. 572, 593 (2007), which replaced the program with the Technology Innovation Program. The Technology Innovation Program was repealed in 2017.

different sectors; (3) active project management and workshops that taught awardees how to pitch their technology to venture capital investors, according to one expert.[118] One expert noted that the program collaborated with NIH to develop diagnostic approaches that advanced the genomic revolution.

- **ARPA-E.** Experts described ARPA-E—which was modeled after DARPA—as an important challenge-based federal effort to advance technologies in areas aligned with DOE's mission.[119] Aspects of the ARPA-E model one expert cited as important to the program's ability to support transformational technological advances included, among others, support for higher-risk research and the autonomy that program directors have in seeking expert input and selecting research projects.[120]
- **Manufacturing USA Institutes.** One expert described the Manufacturing USA institutes as an important federal effort to support emerging technologies across multiple stages of innovation. Another expert explained that in order to continue to capture the economic benefits of the innovation system, the United States needs to embed the knowledge for technology production locally within the country. The first expert said the Manufacturing USA institutes help increase the connectivity among different actors involved with specific

[118]One expert clarified that the Advanced Technology Program did not provide awardees with financial assistance to commercialize technologies.

[119]As specified by statute, ARPA-E's program goals are to enhance the nation's economic and energy security through the development of energy technologies and to ensure that the United States maintains a technological lead in developing and deploying advanced energy technologies. 42 U.S.C. §16538(c)(1).

[120]The National Academies conducted an assessment of ARPA-E under a Congressional mandate. Specifically, COMPETES 2007 provided that after ARPA-E had been operational for 6 years, the Secretary of Energy was to offer to enter into a contract with the National Academy of Sciences for it to conduct an evaluation of how well the agency was achieving its mission and goals. 42 U.S.C. § 16538(l). The National Academies issued its report in 2017. See Pradeep K. Khosla and Paul T. Beaton, Editors, Committee on Evaluation of the Advanced Research Projects Agency-Energy; Board on Science, Technology, and Economic Policy; Policy and Global Affairs; Board on Energy and Environmental Systems; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine, *An Assessment of ARPA-E* (Washington, D.C.: National Academies Press, 2017). GAO has also reported on ARPA-E. See GAO, *Department of Energy: New Process to Review Financial Assistance for Research Projects Created Uncertainty*, GAO-18-278 (Washington, D.C.: Feb. 28, 2018); and GAO, *Department of Energy: Advanced Research Projects Agency-Energy Could Benefit from Information on Applicants' Prior Funding*, GAO-12-112 (Washington, D.C.: Jan. 13, 2012).

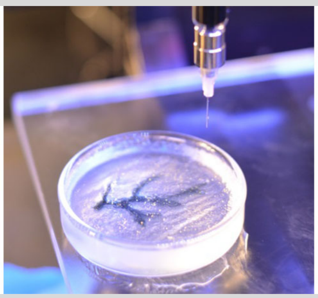
technology areas and improve their ability to leverage advances in those areas.

Experts also discussed how other countries' long-term funding for research efforts may help them support technology development. For example, one expert discussed Germany's Fraunhofer Institutes, where the government makes research investments over time frames of 5 or even 20 years and rewards successful projects with funding increases each year.[121] In addition, one expert noted that other countries such as the Netherlands and Singapore also provide long-term research funding, allowing them to develop the broader research infrastructure necessary to support technology development. In the area of quantum computing, one expert stated that the Netherlands' investment has contributed to one of the largest quantum computing-focused efforts in the world. According to one expert, if U.S. researchers do not conduct the research necessary over the long term to prove their research ideas, other countries will have the opportunity to pick up where U.S. researchers leave off and commercialize technologies based on this research.

[121]According to Fraunhofer's 2016 annual report, they conduct applied research that is intended to drive economic development and benefit society. Projects are initially established for 5 years and, at the end of this period, the projects' performance is evaluated to determine eligibility for additional funding. Fraunhofer-Gesellschaft, *Annual Report 2016 Embracing Digitalization*, (Munich, Germany: 2017). One expert described the Fraunhofer Institutes as using a shared technology development model between industry, engineering schools, and federal and state governments.

Supporting Development of Tools to Enhance Innovation

3D Bioprinting



A bioprinted coronary artery.

3D bioprinting is a tool that scientists are developing in the field of regenerative medicine. 3D bioprinting uses 3D printing with biological materials to create skin, bones, arteries, and a variety of other tissues and organs. For example, the Department of Defense has conducted research into using 3D bioprinting to repair skin damaged by burns—injuries that account for 10 to 30 percent of battlefield casualties. To repair burned skin, researchers have created scans of burns that a computer then uses to have a 3D printer reconstruct the burned skin.

3D bioprinting has also been used to create small blood vessel networks that contain living cells that have joined with the blood vessel networks in a mouse, allowing blood to circulate through them. Such printed blood vessels could be used to replace a damaged heart muscle. In the future, such organs could be grown using 3D bioprinting and the cells of the person who needs the organ, and they could be used in place of transplanted organs. 3D bioprinted tissues could also be used to test the safety of new drugs. 3D bioprinting is in the early stages of development.

