



U.S. GOVERNMENT MECHANISMS TO SUPPORT THE DEVELOPMENT AND COMMERCIALIZATION OF “DEEP” TECHNOLOGIES

A Report to NEDO

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PREFACE

The study underlying this report was commissioned by the Washington, D.C., office of Japan's New Energy and Industrial Technology Development Organization (NEDO) and was conducted by Technology Policy International, LLC.

The opinions expressed in this report do not necessarily reflect the views of NEDO or of other institutions with which the TPI partners are affiliated.

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EXECUTIVE SUMMARY

This report addresses how the U.S. government supports the development and commercialization of major innovations based on significant advances in science and technology. As has become common, we use “deep tech” as a shorthand for this kind of innovation, to distinguish it from “tech,” which is often associated with information technology innovation based on minimal research and development (R&D).

For the purposes of this report, deep technologies are those that:

- Potentially provide new capabilities or major improvements in performance and/or cost based on advances in science or engineering.
- Have high technical risk (and thus significant chance that R&D projects will not achieve their goals).
- Require substantial R&D and capital investment before successful commercialization.
- Typically generate valuable intellectual property.
- Have a combination of risk, cost, and development time that generally prevents the private sector from developing and commercializing the technologies without government support.

While the term “deep tech” is not limited to specific technologies, many observers refer to specific technologies as examples of deep tech. These typically include biotechnology, robotics, electronics, artificial intelligence, synthetic biology, nanotechnologies, and quantum information technology, extended reality, blockchain, Internet of things, 3D printing, and others. Deep tech companies may apply these technologies, or combinations of them, in many markets and industries including aerospace, agriculture, energy, health, and many others.

A combination of traditional American political views and changing national needs has shaped U.S. R&D policies and support for deep tech. While U.S. government support for science and technology has earlier roots, current U.S. policies and institutions that support deep tech have their roots in World War II.

Before World War II, industry, government, and academia worked separately on their scientific and technical endeavors. During World War II, to address the needs of the armed forces, the federal government adopted several new approaches to supporting and conducting organized research and development. These included creating several military-oriented, government-sponsored research laboratories; creating procedures for contracting with private industry for research on new technologies; and awarding major grants to academic institutions for the conduct of research of potential military value. Overall, these new approaches proved to be spectacularly successful in creating major new technologies, and they laid the groundwork for substantial post-war expansion of R&D activity and spending by all three sectors: government, industry, and universities.

In the following decades (1950s and 1960s), the United States was able to establish leading positions among all nations in fundamental research, technology development, and industrial applications. What we think of today as “deep technologies” emerged at a furious pace from the U.S. system, based on advances in, and applications of, R&D. Despite advances by the

Soviet Union, U.S. dominance was unchallenged from the mid-1940s until the late 1970s and early 1980s.

U.S. post-World War II science policies were based on a political consensus that allowed government support for basic research and R&D for the government's own needs (primarily defense), but held that the private sector was responsible for technology development for commercial purposes. This system worked well when U.S. industry had few international competitors.

By the 1980s, however, U.S. dominance had come under significant challenges from revitalized Europe and Japan. Recognition that these challenges were real and substantial, the U.S. began to cast about for steps it could take to counter them. Efforts were made to rethink the U.S. system, both its institutions and its strategy.

On the strategic side, interest emerged in ways to marshal the nation's scientific and technical resources and to focus more of them on what were perceived to be key national challenges and critical technologies that could underlie a strong competitive position in the future. Policymakers, industrial leaders, and academic strategists began to identify what would be the most important such technologies and to support efforts to focus on them. Out of this grew not only several versions of the "critical technologies" movement but also major technology initiatives in both the private and public sectors in fields such as semiconductor manufacturing technology, advanced manufacturing and robotics, high performance computing and networking, and aerospace; and more recently in artificial intelligence, quantum computing, neuroscience, and many others. Due to the U.S. political system's aversion to government support for commercial technology development, government efforts to support critical technology largely focused on expanding university research and on developing technologies important for national security, most notably through the Defense Advanced Research Projects Agency (DARPA).

On the institutional side, major strides were made in the 1980s and early 1990s to reframe how R&D and technological innovation were organized in the United States. Most important, multiple steps were taken to break down barriers among researchers and innovators at many levels. For example, new legislation adopted in the 1980s and early 1990s facilitated R&D collaboration among companies, often in conjunction with elements of universities. Government research facilities were opened to participation by industry in a variety of modalities including collaborative research, instrumentation sharing, and intellectual property licensing. Collaborative research centers proliferated. In academia, intellectual barriers that separate disciplines and fields were overcome to take advantage of the possibilities offered by cross-disciplinary research teams. Mechanisms were established to coordinate and prioritize science and technology activities across Federal agencies.

Today, U.S. R&D and innovation can fairly be characterized as a system of interlocking systems of public, private, and non-profit research and educational institutions working together in collaborative arrangements in pursuit of scientific understanding, invention, innovation, entrepreneurship, and commercialization of highly complex, high risk, long-term technologies that can transform markets and even entire societies. U.S. innovation and commercialization

of deep technologies relies on this total system. Recent efforts to strengthen U.S. support of deep technologies have focused on:

- Developing national initiatives to coordinate and prioritize science and technology efforts across the Federal government in key areas
- Creating new university-industry-government research centers to generate ideas, train researchers, develop infrastructure, and share knowledge
- Applying DARPA's model of advanced technology development to other agencies of the Federal government.

In addition, the U.S. occasionally uses other mechanisms, including prize competitions, and advanced purchase commitments to stimulate R&D, as well as demonstration projects, government procurement, standards support, regulatory requirements, tax incentives, and others to aid the commercialization of deep technologies.

Quantum information science (QIS) and artificial intelligence (AI) are important areas of deep technology and illustrate many aspects of the U.S. system for supporting such technologies. They both draw on decades of R&D conducted by many Federal agencies. More recently, national initiatives have coordinated and expanded Federal R&D programs and led to the creation of new university- and national laboratory-based research centers. Agencies operating on the DARPA model (DARPA and IARPA) are key contributors to both areas.

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U.S. GOVERNMENT MECHANISMS TO SUPPORT THE DEVELOPMENT AND COMMERCIALIZATION OF “DEEP” TECHNOLOGIES

INTRODUCTION

This report addresses how the U.S. governments supports the development and commercialization of major innovations based on significant advances in science and technology. As has become common, we use “deep tech” as a shorthand for this kind of innovation.

The term “deep tech,” often attributed to venture capitalist Swati Chaturvedi, was first used in the venture capital/start-up community around 2014 to describe “companies founded on a scientific discovery or true technological innovation.”¹ This was to contrast these companies with the many venture-capital-supported startup companies that apply digital business models to existing businesses but are not based on fundamental advances in science or technology. Such “shallow tech” companies typically require less R&D and capital to get products to the market, and are frequently well-funded by venture capital, but produce fewer fundamental advances.

Deep tech companies, on the other hand, typically require significant R&D and longer-term investments, generate significant intellectual property, and make more significant contributions to societal problems. Due to its greater research and capital needs, and longer time horizons, deep tech often requires the collaboration of government, universities, and research labs, as well as firms and private capital.

Different groups define deep tech differently and emphasize different aspects of deep tech, but there are common elements.² Some of the common attributes in most descriptions of deep tech companies are that they:

¹ Swati Chaturvedi, “What attracts me most to Deep Tech Startups?”, November 17, 2020. <https://www.propelx.com/blog/what-attracts-me-most-to-deep-tech-startups/>.

² See, for example, Redmond, Eric. *Deep Tech: Demystifying the Breakthrough Technologies That Will Revolutionize Everything*, Deep Tech Press, Kindle Edition, 2021. Antoine Gourévitch, Massimo Portincaso, Arnaud de la Tour, Nicolas Goeldel, and Usman Chaudhry, “Deep Tech and the Great Wave of Innovation,” Boston Consulting Group, March 11, 2021, <https://www.bcg.com/publications/2021/deep-tech-innovation>. Anastasia Nedayvoda, Fannie Delavelle, Hoi Ying So, Lana Graf, Louise Taupin, “Financing Deep Tech,” International Finance Corporation. Special Note 1 Oct 2021. www.ifc.org/thoughtleadership
J.E Siegel and S. Krishnan, “Cultivating Invisible Impact with Deep Technology and Creative Destruction,” *Journal of Innovation Management*, www.open-jim.org, 8(3), 6-19. (2020). https://journalsojs3.fe.up.pt/index.php/jim/article/view/2183-0606_008.003_0002/459

- Are research-based,
- Focus on solving important and often complex social and environmental challenges,
- Focus on breakthrough rather than incremental advances, and
- Disrupt existing business models.

While the term “deep tech” is not limited to specific technologies, many tech groups refer to specific technologies as examples of deep tech. These typically include biotechnology, robotics, electronics, artificial intelligence, synthetic biology, nanotechnologies, and quantum information technology, extended reality, blockchain, Internet of things, 3D printing, and others. Deep tech companies may apply these technologies, or combinations of them, in many markets and industries including aerospace, agriculture, energy, health, and many others.

While the term “deep tech” was originally used to define a type of start-up company, large and established companies may also be involved in deep tech. In earlier times, most of what is now being called deep tech came out of large industrial laboratories, such as Bell Labs. Today companies involved in deep tech include start-ups, relatively new companies that are past the start-up stages (like Google and Tesla), as well as older well-established companies like Pfizer.

To long time technology policy observers, including TPI, “deep tech” is a new term for an old concept: R&D-based technological innovation. Before the Internet led to many e-commerce-based innovation and business opportunities, much innovation and most government-supported innovation was based on R&D. The term “deep tech” came into use because “tech” became identified primarily with information technology-based innovation.

U.S. science and technology policy has for a long time focused on supporting activities that the private sector will not support, including basic research and R&D to address U.S. government missions. Beginning in the 1980s, U.S. technology policy began to go beyond support for basic research to include support for R&D on generic pre-competitive technologies, some of which might now be called deep technologies.

For this report, deep technologies are those that:

- Potentially provide new capabilities or major improvements in performance and/or cost based on advances in science or engineering,
- Have high technical risk (and thus significant chance that R&D projects will not achieve their goals),
- Require substantial R&D and capital investment before successful commercialization,
- Typically generate valuable intellectual property, and
- Have a combination of risk, cost, and development time that generally prevents the private sector from developing and commercializing them without government support.

By contrast, this report is not focused on:

- Incremental innovation in an existing industry (e.g., next generation of semiconductor, wireless networks, etc.) even when this innovation may require substantial R&D,
- Scientific research that is not motivated by needs or applications,

- Established mega projects (e.g., space exploration or fusion energy). These are a kind of deep technology, but they have established long-term programs that are making mostly on incremental advances. However, radically new approaches within these areas (e.g., novel nuclear reactors or spacecraft technology) are often included as deep tech, or
- Purely private sector innovation (i.e., areas where benefit/risk are such that private sector investment is adequate, such as many areas of e-commerce).

This report discusses U.S. government support for deep technologies. It begins by discussing R&D programs, including both the evolution of deep tech R&D programs in recent decades and the current and expanding mechanisms used to support deep technologies. It then discusses supporting deep technologies through other methods such as prizes and competitions. The next section discusses other government mechanisms to aid implementation or commercialization of deep technologies, and then discusses how these mechanisms are being used in two of the most prominent areas of deep tech today: quantum information science and artificial intelligence.

SUPPORTING DEEP TECHNOLOGIES THROUGH RESEARCH AND DEVELOPMENT

THE HISTORY OF U.S. GOVERNMENT SUPPORT FOR DEEP TECHNOLOGIES

Before 1940, the U.S. Government made only small investments in R&D: modest support for agricultural research at universities and government laboratories, funding for some military research, and the operation of a few federal laboratories, such as the National Bureau of Standards (now the National Institute of Standards and Technology, NIST). This was an era when many Members of Congress as well as industrial leaders and even university researchers and administrators wanted a small federal government and saw little reason to expand federal R&D spending.

This small-government philosophy changed dramatically during World War II and the Cold War. Then in the 1980s and early 1990s Congress and presidents adopted new policies to improve economic competitiveness, and recently – in 2020 to 2022 – Congress and President Biden have made further changes to U.S. policies for the development of new technologies.

U.S. R&D policies since 1940 have several key features:

- During World War II, the U.S. Government greatly expanded defense R&D which was conducted not only in the government's own laboratories but also in universities, companies, and a new set of university-run government laboratories.
- After World War II, the United States greatly expanded support for basic research, primarily at universities and several large university-operated physics laboratories.

Private companies also established or expanded their own basic research laboratories. Defense R&D programs continued to grow during the Cold War.

- In the 1980s and early 1990s, as Japan and Germany became strong economic competitors, the United States enacted new policies designed to speed the commercialization of new technologies and to improve U.S. manufacturing. These policies were intended to encourage more cooperation between universities and companies, to assist high-tech small businesses, to help both large and small manufacturers improve their production technologies, and to help both small and large companies accelerate the commercialization of major new technologies. Some, but not all, of these policy initiatives were politically controversial. During this time, many U.S. private companies also sought ways to reduce barriers between their basic research laboratories and their operating units.
- The period from 1995 to 2020 saw little change in federal R&D policies, although federal R&D funding continued to grow, particularly for defense, health, and some areas of energy.
- By 2020, China's technological ambitions led many U.S. leaders to discuss new policies to keep the United States strong technologically and to speed the commercialization of valuable new technologies. A second theme in this period was to help cities and states across the country develop their own high-tech industries and jobs. A third theme was to use federal R&D not only to support defense, basic research, and other established fields but also to help with newer challenges, including economic opportunity.
- In 2021 and 2022, President Biden and Congress created several new policies and programs, including policies to help the U.S. semiconductor industry, an expansion of NSF's role in helping to develop new technologies, new NSF and Commerce Department programs to help cities develop high-tech industries, and several new "results-oriented" agencies based on the DARPA model, including a new Advanced Research Projects Agency for Health (ARPA-Health).
- An important point is that throughout its history the U.S. has never had a single, unified R&D policy. Instead, over the years Congress and presidents have adopted a wide range of policies, and different U.S. government departments and agencies have their own policies, programs, cultures, and constituencies. Presidents do provide some coordination of these agency programs, but the overall federal system remains decentralized. One advantage of this decentralized R&D system is that federal departments and agencies and their supporters in Congress have the freedom to try policy experiments.

The next few pages of this report provide further details about these key features of the federal R&D programs and how they help the country develop new deep technologies.

By 1940, the military importance of new technologies such as radar and atomic energy was clear to many U.S. leaders, and they not only increased federal R&D spending but also created new organizations to manage and carry out that R&D. Existing federal laboratories and existing companies were not enough. So, President Franklin Roosevelt and Congress created an Office of Scientific Research and Development (OSRD) to manage and fund technology development, and OSRD and other officials encouraged the creation of new laboratories, managed by universities and sometimes companies, to combine advanced scientific knowledge with practical technology development. One famous example was the Radiation Laboratory at MIT, which developed advanced radar systems. Another was the nuclear weapons laboratory at Los Alamos, New Mexico, created and managed by the University of California (which still manages it today). OSRD also funded the development and production of other important technologies, such as synthetic rubber, penicillin, and new treatments for malaria.