Sources: Department of Defense and National Institutes of Health (text); Adam Feinberg, Carnegie Mellon University (image). | GAO-18-656

Experts stated that tool development is critical to transformational technological advances and discussed a need for federal government support for tool development to maintain U.S. competitiveness. A tool is something—such as equipment used for a specific purpose, a modified biological system, or a computer program—that is used to perform a task or that is needed to practice a profession. According to one expert, tools are crucial supporting technologies that are necessary for the product development process. According to recent reports, research in tools development can lead to the introduction of new products, materials, or the ability to produce materials at the commercial level.[122]

Experts explained that the United States is at risk of losing its ability to develop tools, and they identified challenges to tool development, including the following:

- **Unclear needs and long time frames.** According to experts, industry may be less likely to invest in tool development when tools do not support existing products, but, rather, are a part of solving technology challenges that are not clearly defined. In this context, experts explained that tool development can take a relatively long time, which may not be compatible with industry's short innovation time frames.
- **Potentially high or unrecoverable costs.** Developing tools is expensive, according to experts, and when creating a new tool, companies have to consider whether they will be able to recover their costs. One expert described a circumstance in which a modified laser was needed to support research on a quantum system. The expert explained that a laser manufacturing company would need to change its production line in order to make the modified laser, and it would be very expensive for the company to adjust its production line to make only the modified laser.

Experts emphasized the important role federal agencies can play in helping overcome these challenges to tool development. For example, experts described the importance of federal support for developing measurement tools to accelerate and improve the learning cycles around designing, building, and testing technologies and products. Experts

[122]See National Research Council, *An Assessment of the National Institute of Standards and Technology Material Measurement Laboratory: Fiscal Year 2014* (Washington, D.C.: 2015), and Subcommittee for Advanced Manufacturing of the National Science and Technology Council, *Advanced Manufacturing: A Snapshot of Priority Technology Areas Across the Federal Government* (Washington, D.C.: April 2016).

specifically cited NIST's role in the development of measurement tools. For example, through the NIST-on-a-Chip program NIST is developing ultra-compact, inexpensive tools that will measure quantities such as time, distance, current and voltage, and temperature and pressure and that will allow measurement technologies to be deployed without requiring traditional measurement services. In line with NIST's goals, the private sector will manufacture and distribute these technologies.[123] Experts also noted the important role federal agencies play in providing access to tools, such as technology testbed facilities to support de-risking technologies through prototyping and other development activities.

Strengthening the Science and Technology Workforce

Experts identified strengthening the science and technology workforce as a consideration for maintaining U.S. competitiveness through transformational technological advances. According to experts, there is a need for federal agencies to work with academia and industry to improve connections between the training academia provides and what industry needs, such as interdisciplinary training. Experts further discussed the recruitment of researchers and the retention of research talent and a technically trained workforce; according to experts, attracting researchers has historically been a U.S. strength, but this ability may be at risk.

Improving Connections between Academic Training and Industry Needs

Experts identified the need to improve connections between academic institutions and industry so that the training academia provides corresponds to industry's needs, particularly for interdisciplinary research fields. Without strengthening these connections, according to experts, academia may not deliver the interdisciplinary training needed for some research areas. Experts identified the systems engineering training needed to build a quantum computer as one such area of interdisciplinary training.[124] For example, one expert said engineers are usually unfamiliar

[123]We recently reported on the measurement services NIST provides to support U.S. industry's needs, among other things. See GAO, *National Institute of Standards and Technology: Additional Review and Coordination Could Help Meet Measurement Services Needs and Strengthen Standards Activities*, GAO-18-445 (Washington, D.C.: July 26, 2018).

[124]According to the NASA Systems Engineering Handbook, systems engineering is a multidisciplinary approach for the design, realization, technical management, operations, and retirement of a system that includes the hardware, software, facilities, and personnel, among other things, required to produce results. It is a holistic discipline, in which multiple fields' contributions are evaluated and balanced to produce a system that is not dominated by a single field's perspective. It is a way to look at the big picture. *NASA Systems Engineering Handbook,* NASA SP-2016-6105 Rev 2 (Washington, D.C.: 2016).

with the quantum mechanics used in a quantum computer and this is challenging since knowledge of both disciplines—quantum mechanics and engineering—is necessary to develop the technology. Also, not many quantum computing researchers are trained in the fields of computer science or engineering, according to stakeholders and agency officials we interviewed. A few experts said that because universities are not training the researchers needed in some interdisciplinary areas, there are not enough researchers in those areas available for industry to hire.

Experts, other stakeholders and agency officials we interviewed, as well as some recent reports, identified several factors that may contribute to a disconnect between academic training and industry needs. For example, experts explained that universities appear to operate on the assumption that industry, not universities, must teach students the practical skills needed to be productive members of an engineering team.[125] Additionally, according to a 2012 report by the National Research Council, job markets and careers for doctoral scientists and engineers have shifted since 1990 so that more than 50 percent of new doctorates work outside of academia, but there are few incentives to motivate graduate programs to align doctoral education with evolving employment activities.[126] According to one expert, graduate education is largely supported by federally funded research awards to universities which tend to support basic research, not applied research or development. This expert further stated that as a result, graduate students are not taught later stage applied work relevant to industry because that has not been what federal research has historically funded.[127] According to a different

[125]Participants expressed similar observations in a 2016 National Academies workshop on the U.S. science, technology and engineering workforce, which stated that there is often a significant gap between the knowledge, skills, and abilities most often sought by employers, and those that students bring to the workforce upon graduation. See Joe Alper, Rapporteur; Board on Higher Education and Workforce; Policy and Global Affairs Division; National Academies of Sciences, Engineering, and Medicine, *Developing a National STEM Workforce Strategy: A Workshop Summary* (Washington, D.C.: 2016).