Two economic historians describe how federal R&D funding grew during World War II:

...overall federal R&D expenditures (in 1930 dollars) soared from \$83.2 million in 1940 to a peak of \$1313.6 million in 1945. Over the same period, [defense] research expenditures rose from \$29.6 million to \$423.6 million (in 1930 dollars).³

The government abolished the OSRD after the war, but Congress replaced it with a set of R&D agencies for defense, energy, health, and basic research, including the Atomic Energy Commission (whose R&D operations later went to the Department of Energy); defense research agencies such as the Office of Naval Research; the Defense Department's own internal laboratories; a greatly expanded National Institutes of Health; and a new National Science Foundation. Moreover, the U.S. kept its wartime policy of funding R&D not just in the government's own civil-service laboratories but also in companies, universities, and university-run and company-run laboratories.

As the Cold War developed, Congress provided additional funding to Defense Department R&D agencies and laboratories. The Soviet Union's launch of the *Sputnik* artificial satellite in 1957 shocked the United States and led to the creation of two new agencies: the Advanced Research Projects Agency (now DARPA) and NASA.

ARPA/DARPA focused on understanding and supporting advanced new technologies that offered significant advantages over existing capabilities. The U.S. did not want to be surprised again by Soviet technology; ARPA began to see that the best way of avoiding technological surprise was to create surprising new technologies of its own. Following the model of OSRD and even earlier technology-development processes pioneered in the 1930s, ARPA created a system by which highly expert program managers would identify promising new technological opportunities and then fund teams to create them. ARPA focused on the development of new, innovative technologies – often complex and expensive deep technologies.

A later section of this report will discuss DARPA in more detail.

³ David C. Mowery and Nathan Rosenberg, *Paths of Innovation: Technological Change in 20th-Century America* (Cambridge: Cambridge University Press, 1998).

NEW U.S. TECHNOLOGY POLICIES DURING THE 1980S AND 1990S

By the late 1970s and early 1980s, U.S. industry faced new economic challenges from Japan and Germany. While the U.S. remained a world leader in research, many analysts and leaders thought that country was slower than Japan to develop, commercialize, and manufacture promising new inventions. One leader, U.S. Senator Fritz Hollings, Democrat of South Carolina, provided this comment: “We get the Nobel Prizes, and the Japanese get the profits.” His frustration arose from the view that the United States was not rapidly commercializing its own ideas before others did.

From 1980 to the early 1990s, Congress and presidents created, funded, and managed an important set of new policies and programs to help the U.S. accelerate the development of new technologies. One major theme of these policies was to increase cooperation among university basic research groups, government laboratories, and companies.⁴ A second theme was to provide government financial assistance to help both small and large companies accelerate the development of risky but potentially valuable new technologies. A third theme was to help manufacturers to improve their production technologies. Many of these new initiatives – but not all – received bipartisan support.

These new policies and programs included the following:

- ***The Bayh-Dole Act (Patent and Trademark Amendments of 1980)***. Popularly called the Bayh-Dole Act, after the two U.S. Senators who sponsored it, this law allows non-profit organizations (particularly universities) and small businesses to keep the patent rights to the inventions that they create with federal R&D funds. The idea is that the universities and companies will be better than federal civil servants at commercializing these inventions, and that taxpayers will benefit from the jobs and tax revenues that will result from commercialization.
- ***Research and experimentation tax credits***. In 1981, Congress and President Ronald Reagan enacted legislation that created research and experimentation (R&E) tax credits – a set of four credits that encourage companies to increase their corporate R&D spending.

⁴ A related development, briefly mentioned earlier in this report, is that during the 1980s many large U.S. companies also took steps improve cooperation between their basic research laboratories and their business units and the factories operated by these business units. In the early post-World War II years, companies such as AT&T, General Electric, DuPont, and IBM expanded or created university-like research campuses, far from their factories. Both the federal government and the companies believed that basic research teams separated away from applied R&D and manufacturing groups would produce wonderful new ideas. By the 1980s, however, many corporate leaders saw that their companies often had difficulty in commercializing new inventions, largely because researchers did not work closely with development teams and manufacturing groups. Many companies began to create joint teams of researchers and development personnel, to break down barriers. And eventually many companies also reduced or eliminated their basic research laboratories, since they produced little value for their sponsoring companies.

- **Small Business Innovation Research Program.** In the late 1970s and early 1980s, NSF pioneered a program that gave R&D funding to small businesses (defined in the U.S. as companies with 500 or fewer employees). Based on the popularity of the NSF program, Congress then enacted the Small Business Innovation Act of 1982 that required large federal R&D agencies to award small businesses a percentage of their “extramural” R&D funding (funding to organizations outside the government).
- **Cooperation between government laboratories and companies.** Two laws from the 1980s allow government laboratories to enter into “cooperative research and development agreements” (CRADAs) with companies and other non-federal entities. The purpose is to let companies take advantage of technologies and expertise in the laboratories. CRADAs have never become a major part of industrial R&D, but they can be helpful.
- **NSF Engineering Research Centers.** In the 1980s NSF created its ERC program, which supports university centers jointly funded by NSF and companies. The centers have two purposes: to fund research that will help companies and to train students in fields that are important to industry.
- **High-Performance Computing and Computing Initiative.** This was a multi-agency program created by the Reagan Administration, with bipartisan support from Congress. It was an ambitious program to fund R&D on computing hardware, new communications technology (what became the Internet), and applications. It had some major successes, such as the creation of the search algorithm used by Google. It continues today under a different name: the Networking and Information Technology R&D Program.
- **SEMATECH.** In 1987, the U.S. semiconductor industry convinced Congress and the Reagan Administration to contribute federal funding to an industry-led consortium called Semiconductor Manufacturing Technology (SEMATECH). The consortium consisted of major U.S. semiconductor companies and semiconductor equipment and materials firms, with the purpose of helping the U.S. industry improve its manufacturing. Japanese companies were efficiently producing high-quality chips, and the U.S. was behind. For five years, the Defense Department provided half the funds for SEMATECH, while industry provided the rest of the money.
- **Manufacturing Extension Partnership.** Created by the Omnibus Trade and Competitiveness Act of 1988, this program – now called the Hollings Manufacturing Extension Partnership – provides federal funding for a nationwide network of centers that provide technical assistance to small and medium-sized manufacturers. (While this is not a deep technology program, it was an important part of the 1980s and 1990s policy innovations).
- **Advanced Technology Program.** Also created by the Omnibus Trade and Competitiveness Act, this Commerce Department program provided federal money for industry projects to accelerate the development of economically-valuable new technologies. It succeeded in the 1990s in creating several valuable technologies.

However, while the other initiatives listed above generally received bipartisan support, the ATP encountered opposition from Republicans. President Clinton strongly supported it, but Congress terminated funding after he left office.⁵

These various new policies and programs, combined with existing federal R&D spending, helped U.S. industry improve innovation in deep technologies. However, three other points are important.

First, while there was a broadly-shared desire to accelerate the development of new commercial technologies and to improve manufacturing,⁶ these new laws and programs were created one at a time, often with support from different government leaders and different constituencies, and they did not represent a deliberate overall strategy for U.S. technology policy. No one in the White House or Congress really tried to create an overall, unified set of programs to improve U.S. technological competitiveness. The U.S. political system is both very decentralized and “entrepreneurial,” with individuals in Congress, the Executive Branch, and interest groups developing new proposals. No one systematically asked how successful this group of initiatives truly was or what gaps in U.S. technological performance remained. Instead, these laws and programs can be seen as a set of related but still separate “policy experiments” that their advocates hoped would help U.S. industry.

Second, while many of these new initiatives received bipartisan support, a long-lasting U.S. debate over the appropriate role of the federal government in supporting industrial technologies arose again. As mentioned earlier, this debate led Congress to terminate funding for the Commerce Department’s Advanced Technology Program.

Third, when Congress terminated funding for the ATP, the U.S., in effect, reverted to letting the Defense Department and particularly DARPA take the lead in developing new deep technologies. Many of DARPA’s technologies are “dual-use,” meaning that both civilian industries and the defense establishment can use them. The Internet, GPS receivers, advanced materials, and mRNA vaccines are example of dual-use technologies funded by the agency. However, DARPA must always focus on its defense mission; if its technologies have civilian benefits, then that is fine, but DARPA never focuses on developing technologies for civilian

⁵ Shortly before Congress terminated funding for this program, Congress changed the name from the Advanced Technology Program to the Technology Innovation Program. Both names are used to describe the program, although ATP is better known of the two titles.

⁶ An influential report that helped to guide national policy was, President’s Commission on Industrial Competitiveness, *Global Competition: The New Reality* (Washington, DC: Government Printing Office, 1985). John Young, then the Chairman of Hewlett-Packard Corporation, chaired the Commission, and the report is often called the Young Commission report. The Bush and Clinton Administrations also issued general statements about technology policy. The Bush Administration statement was: Office of Science and Technology Policy, Executive Office of the President, “U.S. Technology Policy,” September 26, 1990. The Clinton Administration report was: President William J. Clinton and Vice President Albert Gore, Jr., “Technology for America’s Economic Growth, A New Direction to Build Economic Strength,” February 22, 1993.

industry or the civilian economy. So, it is helpful to civilian industry but never focuses on civilian technology needs.

U.S. R&D POLICIES FROM 1995 TO 2020

The period from 1995 to 2020 saw little change in U.S. policies and programs for R&D and deep technology. There were some additions but not many: a new National Nanotechnology Initiative in 2000; a new set of federally-supported Manufacturing Institutes; and additional federal money for energy R&D, including the creation of a new Advanced Research Projects Agency-Energy (ARPA-E). Overall, however, during these years Congress did not express much concern about U.S. technological competitiveness or consider major new technology initiatives. The U.S. seemed to do well in developing new technologies and industries, such as Internet-based companies and biotechnology.

This situation began to change around 2015. First, some analysts and officials began to express concern about the U.S. position in physical technologies, including the difficulties that deep-tech entrepreneurs faced in finding mentors and raising money. Box 1 describes one small but promising initiative to help deep-tech entrepreneurs; this program is run by a non-profit organization called Activate.

BOX 1: A RECENT U.S. PROGRAM TO HELP DEEP-TECH ENTREPRENURS

Founded in 2015, Activate is a non-profit organization that partners with government laboratories to provide fellowships, mentorship, laboratory support, and introductions to venture capitalists for young people with PhDs who want to start companies that will make physical products. The program began with a partnership with Lawrence Berkeley National Laboratory and now also includes MIT's Lincoln Laboratory. Activate fellows are given laboratory space and equipment at these laboratories. Here is how Activate describes its mission:

Today's innovation ecosystem does not adequately support scientists in creating transformative products....

Activate works between government and the private sector, transforming scientists into high-impact entrepreneurs through a fellowship experience that guides them along every step of the journey.

In doing so, **we are often the difference between our fellows having a real shot at scaling their idea or not getting started at all** [emphasis in original]. We help them go from zero to one.

We find those promising individuals whose research has the potential to transform the world's physical infrastructure and industries and who are driven to bring that

research to market. Through our two-year fellowship, they develop as leaders, mature their ideas, and learn what it takes to build a viable, scalable business. With our support, nearly all of them achieve first financing and product milestones to set them on that path. (Activate, “From zero to one,” <https://www.activate.org/impact>)

Second, around 2015 and later Americans recognized China’s desire to take the lead in important new technologies, through initiatives such as Made in China 2025. Many Democrats as well as Republicans began to express concern about China’s efforts to dominate key technologies and industries – particularly what some analysts call “the industries of the future.”⁷

The Trump years saw some budget increases for key technologies, such as expanded NSF and DOE funding for artificial intelligence and quantum computing. But the Trump Administration did not propose any large increases in support for capital-intensive new technologies. Then in 2020 leaders in Congress began to propose some major changes in U.S. science and technology policy.

2020-2022: NEW PRIORITIES AND NEW LAWS AND PROGRAMS

New Policy Themes

Beginning in 2020, members of Congress – mainly Democrats but also some Republicans – proposed new laws to accelerate the development and adoption of valuable new technologies. The first major bill (proposed law) was the Endless Frontier Act, introduced in May 2020.⁸

Several themes ran through the Endless Frontier Act and related proposals:

Develop technologies that are important to the “industries of the future.” These are industries such as artificial intelligence, electric vehicles, quantum computing, and biotechnology. Concern about economic and military competition with China was the major reason for these proposals. In the case of energy technologies, the goals included helping U.S. companies and workers compete with China as well as helping to reduce greenhouse gas emissions.

Focus more on producing useful results. Related, the Endless Frontier Act and other legislative proposals reflected an undercurrent of dissatisfaction with existing federal R&D programs – a

⁷ See, for example, this report from advisors to President Trump: President’s Council of Advisors on Science and Technology, “Recommendations for Strengthening American Leadership in Industries of the Future,” June 2020, https://science.osti.gov/-/media/_/pdf/about/pcast/202006/PCAST_June_2020_Report.pdf.

⁸ Senate and House versions of the Endless Frontier Act were introduced on May 21, 2020 (S. 3832 and H.R. 2731, 116th Congress). A later and related proposal was the proposed United States Innovation and Competition Act of 2021 (H.R. 4521 and S. 1260, 117th Congress). These bills ultimately led to science portion of the CHIPS and Science Act of 2022 (Public Law 117-167); this new law is discussed later in this report. See also TPI’s report “Science & Technology Policymaking in the U.S. Congress: The Endless Frontier Act.”

https://technopoli.net/assets/docs/ST_Legislation_in_US_final.123172323.pdf

belief that the government should support applied research as well as basic research.⁹ In particular, Congress showed a renewed interest in applying the DARPA model to other policy areas, such as a proposal in the original version of the Endless Frontier Act to create a DARPA-type directorate within NSF.

Help cities across the country develop high-tech industries. Much of the new high-tech growth in the United States has been in a few regions, such as Silicon Valley, Boston, Seattle, and Austin, Texas. Many members of Congress want to help other cities become “regions of innovation.” The Endless Frontier Act proposed new programs to help other cities develop strength in innovation.

U.S. Laws and Programs in 2022

By the end of 2022, Congress and President Biden enacted several major new research and technology laws. These laws aim to accelerate the development, production, and adoption of important but capital-intensive deep technologies in the United States

The CHIPS and Science Act of 2022. The first major new law was the CHIPS and Science Act of 2022 (Public Law 117-167). It combined two sets of proposals: (1) legislation to support the U.S.-based semiconductor industry, and (2) provisions in the Endless Frontier Act and other bills to enhance the contributions of NSF and other agencies to the creation of important new technologies and to help with regional economic development.

The semiconductor portions of the CHIPS and Science Act. An earlier law created a program to support and expand the domestic manufacture of semiconductors but did not provide funding.¹⁰ The first part of the CHIPS and Science Act provided \$52 billion in funds (“appropriations”) for this program, including \$39 billion for financial assistance to companies that build, expand, or modernize semiconductor facilities and equipment in the U.S.; an additional \$11 billion for the Department of Commerce (DOC) to support semiconductor research and development; and \$2 billion to the Defense Department for university-based prototyping of semiconductor technologies. The law also provides an “advanced manufacturing investment tax credit” for the semiconductor industry.

The research and innovation portions of the CHIPS and Science Act. The other part of the Act “authorized” (recommended) additional R&D funding at several federal departments and agencies: NSF, the Department of Commerce, the National Institute of Standards and Technology (NIST, a part of DOC), NASA, and the Department of Energy (DOE).

⁹ Academic scholars were also asking how much of today’s government-supported research actually produces “disruptive” science and patents – that is, highly innovative new results. See, for example, Michael Park, Erin Leahey, and Russell J. Funk, “Papers and patents are becoming less disruptive over time,” *Nature*, Vol 613, 5 January 2023, <https://doi.org/10.1038/s41586-022-05543-x>.

¹⁰ The semiconductor program was “authorized” (created but not actually funded) in the William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021 (Public Law 116-283). The semiconductor provisions are in Title XCIX (Title 99) of the Act.

The law created and recommended funding for a new NSF Directorate of Technology, Innovation, and Partnerships (TIP); it also authorized more funding for R&D programs at NIST and DOE. To help states and cities across the entire U.S., the law authorized funding for NSF’s programs for low-population states, for NIST’s Hollings Manufacturing Extension Partnership, and for a new DOC program to help create “regional technology hubs.”

Table 1 summarizes the law’s five-year authorizations for these programs – that is, the total funding amounts that the law recommends over the next five years. The table also specifies how much larger, over five years, the recommended levels are above spending at Fiscal Year 2022 levels (that is, above the “baseline”). Again, these are authorizations – not actual appropriations.¹¹

Table 1. CHIPS and Science Act Authorization Levels

Key Programs	Five-Year Authorization	Increase over Baseline
National Science Foundation (NSF)	\$81 billion	\$36 billion
• NSF Tech Directorate	\$20 billion	\$20 billion
• NSF Core Activities	\$61 billion	\$16 billion
Department of Commerce (DOC)	\$11 billion	\$11 billion
• Regional Technology Hubs	\$10 billion	\$10 billion
• RECOMPETE Pilot	\$1 billion	\$1 billion
National Institute of Standards and Technology (NIST)	\$10 billion	\$5 billion
• NIST Research	\$6.9 billion	\$2.8 billion
• Manufacturing USA	\$829 million	\$744 million
• Manufacturing Extension Partnership	\$2.3 billion	\$1.5 billion
Department of Energy (DOE)*	\$67.9 billion	\$30.5 billion
• DOE Office of Science	\$50.3 billion	\$12.9 billion
• Additional DOE Science and Innovation	\$17.6 billion	\$17.6 billion
Total	\$169.9 billion	\$82.5 billion
<p>*Across all the DOE sections, there is:</p> <ul style="list-style-type: none"> • A total of \$14.7 billion for infrastructure, equipment, and instrumentation across 17 DOE National Laboratories. • A total of \$16.5 billion in new or above baseline authorizations for research in the 10 technology areas identified in USICA across the Office of Science and DOE’s applied R&D offices in advanced energy and industrial efficiency technologies, artificial intelligence and machine learning, advanced manufacturing, cybersecurity, biotechnology, high performance computing, advanced materials, and quantum information science. 		

¹¹ Source: Committee on Commerce, Science, and Transportation, U.S. Senate, “CHIPS and Science Act of 2022 “, <https://www.commerce.senate.gov/services/files/2699CE4B-51A5-4082-9CED-4B6CD912BBC8>. Also, this table does not mention the law’s authorizations for NASA, because while budget authorizations for NASA are included in the law, NASA is not part of the law’s sections regarding general research and innovation.

Clean energy provisions in the Inflation Reduction Act of 2022. Another major 2022 law is the Inflation Reduction Act (Public Law 117-169). This law includes provisions on many topics, including tax policy, agriculture, and health care. The law also contains important sections encouraging environmental protection, new energy production, and the adoption of clean energy technologies such as electric vehicles and energy-efficient home appliances. These provisions do not directly increase federal R&D funding for deep technology. However, the tax credits and related financial assistance encourage people to buy electric vehicles and other new products, thus helping companies and encouraging the companies to increase their own R&D spending.¹²

The law's tax incentives to encourage Americans to buy electric vehicles apply only to vehicles assembled in North America. Democrats wrote that provision to encourage the creation of U.S. jobs. However, U.S. allies in Europe and Asia have objected to this requirement that only North American-assembled vehicles are eligible for the tax credits.¹³

ARPA-Health. Another major initiative in 2021-2022 was the creation of the Advanced Research Projects Agency for Health (ARPA-H). While Congress has given large amounts of funding to the National Institutes of Health (NIH) -- \$47.5 billion for Fiscal Year 2023 -- Congress has also provided funding to the new ARPA-H. The creation of this new agency appears to show that Congress wants not only NIH's basic research but also additional "results-oriented R&D." ARPA-H received an initial \$1 billion for Fiscal Year 2022 and another \$1.5 billion for Fiscal Year 2023. ARPA-H is based on the DARPA model, and in fact Dr. Renee Wegrzyn, the director of ARPA-H, is a former DARPA official.

Other programs. The desire for useful new technologies -- and for R&D programs that produce useful technological results -- also extends to other fields. And once again DARPA serves as a model. For example, the Bipartisan Infrastructure Law (Public Law 117-58) created and authorized funding for an Advanced Research Projects Agency-Infrastructure at the U.S. Department of Transportation. However, so far Congress has not appropriated actual funding for this new agency.

In 2018 Congress also created a new Agriculture Advanced Research and Development Authority (AgARDA), a "pilot" (experimental) effort "designed to generate and deploy advanced agricultural technologies, research tools, and qualified projects and products." So far, Congress has only provided \$1 million for this agency.¹⁴

¹² A four-page summary of the Inflation Reduction Act's environment and energy provisions is available at: Senate Democrats, "Summary of the Energy Security and Climate Change Investments in the Inflation Reduction Act of 2022," https://www.democrats.senate.gov/imo/media/doc/summary_of_the_energy_security_and_climate_change_investments_in_the_inflation_reduction_act_of_2022.pdf.

¹³ For example, see: Reuters, "EV tax credits to dominate U.S.-EU trade talks," *Automotive New Europe*, December 5, 2022, <https://europe.autonews.com/automakers/ev-tax-credits-dominate-us-eu-trade-talks>.

¹⁴ Emily Bass, "What Is the Agriculture Advanced Research and Development Authority?" Breakthrough Institute, August 22, 2022, <https://thebreakthrough.org/issues/food-agriculture-environment/what-is-the-agriculture-advanced-research-and-development-authority>.

We have also seen discussions about possible ARPAs at the Department of Education and the Department of Labor.

THE OPERATION OF GOVERNMENT DEEP TECHNOLOGY PROGRAMS

Many U.S. government R&D programs contribute in some way to the development of deep technologies. Other TPI reports have covered many aspects of major U.S. R&D agencies and programs¹⁵ and U.S. technology transition policies and programs.¹⁶ Here we will focus on the main approaches the U.S. has increasingly used to support deep technologies through R&D in recent years. These approaches, which build on the large set of established Federal R&D programs, can be characterized as:

- High level coordination and prioritization of deep tech R&D programs across government
- Use of university or national laboratory-based centers to support interdisciplinary research and engage industry.
- Expansion of the DARPA model to other agencies to develop technical solutions to specific problems.

COORDINATION AND PRIORITIZATION OF DEEP TECHNOLOGY PROGRAMS

Over the last three decades, there have been a variety of high-profile national R&D programs or “initiatives” in deep technology. These programs began in the late 1980s as efforts to coordinate and prioritize related technology activities across Federal agencies. Current programs are the Networking and Information Technology Research and Development (NITRD) program, the National Nanotechnology Initiative, Manufacturing USA, the National AI Initiative, and the National Quantum Initiative. Some initiatives originated in the executive branch while others originated in the Congress. Some, but not all, of the initiatives have been authorized in laws passed by the Congress.

The initiatives are overseen by committees of the National Science and Technology Council, which is made up of the heads of major science and technology agencies in the U.S. government and is cochaired by the director of the Office of Science and Technology Policy (OSTP) and the Vice President.¹⁷ The technology initiatives coordinate programs across agencies, develop an accounting of the funding in the area, and develop strategic plans and other reports. The initiatives typically represent both a continuation of old programs and the President’s proposals for new activities.

¹⁵ David W. Cheney, Christopher T. Hill, and Patrick H. Windham. “Overview of Major U.S. Research and Development Agencies and Their Programs.” Technology Policy International. March 2021. https://technopoli.net/assets/docs/Major_US_RD_Agencies_and_Programs_3-15-21.115122651.pdf

¹⁶ David W. Cheney, Christopher T. Hill, and Patrick H. Windham. “U.S. Technology Transition Policies and Programs.” Technology Policy International. March 2021. https://technopoli.net/assets/docs/TPI-technology_transition_programs-3-17-21.115123603.pdf

¹⁷ For more information about NSTC, see <https://www.whitehouse.gov/ostp/nstc/>

Most initiatives have created a national coordinating office, usually in one of the participating agencies, to support the initiative. Many of the initiatives also have an external advisory committee, with members from university and industry. The strategies for the initiatives typically encompass R&D funding, R&D infrastructure, workforce development, and applications/commercialization.

While these initiatives provide a mechanism to coordinate programs across federal agencies, draw attention to the importance of the area, and help to set priorities, it is important to note what they are not. They are not centrally planned research programs, but are rather compilations, with some organization, of R&D programs across agencies. The OSTP or the coordinating offices for the program do not manage the programs. Each agency runs its own program as authorized and appropriated by Congress. There is little ability to move funding from one agency to another. While the President’s annual budget request to the Congress does compile the budget for all activities in the initiative, and often requests increases in funding, the funding for the initiatives has to come from through the appropriations legislation for each agency, which are handled by any different appropriation committees within Congress.

The following are brief discussions of the major deep technology initiatives.¹⁸

THE NETWORKING AND INFORMATION TECHNOLOGY RESEARCH AND DEVELOPMENT PROGRAM (NITRD)

NITRD is the largest and oldest of the cross-agency technology programs discussed in this report. NITRD represents an evolution from an earlier interagency High Performance Computing and Communication Program (HPCC) that was first chartered by Congress in 1991. It currently involves 25 NITRD member agencies that now invest approximately \$9.6 billion annually in R&D programs to develop advanced networking and information technology capabilities needed by the Federal Government and the nation.¹⁹ The NITRD web site includes a superb summary and

Box 2. Program Component Areas within NITRD

- Advanced Communication Networks and Systems
- Artificial Intelligence
- Computing-Enabled Human Interaction, Communication, and Augmentation
- Computing-Enabled Networked Physical Systems
- Cyber Security and Privacy
- Education and Workforce
- Electronics for Networking and Information Technology
- Enabling-R&D for High-Capability Computing Systems
- High-Capability Computing Infrastructure and Applications
- Intelligent Robotics and Autonomous Systems
- Large-Scale Data Management and Analysis
- Software Productivity, Sustainability, and Quality

¹⁸ These initiatives have not generally been characterized as “deep technology” initiatives, but they do fulfill the definition of deep technology used in this report.

¹⁹ Subcommittee on Networking and Information Technology Research and Development, and the Machine Learning and Artificial Intelligence Subcommittee of the National Science and Technology Council. *The Networking & Information Technology R&D Program and the National Artificial Intelligence Initiative Office*, Supplement to the President's FY 2023 Budget. <https://www.nitrd.gov/pubs/FY2023-NITRD-NAIO-Supplement.pdf>

background on NITRD.²⁰ Information can be found there on NITRD's objectives, history, funding levels, membership, organization, leadership, and evaluation.

The NITRD program has grown in both size and complexity. There are 12 program component areas (see Box 2) and working groups on different technologies. Artificial intelligence and quantum information science have grown to become separate initiatives. The NITRD budget documents contain funding by program component area and by agency.²¹

THE NATIONAL NANOTECHNOLOGY INITIATIVE (NNI)

The NNI was established by executive action under President Clinton in 2000 and codified in law by Congress in the 21st Century Nanotechnology Research and Development Act passed in 2003. The NNI differs from the other initiatives/programs because it is focused on a particular scale of technologies, rather than a particular type of technology or application area. The initiative encompasses many fields of science and engineering and many application areas, including advanced materials, electronics, and biomedicine.

The NNI coordinates agency and departmental activities in support of nanotechnology and prepares periodic strategic plans and other reports. It also periodically evaluates the NNI's contributions. As with the other initiatives, the NNI is overseen by a subcommittee of the NSTC and is staffed by a National Nanotechnology Coordination Office (NNCO). The NNI has an annual R&D budget of nearly \$2 billion, divided into 5 areas:²²

- Foundational research (45 percent of budget)
- Nanotechnology-enabled applications, devices, and systems (35 percent of budget)
- Research infrastructure and instrumentation (15 percent of budget)
- Education and workforce development (1 percent of budget)
- Responsible development (3 percent of budget)

MANUFACTURING USA

Manufacturing USA had its origin in the National Network for Manufacturing Innovation proposed by President in Obama in 2012. The Obama used existing laws and funding in the Department of Defense and Department of Energy to establish manufacturing institutes. In 2014, Congress passed the Revitalize American Manufacturing and Innovation Act which

²⁰ See: <https://www.nitrd.gov/about/index.aspx>

²¹ Subcommittee on Networking and Information Technology Research and Development, and the Machine Learning and Artificial Intelligence Subcommittee of the National Science and Technology Council. *The Networking & Information Technology R&D Program and the National Artificial Intelligence Initiative Office*, Supplement to the President's FY 2023 Budget. <https://www.nitrd.gov/pubs/FY2023-NITRD-NAIO-Supplement.pdf>

²² Subcommittee on Nanoscale Science, Engineering, and Technology, Committee on Technology of the National Science and Technology Council. *The National Nanotechnology Initiative Supplement to the President' 2023 Budget*. February 2023. https://www.nano.gov/sites/default/files/pub_resource/NNI-FY23-Budget-Supplement.pdf See also https://www.nano.gov/sites/default/files/pub_resource/NNI-2021-Strategic-Plan.pdf .

authorized NIST, DOE, and other agencies to create manufacturing institutes and a network to connect them. In 2016, the name was changed to Manufacturing USA.²³

Manufacturing USA is similar in some ways to the other initiatives, but also differs in some key respects. Like the other initiatives, it is an interagency program overseen by a subcommittee of the National Science and Technology Council. It is managed by an interagency Advanced Manufacturing National Program Office, which is headquartered in the National Institute of Standards and Technology (NIST), in the Department of Commerce. Like other initiatives, there is a strategy document.²⁴

Unlike the other initiatives, Manufacturing USA is not the compilation of different R&D programs spread across many agencies, but instead was established to oversee a group of Manufacturing Institutes and the network that connects them. It is also unlike the other initiatives in that its focus is on manufacturing, which cuts across many technology areas. In addition, the R&D tends to be more applied and industrially oriented.

Each institute in the network is a public-private partnership between a federal agency sponsor and a nonfederal operating entity. Each institute focuses on a particular technology area and includes members such as private companies, nonprofit organizations, academic institutions, federal laboratories, and state and local governments. Most are focused on technology areas commonly considered to be deep technologies. There are currently 16 institutes, one sponsored by the Department of Commerce, nine by DOD, and six by DOE. As of August 2021, the institutes had collectively received approximately \$1.7 billion in Federal support. Support from nonfederal entities, including institute members and state and local governments, totaled approximately \$2.6 billion.²⁵

NATIONAL QUANTUM INITIATIVE (NQI)

The NQI was established by the National Quantum Initiative Act in 2018 and later amended by other legislation. The act created the NQI initiative under the NSTC. It also established the National Quantum Initiative Advisory Committee and the National Quantum Coordination Office to oversee the interagency coordination of the NQI Program, carry out the daily activities needed for coordinating and supporting the NQI, and provide technical and administrative support to the committees. Some parts of the NQI grew out of the NITRD initiative.