[126]The report indicated that, while the nation's scientific workforce needs had evolved over the last several decades with changes in the work of science-based industries, government agencies, and nonprofits, most research universities had not yet adequately adapted to the new realities of these labor markets. Committee on Research Universities, Board on Higher Education and Workforce, Policy and Global Affairs, National Research Council, *Research Universities and the Future of America: Ten Breakthrough Actions Vital to Our Nation's Prosperity and Security* (Washington, D.C.: 2012).

[127]According to this expert, the advanced manufacturing institutes could constitute a departure from the historical federal research model of typically funding basic research at universities.

2012 National Research Council report, cultural barriers often separate industry from academia and are reinforced by organizational incentives—universities have traditionally emphasized the need to publish research, not commercialize it.[128] Further, one expert, a stakeholder, and an agency official we interviewed said that universities generally were not hiring faculty who focus on quantum computing as part of their computer science and engineering departments. The expert attributed this to limited funding available to support those research programs. According to this expert, the financial assistance federal research programs provide can send an important signal to universities that can lead to evolving academic programs and hiring in interdisciplinary fields. A 2016 MIT report made similar observations and said that many universities remain siloed along departmental lines and need resources and structures that allow for team teaching—two people from different research areas co-teaching a course—or research in which students from different disciplines could be paired to answer a research question.[129] However, in synthetic biology, one expert noted that some universities have started entirely new Departments of Bioengineering because aspects of synthetic biology contribute to the development of an independent, distinctive, and complementary type of engineering. This has resulted in the development of a new curriculum that incorporates synthetic biology into the training and development of bioengineers, according to this expert.

Recruitment and Retention of Talent

Experts discussed the importance of recruiting researchers and retaining talent and a technically trained workforce. Experts stated that attracting researchers to come and stay in the United States has historically been a national strength. The Congressional Budget Office has reported that foreign-born workers contribute disproportionately to innovation.[130] Further, according to this report, foreign-born researchers account for a disproportionate number of the scientific researchers who yield many of the big discoveries and conceptual breakthroughs that drive science.[131]

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[128]National Research Council of the National Academies, *Rising to the Challenge.*

[129]Phillip Sharp, Susan Hockfield, and Tyler Jacks, *Convergence: The Future of Health* (Cambridge, MA: June 2016).

[130]Congressional Budget Office, *Federal Policies and Innovation* (2014).

[131]In 2015, according to the National Science Board, 13 percent of the population of the United States was foreign born, but this portion of the population accounted for 29 to 30 percent of college-educated workers employed in science and engineering occupations and 42 to 45 percent of the workers with doctorates. National Science Board, *Science and Engineering Indicators 2018.*

However, according to a few experts, and a National Research Council report, the United States is increasingly competing with other countries to recruit and retain talented researchers.[132] Countries such as Canada, China, and Singapore are attracting talented researchers to their universities and research institutes by offering high salaries and the opportunity to run well-funded programs, according to a National Research Council report.[133] For example, according to a few experts, China started the Thousand Talents Program in 2008 to get talented researchers to return to China.[134] The Thousand Talents Program's goal is to bring top talent trained overseas to China on a full- or part-time basis. One expert gave the example of a university president resigning from a U.S. university because he believed the possibilities for research were greater in Asia. According to one expert, the nation's ability to recruit and retain researchers may be at risk because the United States is not working to retain and incentivize talent. According to that expert, this puts the nation at risk of missing out on the next global transformational technological advance.

According to some experts, one challenge to retaining talent in the United States is that limited job opportunities are available to young researchers trained in certain areas. It is important to create conditions for young researchers to find employment in research and development, according to one expert, so that they can contribute to these areas. Creating the right incentive structure for people to produce transformational technologies in the United States is important, according to another expert, because when technologies are produced in the United States, the skills needed to produce them become embedded in that community. We have previously reported that too much location of skilled manufacturing jobs abroad can, in general, put the United States at a

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[132]National Research Council of the National Academies, *Research Universities and the Future of America: Ten Breakthrough Actions Vital to Our Nation's Prosperity and Security* (Washington, D.C.: 2012).

[133]National Research Council of the National Academies, *Rising to the Challenge.*

[134]According to a research report prepared on behalf of the U.S.-China Economic and Security Review Commission, the Thousand Talents Program is administered by various Chinese entities, including local governments. According to the report, the program administered by the University of the Chinese Academy of Science requires that candidates hold a professorship at a distinguished international university or an equivalent international research institution. See Richard P. Suttmeier, *Trends in U.S.-China Science and Technology Cooperation: Collaborative Knowledge Production for the Twenty-First Century?* Research Report Prepared on Behalf of the U.S.-China Economic and Security Review Commission, September 11, 2014.

disadvantage in terms of its ability to design new products, according to participants in a 2013 forum on nanomanufacturing.[135] Similarly, in a 2012 report, the National Research Council stated that manufacturing is integral to new product development, and production lines are linked to an iterative innovation chain that includes research and development, product refinement, and full-scale production.[136] In many high-technology industries, design cannot be easily separated from manufacturing, and talent availability is the most important factor for deciding where to place a production facility. In some cases, according to this 2012 report, companies are choosing to produce abroad because of concerns related to the capacity of the U. S. supply chain, technical skills of U.S. workers, and the investment climate for high-volume manufacturing. Also according to this report, as a result of these factors, the United States is finding it increasingly difficult to capture the economic value generated by public and private investments in research and development.