As with other initiatives, the NQI has an annual budget document that describes the total budget (\$918 million in FY2022) and the budget for each program component: Quantum Sensing, Quantum Computing, Quantum Networking, QIS for Advancing Fundamental Science,

²³ John Sargent. "Manufacturing USA: Advance Manufacturing Institutes and Network." Congressional Research Service. October 3, 2022. <https://sgp.fas.org/crs/misc/R46703.pdf>

²⁴ *The National Strategy for Advanced Manufacturing*. October 2022.

<https://www.manufacturingusa.com/documents/national-strategy-advanced-manufacturing>

²⁵ U.S. Government Accountability Office. "Advanced Manufacturing: Innovation Institutes Report Technology Progress and Members Report Satisfaction with Their Involvement." December 2021.

<https://www.gao.gov/assets/gao-22-103979.pdf>

and Quantum Technology.²⁶ The initiative also has a strategy that provides recommendations to strengthen the U.S. approach to quantum information science R&D, focusing on six key areas: science, workforce, industry, infrastructure, security, and international cooperation.²⁷ (NQI activities are discussed in greater detail in the case study section of this report.)

NATIONAL ARTIFICIAL INTELLIGENCE INITIATIVE (NAII)²⁸

Artificial Intelligence was previously part of the NITRD initiative described previously, but it was established as a separate initiative, by executive order by President Trump and then by statute in the National Artificial Intelligence Initiative Act of 2020, enacted on January 1, 2021.

The NAII Office is in OSTP and its director is appointed by the director of OSTP. The initiative is overseen by the Select Committee on AI established in 2018 under NSTC and is advised by the National AI Initiative Advisory Committee. The National AI Initiative provides a framework to strengthen and coordinate AI research, development, demonstration, and education activities across all U.S. Departments and Agencies, in cooperation with academia, industry, non-profits, and civil society organizations. The work is organized into six strategic pillars – Innovation, Advancing Trustworthy AI, Education and Training, Infrastructure, Applications, and International Cooperation.²⁹ The National Artificial Intelligence Initiative Act also provided for the establish of AI Research Institutes. There are currently 18 such AI Research Institutes funded at approximately \$20 million each for 5 years. (NAII activities are discussed in greater detail in the case study section of this report.)

²⁶ Subcommittee on Quantum Information Science, Committee on Science of the National Science and Technology Council. *National Quantum Initiative Supplement to the President's FY 2023 Budget*. January 2023.

<https://www.quantum.gov/wp-content/uploads/2023/01/NQI-Annual-Report-FY2023.pdf>

²⁷ Subcommittee on Quantum Information Science, Committee on Science of the National Science and Technology Council. *National Strategic Overview for Quantum Information Science*. September 2018.

https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf

²⁸ See www.ai.gov

²⁹ See <https://www.ai.gov/about/>

CRITICAL AND EMERGING TECHNOLOGIES LISTS

The National Science and Technology Council maintains a list of critical and emerging technologies that are viewed as important to national security. The current list is in Box 3.

Many of these critical and emerging technologies are addressed in the national technology initiatives described in the previous sections.

Most of the remaining technologies are ones that are of primary interest to only one or two agencies, and so require less interagency coordination.

There are also some smaller cross agency initiatives, such as the Materials Genome Initiative, that are lower profile than the various initiatives described previously.³¹ The Materials Genome Initiative is a federal multi-agency initiative for discovering, manufacturing, and deploying advanced materials more quickly and more cheaply than traditional methods. The initiative creates policy, resources, and infrastructure to support U.S. institutions in the adoption of methods for accelerating materials development.

Box 3. U.S. Critical and Emerging Technology List³⁰

- Advanced Computing
- Advanced Engineering Materials
- Advanced Gas Turbine Engine Technologies
- Advanced Manufacturing
- Advanced and Networked Sensing and Signature Management
- Advanced Nuclear Energy Technologies
- Artificial Intelligence
- Autonomous Systems and Robotics
- Biotechnologies
- Communication and Networking Technologies
- Directed Energy
- Financial Technologies
- Human-Machine Interfaces
- Hypersonics
- Networked Sensors and Sensing
- Quantum Information Technologies
- Renewable Energy Generation and Storage
- Semiconductors and Microelectronics
- Space Technologies and Systems

R&D MODELS TO SUPPORT DEEP TECHNOLOGIES

To develop and commercialize deep tech, one generally needs new ideas and knowledge and base of technically skilled people. One also needs R&D programs that turn this knowledge into technologies capable of meeting needs and solving problems. Then one also needs a path to success in the market.

³⁰ Fast Track Action Subcommittee on Critical and Emerging Technologies of the National Science and Technology Council, "Critical and Emerging Technologies List Update February 2022." <https://www.whitehouse.gov/wp-content/uploads/2022/02/02-2022-Critical-and-Emerging-Technologies-List-Update.pdf>

³¹ See <https://www.mgi.gov/about>

In recent years, the approach the U.S. government has taken to advance deep technologies has generally been to support the development of new knowledge and skilled people through university-based centers, and to develop advanced technologies to meet specific needs through R&D projects modeled after the approaches used by the Defense Advanced Research Projects Agency (DARPA). These approaches add to the more traditional approaches of funding individual investigators in universities and supporting government laboratories. This section discusses in considerable detail these approaches. The section ends with brief discussions of four other approaches that have been used, but to a much lesser extent.

In this discussion we refer to the commonly used technology readiness level (TRL) scale to describe technology maturity, as shown in Box 4.

Emerging deep technologies may be predominantly at different TRLs -- quantum computing is largely at early stage TRLs (1-4), while artificial intelligence spans many TRLs. As discussed below, university centers and DARPA model programs also span different TRLs.

Box 4. Technology Readiness Levels	
Level	Definition
1.	Basic principles observed
2.	Technology concept and/or application formulated.
3.	Experimental proof of concept.
4.	Technology validated in laboratory
5.	Technology validated in relevant environment.
6.	Technology (prototype) demonstrated in relevant environment.
7.	System prototype demonstrated in an operational environment.
8.	System completed and qualified through test and demonstration.
9.	Actual system proven in an operational environment.

UNIVERSITY-BASED RESEARCH CENTERS

A main way that the U.S. government supports research on deep technologies is through the establishment or support of research centers that typically involve universities and industry, and sometimes national laboratories.

These can take a wide variety of forms:

- They may be based at a single university or at a consortium of universities.
- They may be largely government-funded or may have substantial industry funding.
- They may range substantially in size and funding (from under \$1 million/year to over \$10 million/year).

There are other organizations with a similar structure, such as the manufacturing institutes discussed above as part of Manufacturing USA, that may be based at a national laboratory or a non-profit organization instead of a university, but that also involve academic and industrial partners. Here we will focus primarily on university-based centers, and especially ones that have substantial industry involvement. Such research centers have become very common –

most major research universities have many research centers that involve faculty in different departments and have collaborations with other universities, industry, or national laboratories.

These centers have the following characteristics:

- They engage professors from multiple departments and disciplinary backgrounds (and often from multiple universities).
- They usually focus on research that has the potential to address important problems.
- They focus on research rather than the development of operational technology, often doing “use-inspired basic research.” They are typically at TRL levels of 1-4 (although some centers go to higher TRL levels).
- They generally receive Federal funding for a limited time, typically five to ten years, after which the participants are expected to find other support or change directions if they wish to continue.
- They are expected to obtain multiple sources of funding, typically from industry, state government, and other sources, reflecting a belief that the research will be more relevant and useful if stakeholders share in its ownership and direction.
- They usually perform only unclassified research and are designed to transfer and commercialize knowledge rather than control information.
- They are usually focused on generating knowledge that can provide long-term economic and social benefits, and on sharing that knowledge with member companies and other partners.
- They have educational components, recognizing both that there is a need for highly skilled workers in areas of emerging technology and that graduating students are an important way to transfer knowledge to companies.
- They typically are committed to generating intellectual property and commercializing technology based on that property through technology transfer or entrepreneurship.

The popularity of university research centers reflects the belief that most important technological opportunities require contributions from different technical disciplines as well as perspectives from industry and/or government regarding market needs. Centers provide a good mechanism for bringing together the different perspectives and skills needed to advance technologies.

Examples of Government-Supported R&D Centers

Many government programs fund university centers involved in deep technology. For example, the National Science Foundation supports:

- **NSF Science and Technology Centers (STCs).**³² These centers typically receive about \$5million/year in NSF funding. They often include partnerships among academic institutions, national laboratories, industrial organizations, and other entities, both domestically and internationally. They are intended to undertake significant investigations at the interfaces of disciplines and/or using fresh approaches within

³² <https://beta.nsf.gov/oia/ia/learn-about-nsf-science-technology-centers>

disciplines. They can involve any areas of science and engineering that NSF supports. There are currently 18 active centers.

- **NSF Industry-University Cooperative Research Centers (IUCRCs)** are usually smaller university centers intended to meet shared industrial needs.³³ The IUCRC program provides Center administrative costs and a governance framework to manage membership, operations, and evaluation. NSF funding is relatively modest -- \$750,000 for 5-year grants in phase 1. Each IUCRC is expected to grow over time and be independently sustainable by the end of the award period. NSF lists about 75 centers across many areas of technology.³⁴
- **NSF Engineering Research Centers (ERCs)**. ERCs are intended to address complex societal problems through a deep integration of knowledge, tools, and ways of thinking across disciplinary boundaries. NSF provides funding for each center for up to 10 years at around \$5 million/year, and additional funds are required from state and industrial partners.³⁵ Since the program's inception, over 75 centers have been funded, and about 22 are currently receiving funding. Many of the others are continuing as centers even after their NSF center funding has run out.³⁶
- **NSF Materials Research Science and Engineering Centers (MRSECs)**.³⁷ The MRSECs support materials research infrastructure in the United States, promote active collaboration between universities and other sectors, including industry and international organizations, and contribute to the development of a national network of university-based centers in materials research, education, and facilities. There are currently 11 centers with average NSF funding of \$3 million/year.
- **Quantum and Artificial Intelligence Centers** (See discussion of these centers in the case study section of this report.)

Other agencies also support university centers related to deep technologies. These include:

- **DARPA's Joint University Microelectronics Program**³⁸ In collaboration with the non-profit Semiconductor Research Corporation (a consortium of semiconductor companies) DARPA funds seven microelectronics research centers spanning over 30 universities and involving over 800 graduate students performing fundamental electronics research across over 240 projects.

³³ See <https://iucrc.nsf.gov/about/>

³⁴ For a list of NSF IUCRCE centers, see <https://iucrc.nsf.gov/centers/?uni=&sta=&prifoc=0&foc=>

³⁵ <https://www.nsf.gov/pubs/2022/nsf22580/nsf22580.htm?org=NSF>

³⁶ For additional information on the ERC program, please see these two websites:

<http://www.nsf.gov/div/index.jsp?div=eec> and <http://erc-assoc.org/>.

³⁷ <https://beta.nsf.gov/funding/opportunities/materials-research-science-engineering-centers>

³⁸ <https://www.darpa.mil/program/joint-university-microelectronics-program> ; <https://www.darpa.mil/news-events/2023-01-04>

- **DOE Energy Frontier Research Centers**³⁹ bring together multidisciplinary and multi-institutional teams of researchers to address scientific challenges at the forefront of energy science research. There are currently 51 EFRCs. Recent competitions have focused on clean energy sciences, transformative manufacturing, microelectronics, polymer upcycling, carbon dioxide reduction, and quantum information science. Centers have universities or national laboratories as their lead institutions.

Benefits and Limitations of Centers as Mechanisms to Support Deep Tech

Benefits of centers include:

- They are a flexible mechanism that can vary in scale and focus and that can be matched to nature of technology and industry.
- Industry participation and cost sharing helps to ensure the relevance of research, helps train students with an appreciation for industry needs, and aids the transfer of knowledge and technology to industry.
- Universities are able to attract and hire talented researchers without many of the limitations placed on Federal employees.
- Center awards are based on competition and merit reviews, aiding quality.
- The limited duration of funding encourages centers to seek new sources of funding and allows agencies to move funding to new areas.
- Providing funds to universities is more politically acceptable in the U.S. than providing funds to industry.
- Universities usually have well-developed tech transfer and entrepreneurship mechanisms.
- Centers are viewed as aiding regional economic growth and the establishment of regional innovation ecosystems, increasing their political appeal.

Limitations of centers include:

- University centers typically work at low TRL levels; more work and funding are needed in most cases before the technologies can be commercialized.
- Industry commitment is difficult; few companies have the time and resource to devote to participation in centers.
- Management of centers is uneven – professors are not always well suited to being center directors.

DARPA MODEL FOR CREATING NEW TECHNICAL CAPABILITIES

Overview

Over recent decades, DARPA has been credited with supporting the successful development of many deep technologies, often resulting in new companies, communities, and industry. These include many of the elements of personal computing as well as the Internet, optical

³⁹ <https://science.osti.gov/bes/efrc>

communications, many aspects of AI (robotics, speech recognition), mRNA vaccines, advanced prosthetics, as well as many military technologies such as stealth aircraft and unmanned aerial vehicles (UAVs).⁴⁰

While other agencies can also point to successful deep technologies that they supported, often their support is less direct. NSF, for example, often points to people trained under NSF grants who later form companies or to fields of science it supported that eventually led to new technologies. Whereas university centers excel at training people and conducting early-stage research (typically TRLs 1-3), DARPA excels at taking new knowledge and creating prototype technologies that demonstrate new capabilities (typically TRLs 2-6).

Due to DARPA's success, its processes have been studied, and there have been efforts to replicate the model in different parts of the U.S. R&D system. For more detailed information on DARPA, see work done by TPI and others.⁴¹

While people often refer to the "DARPA model," it is important to note that DARPA has been around for over 65 years and has changed over time. It is a flexible organization, and it uses different techniques to achieve its results. Different offices within DARPA operate in somewhat different ways. As a result, there is not one single DARPA model. As discussed elsewhere in this report, DARPA at times supports university centers, industry consortia, and prize competitions as needed to meet its mission. What we refer to here as "the DARPA model" is the predominant model that has evolved over recent decades and is used primarily in DARPA's science and technology offices, which focus on creating significant new capability in fundamental technologies. This is in contrast to DARPA's system offices, which focus on developing military systems. It is the model used in the science and technology offices that is being copied in new ARPA agencies.

We first discuss DARPA's overall purpose and culture, then discuss key elements of the DARPA model, DARPA's interactions with the broader technical community, and then discuss some of DARPA program management practices. Finally, we turn to efforts to apply the process and organizational model to other areas of science and technology and some limits of the DARPA model.

DARPA's Overall Orientation

DARPA has a clear mission, which is to make critical investments in breakthrough technologies for national security. Its focus is on making major advances, not on making incremental

⁴⁰ For a historical overview of DARPA, see its 60th anniversary publication, *DARPA: Defense Advanced Research Projects Agency, 1958-2018*. Available at https://www.darpa.mil/attachments/DARPA60_publication-no-ads.pdf

⁴¹ A comprehensive overview is William B. Bonvillian, Richard Van Atta, and Patrick Windham (eds.), *The DARPA Model for Transformative Technologies: Perspectives on the U.S. Defense Advanced Research Projects Agency*. Cambridge, UK: Open Book Publishers, 2019, <https://doi.org/10.11647/OBP.0184>. TPI reports include David W. Cheney and Richard Van Atta, "DARPA'S Processes for Creating New Programs," March 2016. Technology Policy International. https://technopoli.net/assets/docs/TPI_DARPA_Report.16690227.pdf and David W. Cheney, Christopher T. Hill, and Patrick H. Windham, "Personnel Systems of DARPA and ARPA-E." Technology Policy International, March 2019 https://technopoli.net/assets/docs/Personnel_Systems_of_DARPA_and_ARPA-E.131103620.pdf.

improvements. DARPA seeks to create technologies to address needs or meet challenges, rather than to advance science and technology per se.

Because DARPA focuses on hard problems and on making major advances, it is willing to take technical risk and accept failure. DARPA has a well-established tradition of accepting risk in return for high potential payoffs. Technical failures are expected while attempting to achieve ambitious goals, and failures are accepted, so long as the risks are appropriately managed.

DARPA focuses on developing and demonstrating the feasibility of new technology, often ending in an early prototype. It works with partners to encourage further prototyping and production stages in the armed services or in the private sector. DARPA's work is performed entirely by outside performers (in universities, companies, and other research organizations). DARPA has no research laboratories.

DARPA's work is oriented around discrete projects that typically last three to five years rather than on sustained programs.⁴² Some projects lead to follow-on projects, allowing continuation of efforts in major areas.

Key Elements of the DARPA Model

The key to DARPA's approach is its program managers (called "PMs") who are given the authority, responsibility, and resources to design and execute their programs. PMs are generally technical experts drawn from industry, universities, government laboratories and R&D centers, or the military services. PMs typically serve for only three to five years. The PMs' short terms ensure that the agency continually benefits from fresh thinking and perspectives from new PMs.

PMs design and get approval for their programs, including their scope, rationale, technical basis, objectives, the metrics for measuring technical progress, and the proposed budget and schedule. For more detail on DARPA's personnel system, see TPI's previous report.⁴³

PMs are supported by a small and flexible non-hierarchical organization. DARPA consists of only 100–150 professionals, essentially operating at only three levels – the DARPA Director, Office Directors, and Program Managers. The DARPA director and Office Directors' key job is to recruit highly talented program managers and empower them. DARPA's organization is focused on removing impediments to the work of the program managers. Program managers also have contractor support staff and are assigned adequate funding to support their approved programs.

DARPA has substantial autonomy and freedom from bureaucratic impediments. It has special hiring authority to be able quickly hire top talent on a temporary basis from universities and industry. It also has special contracting authority which gives it flexibility and speed in contracting, outside the normally lengthy federal procurement process. DARPA uses technical,

⁴² For information on DARPA's portfolio of projects, see <https://www.darpa.mil/our-research>

⁴³ David W. Cheney Christopher T. Hill Patrick H. Windham. "Personnel Systems of DARPA and ARPA-E. Technology Policy International." March 2019. https://technopoli.net/assets/docs/Personnel_Systems_of_DARPA_and_ARPA-E.131103620.pdf

contracting, and administrative services of other defense agencies, and uses contractors for technical support.

DARPA's Interaction with the Technical Community.

DARPA's reliance on outside organizations for its program managers and for its research performers means that DARPA is deeply involved with the broader technical community, including universities, companies, government laboratories, and other research entities. DARPA interacts with the broader community in numerous ways:

- DARPA is continually seeking talent from the broad technical community to be program managers and DARPA program managers return to the technical community after completing their terms.
- DARPA PMs work with the technical community to define their programs, to determine what is technically feasible, and to learn where the opportunities are to make major advances.
- DARPA PMs stimulate interest in the technical communities to participate in their project, often by articulating a vision for what is possible. DARPA typically builds strong teams and networks of collaborators, bringing in a range of technical expertise and applicable disciplines and involving university researchers and technology firms. PMs both create and direct these teams.
- DARPA programs often serve to create new communities and new academic fields. They often require collaboration of different parts of the technical community that have not previously worked with each other. Examples over the years include materials science and engineering, computer science, and synthetic biology/engineering biology.

DARPA Program Management

DARPA programs typically begin with a PM developing a proposal for a new program. The development of a program typically takes much time and effort. It is important to define a program that is technically challenging, far-reaching, and potentially revolutionary or transformative, but also not impossible. PMs typically use the Heilmeyer Catechism (see Box 5) to define their program. The PM needs to scope the program properly so that the goals can be accomplished within the available time and resources, and so that the goals are aggressive but not completely unrealistic. The development of a program typically requires extensive input from the technical community on technical feasibility as well as input from users/markets on needs. PMs use workshops, requests for information (RFIs), and site visits to gather information from technical experts and potential users to identify what can be done and what should be done. PMs may support small pilot projects ("seedlings") to determine the feasibility of key parts of their programs before seeking approval for a full-scale program.

Once a program is approved, the next step is to get proposals from the research community to conduct the work. DARPA uses what are known as broad area announcements (BAAs) to solicit proposals. BAAs typically define the goals to be achieved but not the methods to achieve them. Proposals need to clearly state why their approach is revolutionary, the challenges, the potential solutions, and their strategy to mitigate risks. Proposals should provide supporting technical and experimental evidence. They need to provide a technical and quantitative

rationale for their ability to achieve results, and clear milestones that will let the program be assessed. They need to have a management plan that describes the coordination and roles of all members, and approaches to manage risk.

Box 5. The Heilmeier “Catechism”

George H. Heilmeier, DARPA director (1975-1977), crafted a set of questions known as the "Heilmeier Catechism" to help Agency officials think through and evaluate proposed research programs.

- What are you trying to do? Articulate your objectives using absolutely no jargon.
- How is it done today, and what are the limits of current practice?
- What is new in your approach and why do you think it will be successful?
- Who cares? If you are successful, what difference will it make?
- What are the risks?
- How much will it cost?
- How long will it take?
- What are the mid-term and final “exams” to check for success?⁴⁴

Source: DARPA, <https://www.darpa.mil/work-with-us/heilmeier-catechism>

The PM may seek input from others in reviewing proposals but is responsible for deciding on which proposals to fund.

After awards are made, DARPA PMs actively manage their programs. PMs interact extensively with their performers and other partners. DARPA holds periodic program reviews among all performers and partners in a program to discuss progress and to get feedback. PMs use quantitative goals and milestones to manage performance. PMs can stop projects or shift funds among performers if milestones are not being met. Being able to stop programs is one way to manage technical risks, by not wasting resources on technologies that prove to be infeasible at the current state of knowledge.

Link to Users, Applications, and Transition Pathways

A key challenge for DARPA is to get the results of its work into practice. DARPA generally focuses on demonstrating the feasibility of new technologies but does not develop technologies to full maturity. As a result, most DARPA technologies require additional development before they are ready for operational or commercial use. Moreover, it is often difficult to transition or commercialize disruptive technologies because they require extensive changes in the organizations that produce and use the technologies. DARPA often needs to convince users (often the military services) that the technology will provide enough benefits to make it worthwhile to change current practices.

Since DARPA deals with a wide variety of technologies, there is not a single way that DARPA transitions technology. In many cases, the U.S. Department of Defense is the end user of the

⁴⁴ In other words, how does one measure progress during the project, and how does one determine if the project is successful in the end.

technology, and DOD has funds and companies (defense contractors) that can be used to further develop the technology and that ultimately produce systems using the technology that DOD can buy. In other cases, the technologies end up being further developed and commercialized by the private sector. Because DARPA technologies often do not fit with the business models of existing companies, DARPA sometimes needs to support new companies to commercialize technologies.

Some approaches DARPA uses to aid the transition of technology include:

- Designing projects to meet clear needs (often military service requirements) or potential uses. DARPA projects are design with a use in mind and involve discussions with potential users and other stakeholders.
- Maintaining continual communication with stakeholders and potential transition partners as the project evolve.⁴⁵ These may include stakeholders within the government and commercial sectors, and military services.
- Being open to different applications than originally expected. Radically new technologies often have many unanticipated uses, some of which may be more significant than the original planned use.

Extension of the DARPA Model to Other Government Agencies

As discussed earlier, post-World War II U.S. science and technology policy was structured to focus on basic research and national defense, and to avoid government involvement in the development of industrial technology. Agencies such as the National Institutes of Health and National Science Foundation were limited to research, not development, and the programs at the Department of Energy (and its predecessor agencies) were also largely limited to early-stage technology R&D. In addition, each of these agencies was perceived as becoming risk averse – supporting incremental science and technology advances rather than higher risk potentially transformative work. They have been criticized for not producing technology breakthroughs that lead to new commercial technologies.

DARPA, by contrast, was established to focus on disruptive technologies, and was enabled by its defense mission to develop technologies to the point of demonstrating their value. In recent years, many have viewed the DARPA model as the United States' most effective model for developing deep technologies, and there have been numerous efforts to apply the model in other domains.

The Advanced Research Projects Agency-Energy (ARPA-E) in the Department of Energy was authorized by Congress in 2007 and first funded in 2009. ARPA-E closely copies DARPA, and it has hired many former DARPA program managers to transfer DARPA's culture and processes. It was funded at \$427 million in fiscal year 2021. While like DARPA in most respects, it differs in that it lacks a government customer for its technologies and must commercialize its

⁴⁵ U.S. Government Accountability Office. "Defense Advanced Research Projects Agency: Key Factors Drive Transition of Technologies, but Better Training and Data Dissemination Can Increase Success". GAO-16-5. Nov 18, 2015. <https://www.gao.gov/assets/gao-16-5.pdf>

technologies in the civilian sector. After 13 years of operation, ARPA-E is widely regarded as successful, having led to much additional investment, many commercialized technologies, and many new companies.⁴⁶

The Intelligence Advanced Research Projects Activity (IARPA) was established in 2008 under the Office of the Director of National Intelligence also using the DARPA model. It was formed from previous intelligence R&D organizations, including the Disruptive Technology Office, which was previously known as the Advanced Research and Development Activity. IARPA's role is to advance science and technology for the intelligence community. It is currently focused artificial intelligence, quantum computing, machine learning, synthetic biology.⁴⁷ It is also generally viewed as successful.⁴⁸

More recently, the Advanced Research Projects Agency for Health (ARPA-H) was established in March 15, 2022 as a part of the NIH within the U.S. Department of Health and Human Services.⁴⁹ It is intended to follow the DARPA model and advance high-potential, high-impact biomedical and health research. Its first director, Renee Wegrzyn, is a former DARPA program manager. ARPA-H- was appropriated \$1.5 billion in FY 2023. It is too early to evaluate ARPA-H.

There has also been interest in applying the DARPA model to NSF. The version of the U.S. Innovation and Competition Act that passed the Senate in 2021 would have established a Directorate for Technology and Innovation in the NSF that was somewhat modeled on DARPA, with DARPA-style program managers. The final version of the law, the CHIPS and Science Act, however, did not include this language. It established a new Directorate for Technology, Innovation, and Partnerships in NSF, but did not include language creating a new kind of program manager. The NSF technology directorate is still new, and it did not receive the funding (appropriations) authorized by the CHIPS and Science Act. It remains to be seen whether it will follow much of the DARPA model, or in effect create a new model.⁵⁰

In addition, as discussed earlier, there has been legislation to create an ARPA-Infrastructure in the Department of Transportation, and an Agriculture Advanced Research and Development Authority (AgARDA). There have also been discussions about possible ARPAs at the Department of Education and the Department of Labor.

It should be noted that not all efforts to replicate DARPA have been successful. When the Department of Homeland Security was set up in 2002, it included a "Homeland Security ARPA," or HS-ARPA. However, it did not fully follow the DARPA model and was not set up as a separate

⁴⁶ See <https://arpa-e.energy.gov/about/our-impact> for information about ARPA-E's impact.

⁴⁷ See <https://www.iarpa.gov/who-we-are/about-us>

⁴⁸ See William B. Bonvillian, "IARPA: A Modified DARPA Innovation Model" p. 435-450 in William B. Bonvillian, Richard Van Atta, and Patrick Windham (eds.), *The DARPA Model for Transformative Technologies: Perspectives on the U.S. Defense Advanced Research Projects Agency*. Cambridge, UK: Open Book Publishers, 2019, <https://doi.org/10.11647/OBP.0184>.

⁴⁹ See ARPA-H's website at <https://arpa-h.gov/>.

⁵⁰ For more information on the NSF Technology, Innovation, and Partnerships Directorate, see <https://beta.nsf.gov/tip/about-tip>.

operating unit in the Department's Science and Technology Directorate.⁵¹ Some of its early staff who came from DARPA left in frustration, and HS-ARPA was disbanded.

The influence of the DARPA model also extends beyond DARPA and the new agencies modeled on it. DARPA program manager alumni and DARPA awardees often spread aspects of the model. SRI International, for example, is a long-time DARPA awardee and also employs several DARPA alumni. SRI models many aspects of its innovation practices after DARPA's. Other DARPA alumni work in venture capital firms, private foundations that support technology development, and in companies conducting advance R&D, and bring their experience with the DARPA model to these organizations.

While the DARPA model has been a critical and expanding element of the U.S. government's support of deep technology, it is important to note that the DARPA model by itself is insufficient. DARPA and the other ARPAs depend on the much broader U.S. science and technology enterprise. The programs at NSF, NIH, DOE, NIST, and other agencies provide the broad bases of research, ideas, infrastructure, and talent that DARPA and other DARPA-like agencies can draw upon. This enables the DARPA-model agencies to choose the most promising research and early-stage technologies to develop further.

LESS COMMON MODELS FOR SUPPORTING DEVELOPMENT OF DEEP TECHNOLOGIES

R&D funding is the main mechanism that U.S. agencies use to support the development of new deep technologies. So far, we have discussed two major ways to make such R&D investments—the centers approach and the DARPA model. In addition, however, agencies sometimes use policy mechanisms other than R&D funding. Here we briefly discuss four alternative mechanisms and when they are appropriate to use. These are the four alternative mechanisms.⁵²

- Prize competitions (where the government holds competitions and awards prizes to the winners)
- Advance purchase agreements (where the government agrees in advance to buy an advanced technology products if companies can successfully develop them)
- Special patent incentives (additional patent protection as a reward for a company developing a new technology or product)
- Non-financial government support (such as public-private R&D partnerships and industry access to government research facilities)

⁵¹William B. Bonvillian. IARPA: A Modified DARPA Innovation Model. Chapter 14 in William B. Bonvillian, Richard Van Atta, and Patrick Windham (eds.), *The DARPA Model for Transformative Technologies: Perspectives on the U.S. Defense Advanced Research Projects Agency*. Cambridge, UK: Open Book Publishers, 2019. <https://doi.org/10.11647/OBP.0184>.

⁵² This list draws on a similar list in Stephen M. Maurer, "Squeezing Value from Homeland Security Research: Designing Better R&D Incentives," in Stephen M. Maurer, editor, *WMD Terrorism: Science and Policy Choices* (Cambridge, MA: MIT Press, 2009), pages 410-424.

Prize Competitions

Prize competitions have a long history, particularly in aviation. In the early days of aviation, newspapers, governments, and wealthy individuals offered cash or other prizes to pilots who won certain races or were the first to accomplish a specific task.