Conclusions

Federal support for research in areas such as quantum computing and synthetic biology can help promote U.S. competitiveness in the global economy. For example, advances in quantum computing have the potential to lead to transformational advances in national security technologies or technology areas that rely heavily on simulation, such as pharmaceuticals and materials science for advanced manufacturing. Research in synthetic biology could help achieve significant advances in health care, energy, and other sectors. When agencies collaborate on their research efforts, they can produce more public value than when they act alone. Moreover, collaboration through mechanisms such as interagency groups can help address complex issues, such as those remaining to be resolved in quantum computing and synthetic biology. Collaboration can also mitigate challenges associated with fragmentation of efforts across multiple agencies, as well as potential overlap and duplication.

NSTC and federal agencies have taken steps, building on earlier efforts, to coordinate their activities in the areas of quantum computing and synthetic biology. Specifically, both the new QIS Subcommittee and the new synthetic biology working group have taken initial steps to implement certain leading practices that can enhance and sustain collaborative

[135] GAO-14-181SP.

[136] National Research Council of the National Academies, *Rising to the Challenge.*

efforts. For example, both have taken steps toward agreeing on roles and responsibilities. These steps could help address problems identified in previous interagency coordination efforts. However, both the subcommittee and working group are recently established and have had limited time to fully implement the leading practices that we describe in this report. As the subcommittee and working group move forward, by taking steps to fully implement these leading practices for collaboration, member agencies could better marshal their collective efforts to support research in quantum computing and synthetic biology and help maintain U.S. competitiveness through transformational technological advances.

Recommendations for Executive Action

We are making a total of five recommendations, including one to OSTP, one to Commerce, one to DOE, and two to NSF.

- As the QIS Subcommittee moves forward, the Office of Science and Technology Policy co-chair, in coordination with other co-chairs and participating agency officials, should take steps to fully implement leading practices that enhance and sustain collaboration. (Recommendation 1)
- As the QIS Subcommittee moves forward, the Department of Commerce co-chair, in coordination with other co-chairs and participating agency officials, should take steps to fully implement leading practices that enhance and sustain collaboration. (Recommendation 2)
- As the QIS Subcommittee moves forward, the Department of Energy co-chair, in coordination with other co-chairs and participating agency officials, should take steps to fully implement leading practices that enhance and sustain collaboration. (Recommendation 3)
- As the QIS Subcommittee moves forward, the National Science Foundation co-chair, in coordination with other co-chairs and participating agency officials, should take steps to fully implement leading practices that enhance and sustain collaboration. (Recommendation 4)
- As the Interagency Working Group on Synthetic Biology moves forward, the Director of the National Science Foundation, in coordination with participating agency officials, should take steps to fully implement leading practices that enhance and sustain collaboration. (Recommendation 5)

Agency Comments, Third-Party Views, and Our Evaluation

We provided a draft of this product to Commerce, DOD, EPA, DOE, DHS, HHS, NASA, NSF, ODNI, OSTP and USDA for comment. Commerce, DOE, NSF, and OSTP generally agreed with the recommendations directed to them.

Commerce, DOE, and NSF provided written comments that are reproduced in appendixes IV, V, and VI, respectively. In expressing concurrence with the recommendations directed to them, these agencies' written comments discussed aspects of the interagency groups' efforts we examined in our report or the agencies' own efforts related to coordination and collaboration.

OSTP's General Counsel provided OSTP's comments by email. In its comments, OSTP stated that it sees value in our recommendation and will implement the recommendation as resources allow. However, OSTP expressed concern about the impact that resource limitations could have on its ability to implement the recommendation. We recognize that OSTP faces certain resource limitations. However, we believe that implementing our recommendation would allow leveraging of limited resources across the agencies participating in a collaborative effort.

In an email from an official with the Office of the Chief Financial Officer in USDA's Agricultural Research Service, USDA provided general comments on our findings and our recommendation pertaining to the Interagency Working Group on Synthetic Biology. Specifically, USDA concurred that federal support for research and development help drive technological advances and promote U.S. competitiveness. USDA also agreed that the leading practices we discuss in our report can enhance and sustain interagency collaboration, and it expressed support for the implementation of these practices in the Interagency Working Group on Synthetic Biology, consistent with our recommendation.

In addition, Commerce, DHS, DOE, EPA, HHS, NASA, and OSTP provided technical comments, which we incorporated as appropriate. Officials from DOD and ODNI stated via email that they had no comments on the report.

We also provided a draft of this report to a participant who served as moderator in our October 2017 expert meeting on research for transformational technological advances. We requested his views on aspects of the report on which he has expertise and, in particular, the characterization of statements made by experts at our meeting. He provided technical comments, which we incorporated as appropriate.