For example, in 1919 French-American hotel owner Raymond Orteig offered a \$25,000 prize to the first pilot who could make a non-stop transatlantic flight between New York and Paris. Eight years later, in 1927, American Charles Lindbergh won that prize.⁵³

In the U.S., Congress has given several agencies what is called “other transactions authority” which means that they can use federal R&D funds in ways beyond standard grants, contracts, and cooperative agreements. NASA received this authority when it was created in 1958. DARPA received this authority in 1989. Other transactions authority allows agencies to conduct prize competitions.⁵⁴

DARPA famously used this authority for its “Grand Challenge” – a set of contests for autonomous vehicles. The first event, in 2004, offered a \$1 million prize to the first autonomous vehicle to complete a route in the California-Nevada desert. None of the 15 teams successfully completed that race. In 2005, DARPA held a second competition, with a \$2 million prize. This time a Stanford University team won the race.⁵⁵

DARPA has continued to use prize competitions. For example, the DARPA Robotics Challenge encouraged teams to build and operate human-like robots. The competition focused on tasks relevant for disaster response. (Japanese and American experience with the use of robots at Fukushima Daiichi played a major role in DARPA’s decision to hold this competition.) In the final competition, held in June 2015, Team KAIST of Daejeon, South Korea, won the \$2 million prize for first place.⁵⁶

Sometimes a prize competition dramatically demonstrates that a new technology has great promise. For example, after the second DARPA Grand Challenge, the success of the contest’s autonomous vehicles contributed to the decision by Google and other companies to invest heavily in self-driving vehicles. Other the other hand, sometimes competitions attract publicity but also show that a technology is not ready for practical use. This situation appears to be the case with disaster-relief robots after the DARPA Robotics Challenge. The robots often had difficulty performing the assigned tasks.

⁵³ “Raymond Orteig,” Wikipedia, https://en.wikipedia.org/wiki/Raymond_Orteig#Orteig_Prize.

⁵⁴ Armani Vadiiee and Todd M. Garland, “The Federal Government’s ‘Other Transactions’ Authority,” Westlaw/Thompson Reuters, 2018, <https://acquisitioninnovation.darpa.mil/docs/Articles/Briefing%20papers%20THE%20FEDERAL%20GOVERNMENTS%20OTHER%20TRANSACTION%20AUTHORITY.pdf>.

⁵⁵ Defense Advanced Research Projects Agency, “The Grand Challenge.” <https://www.darpa.mil/about-us/timeline/-grand-challenge-for-autonomous-vehicles>.

⁵⁶ Defense Advanced Research Projects Agency, “DARPA Robotics Challenge,” <https://www.darpa.mil/about-us/timeline/darpa-robotics-challenge>.

Two of the authors of this TPI report have written papers about prize competitions, what they can accomplish, and when they are useful.⁵⁷ Under what circumstances are prize competitions an effective way to promote advancements in technology?

- Prize competitions work best when the goal is to encourage teams to further develop already existing technologies; when the costs of participating in contests are not beyond the means of small teams (an important point, since the teams usually pay for their own work); when the goals seem exciting (such as winning an aviation contest); and when it is easy to decide who has won and who has lost.
- One advantage of prize competitions is that they attract a wide range of teams and not just companies or university groups that already compete for government R&D grants and contracts.
- Prize competitions are *not* a good way to encourage teams to conduct basic research. Given the uncertainty of basic research, we cannot expect basic research teams to meet specific technical objectives. And basic research usually requires funding beyond what a university team is willing and able to provide on its own.

Advance Purchase Agreements

In an advance purchase agreement, a government agency agrees, in advance, to buy a product if a company can successfully develop it. The promise of large government procurement contracts provides an incentive for the company to invest its own money to develop the product (sometimes with the government also contributing some of the development money).

This mechanism is sometimes used to encourage the pharmaceutical industry to develop new therapeutics (drugs) or diagnostics (test kits). A major example in the U.S. was the development of COVID-19 vaccines. In 2020, the U.S. Government's "Operation Warp Speed" offered large purchase agreements to companies that could develop new vaccines. The vaccines had to be successfully tested and had to receive approval from the U.S. Food and Drug Administration before the government would actually purchase them. So, companies accepted a high level of risk when they agreed to the government's proposal.⁵⁸

Advance purchase agreements can work in the pharmaceutical world because the pharmaceutical industry has a business model that accepts high levels of risk. The companies know that not all drug development projects will succeed but that the ones that do will

⁵⁷ "Innovation Inducement Prizes at the National Science Foundation," Committee on the Design of an NSF Inducement Prize, Board on Science, Technology and Economic Policy, National Research Council, 2007, 72 pages. (Acting as a consultant to the committee, Christopher T. Hill drafted and revised the report at the direction of the committee.) See also: Patrick H. Windham, "Background Paper for a Workshop on the Potential for Promoting Technological Advance Through Federally-Sponsored Contests and Prizes," a report prepared for the National Academy of Engineering, May 10, 1999.

⁵⁸ We should note, however, that Operation Warp Speed also offered R&D funding to vaccine companies, so the government's approach here was mix of advance purchase agreements and more traditional R&D contracts. Moderna and several other companies accepted the R&D money. However, Pfizer did not. So, in the case of the Pfizer-BioNTech mRNA vaccine, the sole government mechanism was the advance purchase agreement.

generate large profits. In effect, drug companies are gamblers. They will place bets – make their own investments in new drugs – if they think they might win big profits. In the case of COVID-19 vaccines, several companies developed new vaccines in the hope of winning large purchase contracts from the government.

In some instances, it makes sense to combine an advance purchase agreement with a prize contest. In such a case, the prize itself may consist, in whole or in part, of an agreement to purchase the prize-winning technology or to purchase or license any intellectual property that may have been created in developing the winning technology.

Advance purchase agreements are unlikely to work in more conservative industries. For example, defense contractors want to be paid for all stages of product development: R&D, the creation of prototypes, and production.

Special Patent Incentives

Another mechanism to encourage companies to develop advanced technologies is the use of special patent incentives. These are incentives that go beyond regular patent protection.

One version is called a “wildcard patent.” This approach makes the most sense when the government wants to work with pharmaceutical companies.⁵⁹

Users of the wildcard mechanism would say to a pharmaceutical company that if it develops a product that the government wants, using its own money, then the government will let the company extend the life of the patent on any other patented drug the company currently owns. For example, if the company has a drug that generates large profits but whose patent is about to expire, the company can use the “wildcard” to extend that patent – and hence the profits – for some additional number of years.

This technology development mechanism is highly controversial in the United States. Members of Congress who object to high drug prices have opposed proposals to provide wildcard patent authority to agencies that want companies to develop new vaccines or other products. TPI is not aware of any use of the wildcard patent by U.S. agencies.

Non-Financial Government Support

Government agencies and laboratories also provide valuable non-financial assistance to companies seeking to develop deep technologies. Here are three examples:

- **CRADAs.** Under two laws passed in the 1980s, government laboratories may enter into “Cooperative Research and Development Agreements” (CRADAs) with companies and other organizations. Under a CRADA, the government and its laboratory provide no

⁵⁹ In the U.S., the term “wildcard” comes from poker and other games that use playing cards. If a player receives a card that she and others have decided is “wild,” then she can use that card to represent any other card that she wants. For example, if cards with the number two on them are declared “wild,” then a player can use that card to represent an ace, a king, or any other card that she prefers.

money to a company but can provide laboratory personnel and facilities for joint research that helps the company develop its technology. Sometimes, the laboratory will also license a patented invention to the company and then pursue joint research to help the company turn that invention into actual products.⁶⁰

- **User facilities.** Many government laboratories, particularly those in the Department of Energy, have specialized facilities such as particle accelerators that can help companies. For example, semiconductor companies and biotechnology firms can use these machines to closely examine advanced materials. Government agencies frequently allow companies to conduct proprietary research using these facilities, but companies pay for this service.
- **Helping deep-tech entrepreneurs.** A non-profit organization called Activate – mentioned earlier in this report – provides two-year fellowships to young PhDs who want to start companies making physical products. Two government laboratories and several other research organizations provide laboratory space and technical assistance to these young entrepreneurs. The program began at DOE’s Lawrence Berkeley National Laboratory. The second government facility is MIT Lincoln Laboratory, which is funded by the Department of Defense.⁶¹

Observations About These Mechanisms

The analysis in earlier sections of this report suggests that in the United States different policy measures are appropriate for different tasks.

- **Basic research.** Basic research, including engineering research on new deep technologies, is best supported by research grants from government agencies.
- **Applied research and early development of new technologies.** The DARPA model of government-funded technology development works well in many cases.
- **Refinements of existing technologies.** If the cost of taking a new technology to a further stage is relatively low, then prize competitions can attract a range of engineering teams. If the cost of technology refinements is high, then government funding or a combination of government funding and private money is appropriate.
- **Finished products.** In the medical world, advance purchase agreements can attract pharmaceutical and biotechnology companies because these agreements fit with the companies’ business models. However, defense contractors and other manufacturers

⁶⁰ In the early 1990s, during the first part of the Clinton Administration, the Department of Energy received funds to help pay for certain CRADA projects – a departure from the usual practice of requiring a company or other R&D partner to provide all the funding. One of us – David Cheney – was then a DOE official helping to design and operate this program of “funded CRADAs.”

⁶¹ For information on Activate and its fellowship program, see: <https://www.activate.org/home>.

usually want regular government payments in return for developing and producing new products for the government.

GOVERNMENT MECHANISMS TO SUPPORT THE COMMERCIALIZATION OF DEEP TECHNOLOGIES

The U.S. Government and other governments can use several policy mechanisms to accelerate the commercialization of new deep technologies.

DEMONSTRATION PROJECTS

Because deep technologies are expensive and risky to develop and commercialize, the federal government has on some occasions paid for part or all the costs of developing large-scale prototypes. Building these prototypes helps reduce both technical and market risk and can show (“demonstrate to”) potential developers and customers that a technology is ready for use in commercial applications.

Not all commercialization projects are successful in bringing new technologies to market. Some have failed because the technical uncertainties could not be resolved or because the costs of overcoming technical uncertainties was much higher than originally anticipated. Others have “failed,” not because of technical uncertainties and costs, but because proponents of the new technology had not adequately accounted for non-market factors that inhibit technology adoption. Despite these limitations, demonstration projects remain a favorite mechanism among political leaders who seek to support a technology but are unable to get Congress and the President to agree to large scale implementation.

In the U.S., the federal government has helped to fund demonstration projects in defense, space, and energy. For example, the Defense Department pays companies to develop prototype aircraft, and DARPA and NASA provided early assistance to SpaceX and other commercial space companies to help them develop and sell their first products.

Government-assisted demonstration projects are also important in the energy field. For example, utility companies may be reluctant to buy a new type of electricity-generating power plant if they have not seen a successful large prototype. Because large prototypes are expensive, government money helps industry develop and eventually adopt new types of power plants.

Since the 1950s, the U.S. Government has helped to finance and build several large energy demonstration projects, including the first commercial nuclear power plant in the U.S., at Shippingport, Pennsylvania; a large prototype “breeder reactor” at Clinch River, Tennessee; 1970s synthetic fuel plants to convert coal to oil and natural gas; and more recently the FutureGen “clean coal” project in Illinois focused on capture and recovery of greenhouse gas

emissions from coal-fired utility plants. However, these large projects are not always technically or economically successful. For example, the synthetic fuels plants of the 1970s did work technically, but the oil and natural gas they produced was very expensive. The government cancelled its investment in the FutureGen project when private companies stopped contributing their portion of the funding.⁶²

More recently, DOE has focused on smaller demonstration efforts, such as the Department's Advanced Reactor Demonstration Project. In 2020 DOE began to pay half of the cost of 10 projects in which companies will demonstrate new nuclear reactor designs.⁶³

GOVERNMENT PROCUREMENT

Government purchases of equipment and services from private companies also help those companies commercialize new technologies. In the U.S., Defense Department procurement has played a huge role in the commercialization of new deep technologies. For example, the first major customer for Intel's microprocessors was the U.S. Air Force. NASA buys equipment and services from new commercial companies, including its contract with SpaceX to take astronauts and cargo to and from the International Space Station. Even state and local governments can help new technologies, such as when they purchase hybrid or electric vehicles for government use.

REGULATORY REQUIREMENTS

Government regulatory requirements can accelerate the commercialization of new deep technologies. The requirements in the Clean Air Act of 1970 that regulated companies use "Best Available Technology" to limit emissions of air pollutants created markets for new technologies to capture pollutants as well as for new technologies that avoided producing regulated pollutants in the first place.⁶⁴ In the U.S., a dramatic example is when state governments adopt "renewable portfolio standards" (RPS's) – regulations that require utility companies to produce electricity from renewable sources such as solar, wind, and geothermal energy. California has long used RPS regulations, and a recent California law (Senate Bill 100) requires that by 2045 utilities must produce all their electricity from "clean sources" – with a minimum of 60 percent coming from renewable sources and the remaining 40 percent either from additional renewables or from other clean sources such as nuclear energy or large hydroelectric dams.

⁶² For a discussion of the FutureGen project, see Jeff Tollefson, "US government abandons carbon-capture demonstration," *Nature*, 5 February 2015, <https://www.nature.com/articles/nature.2015.16868>.

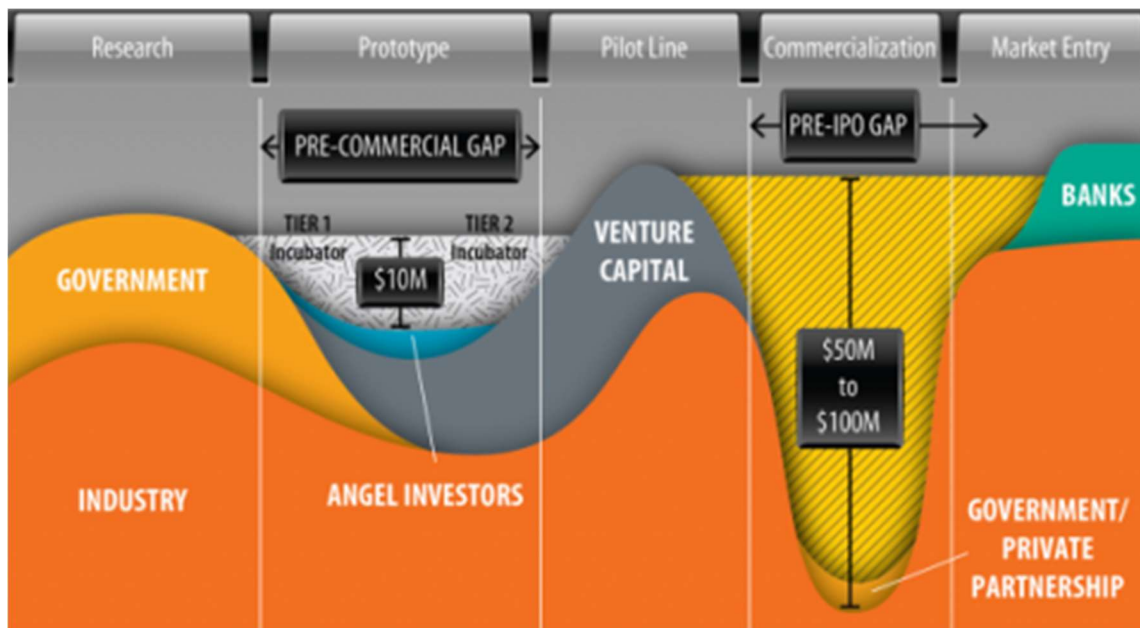
⁶³ U.S. Department of Energy, Office of Nuclear Energy, "INFOGRAPHIC: Advanced Reactor Development," December 15, 2020, <https://www.energy.gov/ne/articles/infographic-advanced-reactor-development>. See also: Adrian Cho, "U.S. Department of Energy rushes to build advanced nuclear reactors," *Science*, 20 May 2020, <https://www.science.org/content/article/us-department-energy-rushes-build-advanced-new-nuclear-reactors>.

⁶⁴ N.A. Ashford, C. Ayers, and R.F. Stone, "Using Regulation to Change the Market for Innovation," *Harvard Environmental Law Review*, Summer 1985, pp. 419-466. <http://dspace.mit.edu/bitstream/handle/1721.1/1555/%2319.PDF?sequence=1>

Regulations are particularly helpful to innovators when they give regulated companies the flexibility to use new innovative equipment to meet regulatory requirements. Less flexible regulations force companies to buy older technologies.

GOVERNMENT FINANCIAL ASSISTANCE TO INNOVATIVE COMPANIES

Innovative deep-tech companies often face two big financial problems – funding gaps that are sometimes called “valleys of death,” because companies may die if they do not get funding at these two stages of their lives. These problems particularly affect start-up companies, but they can also hurt larger firms. The diagram below, from the Obama-era Energy Department, illustrates these two “valleys of death.”⁶⁵



The first funding gap that a start-up confronts occurs when it needs money to turn a promising new invention into a working prototype – a prototype that will attract further funding from venture capitalists or large industry. NSF-type grants do not usually pay for prototype development, and private investment can be hard to obtain. The government can help here, though, for example, awards from the Small Business Innovation Research Program.

The second funding gap comes when a deep-tech start-up needs further funding to commercialize and manufacture its first products. Manufacturing physical products is expensive, and venture capitalists usually do not want to finance production. Moreover, banks

⁶⁵ The webpage that contained this diagram was: <http://energy.gov/eere/sunshot/technology-market>. However, that webpage is no longer active.

typically will not loan money in this situation, because the innovative start-up does not yet have significant revenues or assets.

In the energy field, Congress has provided authority and funding for three types programs that can help companies with this problem: tax credits to help reduce the cost of manufacturing, direct government loans to companies, and loan guarantees (where the government asks banks to give the companies loans at good interest rates in exchange for a government promise that government will repay the loans if the companies fail). The Energy Department's loan and loan guarantee program has sometimes been politically controversial, but the Energy Department has used loans and loan guarantees successfully.⁶⁶

GOVERNMENT FINANCIAL INCENTIVES THAT ENCOURAGE CUSTOMERS TO BUY NEW PRODUCTS

In addition to programs that directly help innovative companies, the U.S. Government also provides tax credits to consumers to encourage them to buy innovative deep-tech products, such as solar panels, electric vehicles, and energy-efficient heat pumps. These tax credits reduce the total cost to consumers of buying a new product and are particularly important when the new product is more expensive than traditional products, such as when electric vehicles are more expensive to buy than conventional gasoline-powered automobiles. The Inflation Reduction Act of 2022 provides tax credits to encourage consumers to buy electric vehicles and energy-efficient home appliances. By encouraging these purchases by consumers, the tax credits help companies bring new products to market and expand their sales.

OTHER SUPPORT FOR NEW INDUSTRIES: TECHNICAL STANDARDS, REGULATORY APPROVAL, INFRASTRUCTURE, AND EDUCATION AND TRAINING

In addition to direct assistance to companies and consumers, governments can also use other mechanisms to help accelerate the commercialization of new deep technologies. These mechanisms include:

- Technical standards for new industries or new advanced products. Examples include new technical standards for mobile telephones (5G, etc.) and advanced Wi-Fi.
- Regulatory approvals, such as the U.S. Nuclear Regulatory Commission preparing regulatory approval for new reactor designs or the U.S. Federal Aviation Administration allowing rocket launches by new commercial space companies.
- Infrastructure investments can be valuable, such as government assistance for expanding broadband Internet connections or to help install electrical charging stations for electric vehicles.

⁶⁶ More information about DOE's Loan Programs Office is available at: <https://www.energy.gov/lpo/mission>.

- Education and training are also important since the development and production of new deep-tech programs requires skilled engineers and technicians. Government programs can help. For example, when NSF expands its funding for university research on artificial intelligence or quantum computing, it is also helping to fund the training of PhD students in these fields, many of whom will join technology-based companies after graduation.

EXAMPLES OF GOVERNMENT SUPPORT FOR DEEP TECHNOLOGIES: QUANTUM INFORMATION SCIENCE AND ARTIFICIAL INTELLIGENCE.

The final section of this report discusses examples of two important areas of deep technologies: quantum Information science (QIS) and artificial intelligence (AI). These examples illustrate many aspects of the U.S. support for deep technologies, including the broad base of R&D funding, the coordination across agencies, the expanding use of university and national laboratory-based centers, the role of DARPA agencies, and some activities that promote commercialization of the technologies.

QUANTUM INFORMATION SCIENCE

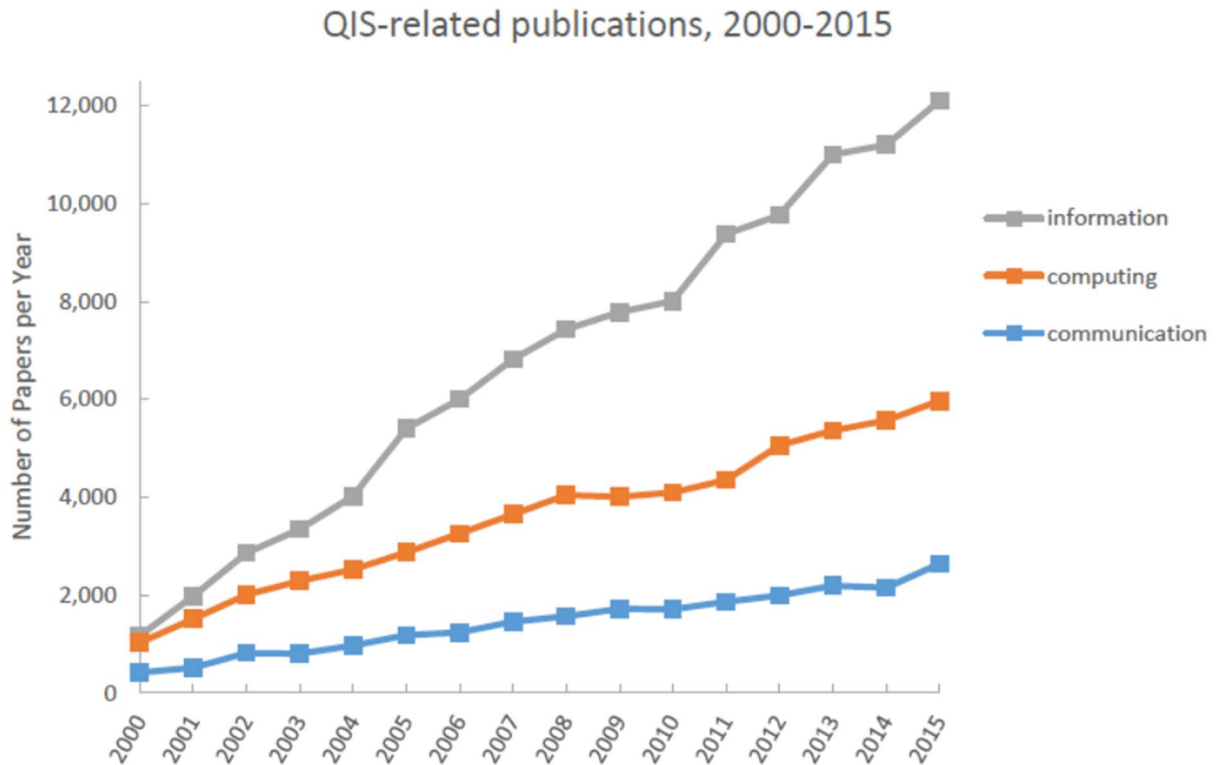
DEVELOPMENT OF QIS

Quantum information science has its origins in the development of quantum physics and quantum mechanics in the early 20th century. In the 1970s and 1980s scientists began exploring the use of quantum phenomenon in information science for such possible applications as cryptography and computing.

In 1994, interest in quantum computing increased dramatically when it was shown that quantum computers would have the potential to factor large integers quickly, which could defeat leading encryption methods and thus undermine secure computing. Many U.S. science and technology agencies increased their activity in the area. NIST, DOD, NSF, and DOE held workshops and expanded their quantum information programs in the late 1990s and early 2000s.⁶⁷ In 1999, NSF held a major workshop on quantum information science attended by over 100 scientists from universities, government agencies and laboratories, and a few

⁶⁷ Alex Cronin “NQI Program and U.S. QIS R&D Coordination” National Quantum Coordination Office. https://science.osti.gov/-/media/nqi/ac/pdf/NQI_Program-coordination_NQIAC_20201027.pdf. See also https://en.wikipedia.org/wiki/Timeline_of_quantum_computing_and_communication

companies.⁶⁸ Work in the field expanded rapidly, both in the U.S. and abroad, as shown by rapidly increasing publications.



Source: National Science and Technology Council, Advancing Quantum Information Science: National Challenges and Opportunities. July 2016. Based on a Google Scholar search of publications containing terms “quantum information,” “quantum computing,” and “quantum communications.” https://obamawhitehouse.archives.gov/sites/default/files/quantum_info_sci_report_2016_07_22_final.pdf

Each agency pursued programs related to its own mission and interests. NIST became involved in QIS through its efforts to improve measurement and time keeping. NSF supported a broad range of university research as well as training and support for young scientists. DOE had long-standing programs in high energy and nuclear physics, and computing related to QIS. DOD and intelligence agencies supported research that could have potential national security uses.

⁶⁸ Quantum Information Science: An Emerging Field of Interdisciplinary Research and Education in Science and Engineer. Report of the NSF workshop, October 28-29, 1999. Arlington, VA. <https://www.nsf.gov/pubs/2000/nsf00101/nsf00101.htm>

DARPA established QIS programs, such as the \$100 million, five-year Quantum Information Science and Technology (QuIST) program from 2001 to 2005.⁶⁹ The Advanced Research and Development Activity, the predecessor of IARPA (conducting R&D for the intelligence community) supported the development of a Quantum Information Science and Technology roadmap in 2002 and 2004. NASA also started a QIS program.

Throughout the 2000s, QIS R&D continued to grow in academia, industry, and government. NIST and NSF both established several university-based centers focused on QIS. Several companies, including IBM, Google, and Microsoft, established programs.

In 2009, the National Science and Technology Council (NSTC)'s Committee on Technology established a Subcommittee on Quantum Information Science (SQIS), which developed "A Federal Vision for Quantum Information Science."⁷⁰ This began NSTC's efforts to bring focus to the QIS programs across Federal agencies, which now included research in the National Security Agency, IARPA, DARPA, NSF, NIST, DOE, the Army Research Laboratory, the Air Force Research Laboratory, and the Naval Research Laboratory.

In 2016, the NSTC examined QIS again, and recommended that the quantum program needed more collaboration across institutional boundaries (for example, more interdisciplinary centers), expanded education and workforce training, increased technology transfer to industry, better materials and fabrication methods, and increased and more stable funding.⁷¹

In 2017, the House Science Committee held a hearing on American Leadership in Quantum Technology. Witnesses from NIST, NSF, DOE, IBM, the University of Maryland, and Argonne National Laboratory emphasized the importance of QIS, citing the need for new approaches to computing due to the end of Moore's law, the important problems that can potentially be solved by quantum computers, the many national security needs, and the heavy investments being made in China and Europe. Witnesses supported the need for quantum centers at universities and national laboratories.⁷²

The hearing was followed by legislation, the National Quantum Initiative Act (Public Law 115-368), which established a 10-year National Quantum Initiative (NQI). The law, which passed with strong bipartisan support, provided for the establishment of a NSTC Subcommittee on Quantum Information Science, a National Quantum Coordination Office, and a National Quantum Initiative Advisory Committee.⁷³ It also authorized:

⁶⁹ See <https://www.govcon.com/doc/darpa-announces-quist-program-baa-0001>

⁷⁰ National Science and Technology. "A Federal Vision for Quantum Information Science." 2009. https://science.osti.gov/-/media/_pdf/initiatives/qis/FederalVisionQIS.pdf

⁷¹ National Science and Technology Council, "Advancing Quantum Information Science: National Challenges and Opportunities," July 2016. https://obamawhitehouse.archives.gov/sites/default/files/quantum_info_sci_report_2016_07_22_final.pdf

⁷² <https://science.house.gov/2017/10//american-leadership-quantum-technology> See especially the testimony of Scott Crowder Vice President and Chief Technology Officer for Quantum Computing, IBM Before the House Committee on Science, Space, and Technology Subcommittee on Research and Technology and Subcommittee on Energy, Tuesday, October 24, 2017 https://science.house.gov/index.cfm?a=Files.serve&file_id=DDF32E55-D9A0-4CAD-A926-A462E6338BE3

⁷³ Public Law No. 115-368. <https://www.congress.gov/115/plaws/publ368/PLAW-115publ368.pdf>

- NIST to spend \$80 million in funding per year for 5 years (an increase of \$50 million/year) for quantum work and to establish or expand collaborative ventures or consortia with other public or private sector entities.
- NSF to create up to 5 multidisciplinary centers for quantum research and education, with funding of \$10 million/year for each center for 5 years.
- DOE to create up to 5 national quantum information science research centers with funding of \$25 million per year for each center for 5 years.

In addition to the National Quantum Initiative Act, provisions in the National Defense Authorization Acts in 2018 (PL 115-232) and in 2019 (PL 116-92) authorized defense QIS activities, including the establishment of additional centers by the DOD.⁷⁴

As a result of these laws and related appropriations laws that provided actual funding, five NSF “Quantum Leap Challenge Institutes”, five DOE QIS Research Centers, and five DOD QIS Research Centers have been established.⁷⁵ These centers add to the large foundation of ongoing QIS work across the Federal government. This includes smaller centers and individual investigators funded by NSF, ongoing work at NIST, DOE National Laboratories, DOD laboratories and university programs, and work funded by the intelligence community.⁷⁶

The NQI has an annual budget of \$918 million in FY2022 grouped by five program component areas: Quantum Sensing, Quantum Computing, Quantum Networking, QIS for Advancing Fundamental Science, and Quantum Technology.⁷⁷ NQI includes establishment of an industry consortium, the Quantum Economic Development Consortium (QED-C), managed by SRI International.⁷⁸

The initiative includes a strategy that provides recommendations to strengthen the U.S. approach to quantum information science R&D, focusing on six key areas: science, workforce, industry, infrastructure, security, and international cooperation.⁷⁹ The NQI advisory committee has been meeting and making recommendations on the program.⁸⁰

⁷⁴ Public Law 116-92. <https://www.congress.gov/116/plaws/publ92/PLAW-116publ92.pdf>

⁷⁵ See <https://www.quantum.gov/science/#QIS-CENTERS> for information about each of these centers.

⁷⁶ These are also described in <https://www.quantum.gov/science/#QIS-CENTERS>, under the heading of “Core Programs.”

⁷⁷ Subcommittee on Quantum Information Science, Committee on Science of the National Science and Technology Council. *National Quantum Initiative Supplement to the President’s FY 2023 Budget*. January 2023.