We are sending copies of this report to the appropriate congressional committees; the Secretaries of Agriculture, Commerce, Defense, Energy, Health and Human Services, and Homeland Security; the Administrators of the Environmental Protection Agency and the National Aeronautics and Space Administration; the Directors of National Intelligence, the National Science Foundation and the Office of Science and Technology Policy; and other interested parties. In addition, this report is available at no charge on the GAO website at http://www.gao.gov.

If you or your staff members have any questions about this report, please contact me at (202) 512-3841 or neumannj@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. Key contributors to this report are listed in appendix VII.

John Neumann
Director, Natural Resources and Environment

Appendix I: Objectives, Scope, and Methodology

The objectives of our review were to (1) describe federal agencies' and nonfederal entities' support for research for transformational technological advances in selected areas, (2) examine federal agencies' coordination on this research, and (3) provide experts' views on considerations for maintaining U.S. competitiveness through transformational technological advances.

For the purposes of this report, we selected quantum computing (a sub-area of quantum information science) and synthetic biology (the intersection of biology and engineering that focuses on the modification or creation of novel biological systems) as examples of research for transformational technological advances. We selected these two areas of research because they: (1) represent enabling or platform technologies, which could lead to other advances, (2) are supported by a mix of federal agencies and nonfederal entities, and (3) represent areas of congressional interest in which we have not recently conducted work.

We conducted this performance audit from November 2016 to September 2018 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Support for Research

To describe federal agencies' and nonfederal entities' support for research for transformational technological advances in quantum computing or synthetic biology we reviewed agency documentation, relevant literature, and our prior work related to federal research efforts. We focused on federal and nonfederal efforts in fiscal years 2016 through the second quarter of fiscal year 2018. For example, we reviewed the National Science and Technology Council's 2016 report on advancing quantum information science which discusses the state of the research area and federal involvement. We also interviewed officials from 10 agencies and departments that have ongoing work in either quantum computing or synthetic biology, or in some instances, work in both research areas. These agencies were the: Department of Commerce, Department of Defense, Environmental Protection Agency, Department of Energy, Department of Homeland Security, Department of Health and Human Services, National Aeronautics and Space Administration, National Science Foundation (NSF), Office of the Director of National Intelligence, and U.S. Department of Agriculture. We initially selected federal agencies on the basis of those that had total research and development obligations of $500 million or greater in fiscal year 2016 according to NSF's Survey of Federal Funds for Research and Development. Additionally, we included an agency which we learned, through the course of our work, had significant ongoing work in both research areas. We did not seek to develop comprehensive information on federal agencies' efforts to support research in quantum computing and synthetic biology. As a result, federal agencies could have ongoing efforts in these two areas that we do not discuss in our report.

To examine the funding federal agencies provide for quantum computing and synthetic biology research, we requested data on obligations for quantum computing and synthetic biology research for fiscal years 2016 through 2017, information on the type of research funded, and the names of individual studies or projects. We requested funding data from all agencies within our scope but some agencies did not provide such data. We assessed the reliability of the data we obtained by checking for obvious errors in accuracy and completeness and by comparing the data with other sources of funding information, such as agency budget documents, where possible. We determined that the data were sufficiently reliable for reporting an approximate, minimum amount of federal financial assistance obligated for quantum computing and synthetic biology research.

To examine the extent to which nonfederal entities have supported research related to synthetic biology and quantum computing, we interviewed stakeholders from 21 nonfederal entities with experience in the areas of quantum computing, synthetic biology, or federal research more broadly. To collect a range of viewpoints, we selected nonfederal entities from industry, academia, nonprofit organizations, and professional associations. The 21 nonfederal entities we interviewed included:

1. American Chemical Society
2. American Physical Society
3. Arizona State University
4. Georgia Institute of Technology
5. Ginkgo BioWorks
6. Google
7. Harvard University
8. IBM

9. Institute of Electrical and Electronics Engineers
10. Information Technology and Innovation Foundation
11. IonQ
12. Massachusetts Institute of Technology (MIT)[1]
13. Materials Research Society
14. Microsoft
15. National Venture Capital Association
16. Purdue University
17. Science and Technology Policy Institute
18. University of California
19. University of Colorado
20. Virginia Tech
21. Yale University

We also defined the people cited in this report in the following manner:

1. Experts: individuals who participated in our expert meeting.
2. Stakeholders: academic researchers, industry officials, and representatives of professional organizations who we interviewed. This group does not include agency officials.
3. Agency officials: federal officials we interviewed.

We identified and selected these stakeholders through a literature review and referrals. We conducted a literature review to learn about the current state of each research area as well as to identify relevant stakeholders in the areas of synthetic biology and quantum computing. We then contacted the stakeholders for interviews and asked them for additional references. We interviewed stakeholders both in person and over the phone.

We did not seek to develop comprehensive information on nonfederal efforts to support research in quantum computing and synthetic biology. As a result, we acknowledge that there are nonfederal entities that may

[1]We interviewed stakeholders from MIT, including researchers from MIT's Lincoln Laboratory.

have ongoing efforts in these two areas that we do not discuss in our report.

Federal Agencies' Coordination on Research

To examine federal agencies' coordination on quantum computing and synthetic biology research, we identified coordination efforts in fiscal year 2016 through the second quarter of fiscal year 2018 through our review of agency documentation and interviews with federal officials. Additionally, we interviewed officials with the Office of Science and Technology Policy. For ongoing interagency coordination efforts, we compared agencies' efforts with selected leading practices for enhancing and sustaining collaboration.[2] We selected six of the eight practices based on their relevance to the operations of the interagency coordination efforts we identified.[3] In this report, and in our past work, we define collaboration broadly as any joint activity that is intended to produce more public value than could be produced when organizations act alone.[4] Through interviews and a data request, we asked agency officials to provide information on their efforts to coordinate quantum computing and synthetic biology research from fiscal year 2016 through the second quarter of fiscal year 2018. For interagency groups related to quantum computing and synthetic biology, we obtained information through June 2018.

Experts' Views

To provide experts' views on considerations for maintaining U.S. competitiveness through transformational technological advances, we convened a meeting of 19 experts on October 12 and 13, 2017, with the assistance of the National Academies of Sciences, Engineering, and Medicine.[5] The experts included current and former federal officials, as well as subject matter experts from industry, academia, nonprofit organizations, and professional associations. About half of the experts

[2]GAO, *Results-Oriented Government: Practices That Can Help Enhance and Sustain Collaboration among Federal Agencies*, GAO-06-15 (Washington, D.C.: Oct. 21, 2005).

[3]We excluded from our review two leading practices related to reinforcing agency accountability and individual accountability for collaborative efforts.

[4]We also refer to coordination as collaboration in our work.

[5]We planned and convened this meeting of experts with the assistance of the National Academies to better ensure a breadth of expertise; however, we were responsible for all final decisions regarding meeting substance and expert participation. Any conclusions and recommendations in our reports are solely our own.

were subject matter experts in the areas of quantum computing or synthetic biology, while the other half were experts with broader perspectives on the role of federal and nonfederal entities in supporting research for transformational technological advances. We worked with the National Academies staff to select experts with a range of viewpoints.

Prior to the meeting, we worked with National Academies staff to help ensure balance and to assess potential conflicts of interest among the experts. For example, we asked all participating experts to provide information on (1) whether their immediate family had any investments or assets that could be affected, in a direct and predictable way, by a decision or action based on the information or opinions they would provide to GAO; (2) whether they or their spouse received any income or hold any organizational positions that could be affected, in a direct and predictable way, by the information or opinions they would provide GAO; and (3) whether there were any other circumstances, not addressed in the two previous questions, that could be reasonably viewed by others as affecting participants' point of view on the topics to be discussed. We received signed responses from all participating experts. Three of the 19 experts reported potential conflicts. We evaluated their statements and determined that they did not have any inappropriate biases when taken in the context of the overall group of experts taking part in the meeting. As a result of these efforts, we determined that the group of 19 experts, overall, was balanced and had no inappropriate biases. However, the views of these experts cannot be generalized to everyone with expertise on research for transformational technological advances; they represent only the views of the experts who participated in our meeting. We list the experts who participated in our meeting in Appendix II.

We divided the 2-day expert meeting into 8 sessions focused on a range of topics, such as the role of federal and nonfederal entities in keeping the United States competitive. Each session featured an opening presentation by two selected experts, followed by open discussion among all meeting participants. At the end of each session, one expert was tasked with highlighting the key themes discussed during that session. We then solicited feedback from the experts to determine whether there were any additional comments they wanted to add to those themes. We recorded and transcribed the meeting to ensure that we accurately captured the experts' statements.

We analyzed the information gathered from the experts by reviewing and conducting a content analysis of the transcript and identifying considerations for maintaining U.S. competitiveness based on categorizing the experts' comments. For purposes of quantifying expert remarks, we refer to a statement from an individual expert as being from one expert, and unless there is significant disagreement in the transcript, we refer to statements from two or more experts as being from experts. In cases of significant disagreement in the transcript, we refer to statements from two to three experts as being from a few experts, and statements from four to six experts as being from some experts. Before publication and consistent with our quality assurance framework, we provided the experts with a draft of our report and asked them to provide their views on whether our overall characterization of the meeting generally reflected the considerations discussed during the meeting.[6] Of the 18 experts who responded to our request for review, 13 experts agreed that our overall characterization generally reflected the key considerations identified during the meeting, one partially agreed, and one differed with our report's presentation of specific issues regarding synthetic biology.[7] We incorporated feedback experts provided on the draft, as appropriate.

To corroborate statements made by the experts on particular topics, as appropriate, we identified and analyzed studies and reports by agencies, the National Academies, and others that were recommended to us by experts. In addition, we compared the experts' statements to other information provided by agency officials and stakeholders we interviewed.

[6]We also asked experts to provide clarifying information on statements made during the meeting, as necessary.

[7]Three experts did not provide comments on if they agreed or disagreed with our overall characterization of the meeting and one expert did not respond to our requests for feedback.