<https://www.quantum.gov/wp-content/uploads/2023/01/NQI-Annual-Report-FY2023.pdf>

⁷⁸ See <https://quantumconsortium.org/>

⁷⁹ Subcommittee on Quantum Information Science, Committee on Science of the National Science and Technology Council. *National Strategic Overview for Quantum Information Science*. September 2018.

https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf

⁸⁰ See for example the webpage of the advisory committee <https://www.quantum.gov/about/nqiadc/> and slides from its most recent meeting:

<https://www.quantum.gov/wp-content/uploads/2023/03/NQIAC-Slides-2023-03-24-Draft.pdf>

COMMERCIALIZATION OF QIS

QIS is still at an early stage – it is not yet clear what applications are likely to succeed and on what time frame. There are some commercial activities in the U.S. and abroad. Many large companies have QIS programs, including IBM, Google, Microsoft, Intel, and Amazon in the U.S., and Alibaba and Baidu in China. There are also many startups, often with venture funding, that are developing quantum computers or research tools. Examples are IonQ, Rigetti Computing, Zapata Computing, and Quantum Computing Inc, in the United States and D-Wave Systems and Xanadu in Canada.⁸¹ There are also a variety of companies in quantum sensing and quantum communications.

The U.S. Federal government is supporting the commercialization of quantum-based technology in several ways. As mentioned before, the various quantum centers are intended to share knowledge with industry. The quantum consortium, QED-C, has been established with NIST support to develop consensus on what is needed to grow the industry. The NQI also contains substantial support for activities at NIST to support the development of measurement technology and standards related to QIS. There is limited Federal procurement, mostly related to quantum research projects.

While there are some 15 current DARPA quantum projects, quantum is still at an early stage for DARPA.⁸² Most projects are in DARPA's Defense Sciences Office, focused on exploring new concepts rather than developing and demonstrating systems. It is likely that as QIS matures, there will be more DARPA projects in the technology offices that demonstrate potential uses of QIS and bring it closer to commercialization.

DISCUSSION OF QIS INNOVATION POLICY

QIS illustrates the current U.S. approach to emerging deep technologies. This approach includes:

- A very broadly-based research program with different agencies each supporting their mission. NSF supports basic science and the development of the scientific workforce; DOE supports physical science and infrastructure at the national laboratories; NIST supports measurement technology; and DOD funds R&D with an eye towards avoiding technical surprise and seeking potential advantage.
- The development of a national initiative through the NSTC to give priority to agency programs. While the initiative provides some coordination, it is still a collection of individual programs rather than a planned program. The initiative did not create or

⁸¹ See for example, <https://technologymagazine.com/top10/top-10-companies-in-the-world-of-quantum-computing> and <https://thequantuminsider.com/2022/09/05/quantum-computing-companies-ultimate-list-for-2022/>

⁸² DARPA quantum projects can be found at <https://www.darpa.mil/our-research>

manage the agency R&D programs, which have often existed for decades. But the creation of a formal multi-agency initiative typically results in increased funding.

- In the case of QIS, the national initiative was authorized by Congress, giving greater priority and stability to the initiative.
- The use of centers and industry consortia to expand interdisciplinary research and share knowledge with the hopes of accelerating commercialization.

ARTIFICIAL INTELLIGENCE (AI)

DEVELOPMENT OF AI

Although there were earlier discussions of machine intelligence and robots, artificial intelligence is usually considered to have started around 1950 with Alan Turing's discussion of computing machinery and intelligence, as well proposals for chess and checker playing computer programs.⁸³ The term "artificial intelligence" was first used at a conference held at Dartmouth University in 1956. Following some early involvement by AT&T Bell Labs and IBM, early work was supported at MIT and what is now Carnegie Mellon University by the U.S. Air Force and Navy.

DARPA established its Information Processing Techniques Office in 1962, and quickly became the dominant supporter of AI research. (This same office supported work that led to many aspects of personal computing and the Internet). It funded three main academic artificial intelligence centers at MIT, Stanford University, and Carnegie Mellon University, and a center at the Stanford Research Institute (now SRI International).⁸⁴ Unlike the DARPA model today, at the time DARPA provided sustained funding for fundamental research in a few main centers and gave top people a large amount of freedom in the work they could pursue.

In the 1980s and 1990s, DARPA's work became more focused on military applications. In 1988, DARPA's \$187 million AI budget accounted for 68 percent of Federally funded basic and applied research in AI, with other parts of DOD accounting for another 15 percent.⁸⁵ While DARPA continued to be a major supporter of AI, over time NSF gradually became the main supporter of fundamental AI research in universities.⁸⁶

⁸³ National Academy of Sciences. *Funding a Revolution: Government Support for Computing Research*. National Academies Press. 1999. Chapter 9. Developments in Artificial Intelligence.

<https://nap.nationalacademies.org/read/6323/chapter/11>

⁸⁴ Ibid.

⁸⁵ Ibid.

⁸⁶ James F. Kurose, Testimony before the Subcommittee on Information Technology, Committee on Oversight and Government Reform, U.S. House of Representatives, March 7, 2018. <https://oversight.house.gov/wp-content/uploads/2018/03/Kurose-NSF-Statement-AI-II-3-7.pdf>

Although there was much optimism in the 1970s and early 1980s about the potential of AI, progress was slow. It became clear that it was much more difficult than expected to get anything that resembled human intelligence. One issue was that the speed and data handling capabilities of the computers of the day were not adequate. Due to disappointing results, AI funding decreased in the late 1980s, which is often referred to as the “AI winter.” The term “artificial intelligence” was used less frequently, although work continued on the various components of AI, such as speech recognition, natural language processing, pattern recognition, and robotics.

While AI R&D was part of the government’s formal multi-agency Networking and Information Technology Research and Development (NITRD) initiative, it did not receive a prominent role. In many of the annual budget supplements and program descriptions, AI is not mentioned explicitly, but AI-related activities are included under “human computer interactions,” “information management,” and “cognitive systems.”⁸⁷

Progress continued to be made. In 1997 Deep Blue, an IBM chess-playing computer, became the first system to win a match against the reigning world chess champion Garry Kasparov. DARPA funded projects led to startup companies in speech recognition (Dragon Systems, Nuance) as well as language translators for the military.

In 2004, NASA sent unmanned rovers to Mars, which explored the planet with a degree of autonomy. DARPA held several Grand Challenge prize competitions for autonomous vehicles in 2004 to 2007, demonstrating the potential of self-driving cars.

DARPA’s Cognitive Agent that Learns and Organizes (CALO) project, which integrated advances being made in speech recognition, cognition, and machine learning, began in 2002 and eventually led to Apple Inc.’s Siri in 2011.⁸⁸ Also in 2011, IBM’s question-answering computer Watson won the U.S. TV game show “Jeopardy!”⁸⁹ and in 2017 Alphabet’s (Google’s parent company) AlphaGo defeated the world’s best player of Go.⁹⁰

These successes were largely based on machine learning – in which AI systems learn from experience – and were enabled by the adoption of statistical and probabilistic methods, the availability of large amounts of data, and increased computer processing power. The development of machine learning techniques was heavily supported by DARPA.⁹¹ AI has

⁸⁷ See, for example, the Networking and Information Technology Research and Development Supplement to the President’s Budget for various physical years, available at <https://www.nitrd.gov/publications/>.

⁸⁸ David W. Cheney and Richard Van Atta, “DARPA’S Processes for Creating New Programs,” March 2016. Technology Policy International. https://technopoli.net/assets/docs/TPI_DARPA_Report.16690227.pdf

⁸⁹ National Science and Technology Council Committee on Technology. “Preparing For The Future Of Artificial Intelligence,” October 2016. https://obamawhitehouse.archives.gov/sites/default/files/whitehouse_files/microsites/ostp/NSTC/preparing_for_the_future_of_ai.pdf

⁹⁰ Mozur, Paul, “Googles’ AlphaGo Defeats Chinese Go Master in Win for A.I.,” New York Times, May 23, 2017. <https://www.nytimes.com/2017/05/23/business/google-deepmind-alphago-go-champion-defeat.html>

⁹¹ Joshua Alspector and Thomas G. Dietterich, DARPA’s Role in Machine Learning. AI Magazine. Summer 2020. <https://ojs.aaai.org/aimagazine/index.php/aimagazine/article/view/5298/7231>

demonstrated improved results at a rapid pace, causing much excitement about the near-term prospects of AI.

In 2016, under President Obama the first AI R&D Strategic Plan was developed by the NITRD NSTC subcommittee.⁹² It called for expanding research, developing infrastructure and standards, addressing legal, ethical, social, and safety issues, and developing the workforce.

Industry also increased its investment in AI across many domains. Machine learning applications include online assistants, computer vision, face recognition, as well as applications in manufacturing, health and medicine, finance, law, and agriculture.⁹³

In 2018, Congress, passed a law that established the National Security Commission on Artificial Intelligence.⁹⁴ The Commission's charge was to consider how to advance artificial intelligence, machine learning, and associated technologies that affect U.S. national security. The Commission recommended strengthening AI research, the AI workforce, and associated technologies (including biotech, electronics, quantum, additive manufacturing, energy storage, robotics, and 5G communications). The Commission drew attention to rapid advances being made by China, as well as Russia's use of AI in disinformation campaigns. The Commission added to the growing bipartisan view that the U.S. needed to invest more in critical technologies, including AI.⁹⁵ (The Commission also helped lay some of the groundwork for the Endless Frontier Act, which led to CHIPS and Science law.)

In 2019, President Trump signed an Executive Order 13859 on Maintaining American Leadership in AI. This established an American AI initiative, highlighted the importance of AI, and directed Federal agencies to give priority to AI research, data and computing resources, standards, workforce development, and use of AI.⁹⁶

The AI initiative was then established in law by the National Artificial Intelligence Initiative Act of 2020 enacted on January 1, 2021 (as part of the Defense Authorization Act).⁹⁷ This law renamed the initiative as the National Artificial Intelligence Initiative, established the NAI Office in OSTP, and established the National AI Advisory Committee. It also authorized the creation of National Artificial Intelligence Research Institutes by NSF and other agencies, and

⁹² National Science and Technology Council Networking and Information Technology Research and Development Subcommittee. *The National Artificial Intelligence Research and Development Strategic Plan*. October 2016. https://www.nitrd.gov/pubs/national_ai_rd_strategic_plan.pdf

⁹³ National Science and Technology Council Committee on Technology. *Preparing For The Future Of Artificial Intelligence*, October 2016. https://obamawhitehouse.archives.gov/sites/default/files/whitehouse_files/microsites/ostp/NSTC/preparing_for_the_future_of_ai.pdf

⁹⁴ This was in the 2018 Defense Authorization Act (P.L. 115-232).

⁹⁵ The Commission's final report, is available at <https://www.nscail.gov/2021-final-report/>

⁹⁶ Donald Trump, "Maintaining American Leadership in Artificial Intelligence." Executive Order 13859. February 11, 2019. <https://www.federalregister.gov/documents/2019/02/14/2019-02544/maintaining-american-leadership-in-artificial-intelligence>

⁹⁷ See Public Law 116–283, JAN. 1, 2021 William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021. Division E. <https://www.congress.gov/116/plaws/publ283/PLAW-116publ283.pdf>

authorized other AI R&D activities in NSF, Department of Commerce, and the Department of Energy.⁹⁸

In Fiscal Year 2022, the total AI R&D funding in the Federal government coordinated through the AI Initiative was \$2.5 billion. NSF had the largest share (\$653 million), followed by NIH (\$548 million) and DARPA (\$456 million).⁹⁹ There are currently 18 National Artificial Intelligence Research Institutes supported by NSF and other agencies, each funded at about \$20 million over five years. In FY2022, the total budget for National AI Research Institutes was \$73.3 million.¹⁰⁰ While these are important new initiatives, they currently make up less than 3 percent of the total Federal spending on AI R&D.

FEDERAL SUPPORT FOR THE COMMERCIALIZATION OF AI

For much of AI's history, from the 1960s into the 1990s, there was little commercialization of AI. For the most part, the technology was not capable enough. Starting in the 2000s, driven primarily by advances in machine learning, AI became more capable and there were demonstrations of how the technology could work. AI is less capital intensive than many other deep technologies. Once the technology has been demonstrated to work and markets have been identified, commercialization can proceed with largely private sector financing. In the last decade, AI has been commercialized in many areas, including personal assistant apps in cell phones, credit card fraud detection algorithms, targeting of advertising, and many other areas. Ample market forces now drive the technology.

The Federal government has assisted commercialization of AI through many means. These include:

- Demonstration projects. DARPA projects, such as the CALO project that led to Siri (described earlier), create prototypes that demonstrate the feasibility of the technology.
- Prizes. As discussed earlier, DARPA prizes in areas such as self-driving vehicles have stimulated commercial interest (and demonstrated the feasibility of technologies).
- Procurement. Many Federal agencies are seeking to use AI in their mission functions. DOD buys AI technology and services from many contractors. The U.S. Postal Service was an early and large user of optical character recognition, and now is using AI procured from a vendor to help find lost packages.
- Standards. NIST's AI program supports the development of metrics and standards for AI, and DARPA projects have also developed ways of measuring aspects of AI (such as the performance of speech recognition systems).

⁹⁸ See www.ai.gov

⁹⁹ The Networking & Information Technology R&D Program and the National Artificial Intelligence Initiative Office, *Supplement to the President's FY 2023 Budget*. National Science and Technology Council. November 2022. <https://www.nitrd.gov/pubs/FY2023-NITRD-NAIIO-Supplement.pdf>

¹⁰⁰ See <https://www.nsf.gov/cise/ai.jsp> for more information about the centers.

Another important function to aid the long-term growth of AI is to address the many ethical, legal and social implications of AI, including the safety of self-driving cars, the likely impact of AI on jobs, and frequent bias in AI algorithms. While addressing these concerns may not promote commercialization in the short run – regulations may constrain the use of AI -- it is likely that thoughtful ethical and legal standards will aid the orderly growth of AI in the long run. Addressing social issues early may prevent AI from developing in harmful directions that could lead to strong social opposition to AI.

DISCUSSION OF AI INNOVATION POLICY

AI is both like and different from quantum information science as case studies in the development and commercialization of deep technology. AI is like QIS in the following ways:

- Both are important emerging technologies that have received the attention of policymakers.
- There was extensive Federal support for many years before the creation of formal multi-agency initiatives. The initiatives organize, prioritize, and supplement Federal support for the technology, but they also build on decades of earlier work in government agencies, universities, and even companies.
- Fear of rapid Chinese advances have spurred U.S. action.
- Both initiatives use university-industry centers as a key approach to accelerate research, spread knowledge, and expand the workforce.

AI is different from QIS in several ways:

- AI is a more mature technology than QIS. AI research has been supported by the U.S. government, especially DARPA, for decades. Many products have been commercialized in many segments of AI (e.g., robotics, machine vision, speech recognition, natural language, personal assistants, etc.) Major U.S. companies like Google, IBM, Facebook, and others have invested heavily in AI R&D, and many other companies are already users of AI.
- AI is less capital intensive and less dependent on large research facilities than QIS. While like other “deep” technologies AI is research-based, from a commercialization viewpoint – capital requirements, speed to market, and scalability – AI is more like the many “shallow” digital and software technologies that the U.S. innovation system has supported well through private capital.
- AI has significant ethical, legal, and social implications. Understanding and shaping these implications is an important part of the development of AI. These concerns are (so far) less apparent with QIS.
- DARPA has played a much more central role in the development of AI compared to QIS, including DARPA’s support of the early development of AI in university centers, support

and demonstration of autonomous vehicles, and many other areas. This is likely because the potential military applications have been clearer.