Appendix II: Participants in GAO's Meeting on Research for Transformational Technological Advances

Table 3: Experts Who Participated in GAO's Meeting on Research for Transformational Technological Advances, Held October 12-13, 2017

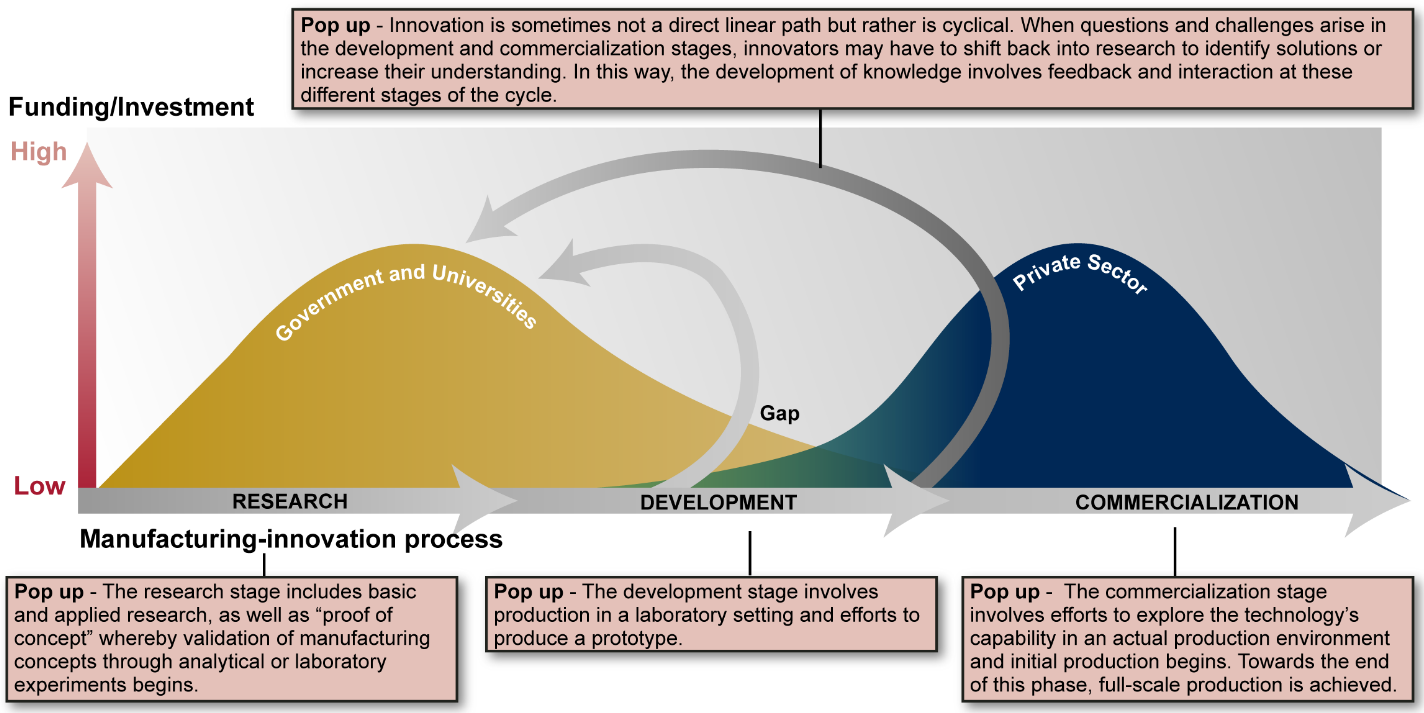
Expert	Affiliation
Robbie Barbero	Ceres Nanosciences, Inc.
Brad Blakestad	Intelligence Advanced Research Projects Activity
William B. Bonvillian	Massachusetts Institute of Technology
Michael Borrus	XSeed Capital
Tony Dickherber	National Cancer Institute
Drew Endy	Stanford University
Maryann Feldman	University of North Carolina at Chapel Hill
Ralph Gomory	New York University Stern School of Business
Richard Johnson	Global Helix LLC
Christopher Monroe	University of Maryland and IonQ
Pablo Rabinowicz	Department of Energy Office of Science
Marc Salit	National Institute of Standards and Technology
Daniel Sarewitz	Arizona State University
John Sarrao	Los Alamos National Laboratory
Lou Schick	NewWorld Capital
Stephanie Shipp	Biocomplexity Institute of Virginia Tech
Neil Thompson	Massachusetts Institute of Technology
Carl J. Williams	National Institute of Standards and Technology
Robert Wisnieff	IBM TJ Watson Research Center

Source: GAO. | GAO-18-656

Appendix III: Funding/Investment Gap in the Manufacturing-Innovation Process (Corresponds to fig. 1)

Figure 3 shows the potential gap during the middle stages of innovation, in which innovators may have difficulty finding financial support. The figure includes a static display of the rollover information included in figure 1, which is interactive.

Figure 3 Funding/Investment Gap in the Manufacturing-Innovation Process (Corresponds to fig. 1)



Source: GAO. | GAO-18-656

Appendix IV: Comments from the Department of Commerce

UNITED STATES DEPARTMENT OF COMMERCE
The Secretary of Commerce
Washington, D.C. 20230

September 10, 2018

Mr. John Neumann
Director, Natural Resources and Environment
U.S. Government Accountability Office
441 G Street, NW
Washington, DC 20548

Dear Mr. Neumann:

Thank you for the opportunity to review and comment on the Government Accountability Office's draft report titled *Science and Technology: Considerations for Maintaining U.S. Competitiveness in Quantum Computing, Synthetic Biology, and Other Potentially Transformational Research Areas* (GAO-18-656).

On behalf of the Department of Commerce, I have enclosed our comments on the draft report. We concur with the recommendation to the Department of Commerce and will take steps to implement it.

If you have any questions, please contact MaryAnn Mausser, Department of Commerce Audit Liaison, at (202) 482-8120.

Sincerely,

Wilbur Ross

Enclosure

Department of Commerce's Comments on GAO Draft Report titled *Science and Technology: Considerations for Maintaining U.S. Competitiveness in Quantum Computing, Synthetic Biology, and Other Potentially Transformational Research Areas* (GAO-18-656)

The Department of Commerce has reviewed the draft report, and we offer the following comments for the Government Accountability Office's (GAO) consideration.

Comments on Recommendations

The GAO made one recommendation to the Department of Commerce in the report.

- **Recommendation 2:** As the QIS Subcommittee moves forward, the Department of Commerce co-chair, in coordination with other co-chairs and participating agency officials, should take steps to fully implement leading practices that enhance and sustain collaboration.

  Commerce Response: The Department of Commerce concurs with this recommendation.

  The National Institute of Standards and Technology (NIST) of the Department of Commerce is actively engaging with the Department of Energy, the Office of Science and Technology Policy, and the National Science Foundation through the National Science and Technology Council Interagency Subcommittee to ensure that we collaborate closely in guiding and steering our interactions and engagement to maximize the benefit to the U.S. taxpayer. NIST will work to use best practices in this coordination effort. NIST is in the process of establishing an industrial consortium, and invitations to the consortium's inaugural event will include the co-chairs and numerous representatives of the Interagency Subcommittee.

Appendix V: Comments from the Department of Energy

Department of Energy
Office of Science
Washington, DC 20585

SEP 10 2018

Mr. John Neumann
Director
Natural Resources and Environment
U.S. Government Accountability Office
441 G Street N.W.
Washington, DC 20548

Dear Mr. Neumann:

We appreciate the opportunity to comment on the draft Government Accountability Office (GAO) report: *Science and Technology: Considerations for Maintaining U.S. Competitiveness in Quantum Computing, Synthetic Biology, and Other Potentially Transformational Research Areas* (GAO-18-656).

Recommendation 3: As the QIS Subcommittee moves forward, the Department of Energy co-chair, in coordination with other co-chairs and participating agency officials, should take steps to fully implement leading practices that enhance and sustain collaboration.

DOE Response: The Department of Energy, including the National Nuclear Security Administration, concurs with the recommendation.

The leadership of the Quantum Information Science (QIS) Subcommittee has developed a strategic overview for QIS that is under review at the participating agencies. The release of strategic overview is planned for September 2018. Upon release, the QIS Subcommittee will proceed with the development of an implementation plan. To inform the implementation plan, the QIS Subcommittee is planning several workshops and summits to discuss leading QIS practices and possible collaborations between industry, academia, and Federal agencies.

Please find an additional technical comment on the report attached. If you have any questions, regarding this response, please contact Barbara Helland, Associate Director for Advanced Scientific Computing Research at (301) 903-7486.

Sincerely,

J. Stephen Binkley
Deputy Director for Science Programs
Office of Science

Appendix VI: Comments from the National Science Foundation

National Science Foundation
Office of the Director

August 31, 2018

John Neumann
Director
Natural Resources and Environment
U.S. Government Accountability Office
441 G Street, NW
Washington, D.C. 20548

Dear Mr. Neumann:

The National Science Foundation (NSF) appreciates the opportunity to review and provide comments on the Government Accountability Office (GAO) draft report, "*Science and Technology: Considerations for Maintaining U.S. Competitiveness in Quantum Computing, Synthetic Biology, and Other Potentially Transformational Research Areas*" (GAO-18-656). Interagency collaboration and coordination is essential to be able to leverage limited federal resources and maximize the impact of strategic investments in research areas such as quantum computing and synthetic biology. Research in these areas have the potential to lead to scientific and technological innovations that will contribute to US economic competitiveness and prosperity.

NSF concurs with the GAO recommendations concerning QIS and synthetic biology. We note that the NSF Director co-chairs the NSTC Committee on Science that oversees the work of both the NSTC QIS subcommittee and the NSTC subcommittee on Biological Sciences, and NSF staff co-chair both of these subcommittees. Thus NSF is well positioned to insure steps are taken to (a) fully implement leading practices that enhance and sustain collaboration in QIS; (b) foster collaboration both across government and with academia and industry to achieve the goals agreed upon by the QIS subcommittee; and (c) enhance and sustain collaboration among the agencies in the area of synthetic biology, a prime goal of the Biological Sciences subcommittee.

On behalf of the NSF staff participating in the GAO review, I would like to acknowledge the GAO team for their diligence and commitment in conducting this review and issuing this report. Please contact Veronica Shelley at (703) 292-4384, if you have any questions or require additional information.

Sincerely,

France A. Córdova
Director

2415 Eisenhower Avenue | Alexandria, VA 22314

Appendix VII: GAO Contact and Staff Acknowledgments

GAO Contact

John Neumann, (202) 512-3841 or neumannj@gao.gov

Staff Acknowledgments

In addition to the contact named above, the following individuals made contributions to this report: Christopher Murray (Assistant Director), Angela Miles (Analyst-in-Charge), Justin Fisher, Scott Fletcher, Ashley Grant, Charlotte E. Hinkle, Gwen Kirby, Patricia Moye, Cynthia Norris, Emily Pinto, Tind Shepper Ryen, McKenna Storey, and Walter Vance.

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