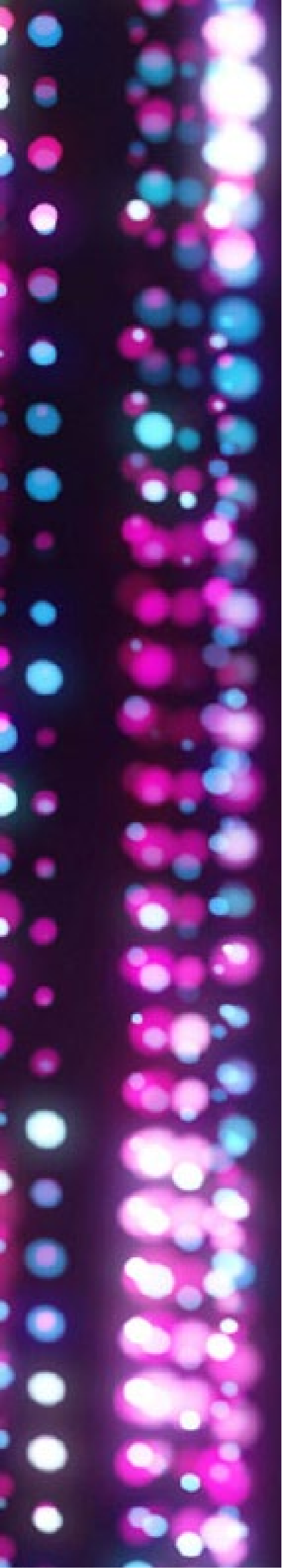

Public-Private Partnerships in Quantum Computing

The Potential for Accelerating Near-Term Quantum Applications

September 2022

About the Quantum Economic Development Consortium

The Quantum Economic Development Consortium (QED-C®) is an industry-driven consortium managed by SRI International (SRI). The consortium seeks to enable and grow the quantum industry and associated supply chain. QED-C is supported by the National Institute of Standards and Technology (NIST) in the U.S. Department of Commerce and about 200 members, including component manufacturers and suppliers, software and hardware system developers, researchers, professional service providers, and end users. Consortium membership represents companies, universities, federally funded research and development centers, government, and other stakeholders. Learn more about QED-C at quantumconsortium.org.

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Executive summary

Quantum computing (QC) is a technology with enormous potential, but for the moment, it is one only of potential. Despite the considerable amount of QC research and development (R&D) underway, to date, no *economically* meaningful use cases have been demonstrated. Over time, quantum computing is likely to follow Amara's law regarding technology forecasting—its uses and benefits will be overestimated for the near-term and underestimated for the long-run.[1] This report focuses on the near-term. It evaluates potential near-term QC applications as well as the prospect of using public-private partnerships (PPPs) to accelerate the time horizon for meaningful applications of quantum computing.

Numerous proof-of-concept applications for quantum computing have been explored and reported. There is consensus that many applications, especially the more ambitious, will require true fault-tolerant quantum computers with large (on the order of 100-1,000) qubit counts[2] to run effectively. It is unknown when such fault-tolerant computing will be available. Before then, it is possible that algorithms running on noisy intermediate-scale quantum (NISQ) computers, including quantum annealers, may compete favorably against classical approaches, especially for optimization and selected machine learning (ML) applications. It is also unclear when this may happen. As a proof of concept, it may happen within the next three years. A review of the QC application literature indicates that on an economic basis, it is unlikely to happen within the next three years.

This is due both to the technological uncertainty surrounding QC development paths and to the fact that the classical computing approaches against which quantum computing must compete are continuously improving. They are a moving target. Quantum computing will only be useful when it can surpass the performance of the very best classical methods for a given computational problem. And it cannot merely be marginally better. It must be dramatically better if organizations are to incur the significant switching cost and potentially dramatic changes to commercial, industrial, and government workflow required to migrate from classical to quantum computing processes.

The combined technology and market uncertainty means that predicting when or even if economically meaningful QC applications will appear is impossible. Any forecast regarding quantum computing is inherently speculative. Nevertheless, several areas are believed to have the greatest potential for near-term use. These areas include:

- Pharmaceuticals
- Chemicals and materials
- Batteries
- Manufacturing and warehousing
- Logistics, supply chain management, traffic, and route management
- Financial fraud detection

Many of these use cases rely on hybrid quantum-classical approaches to computation. Hybrid approaches perform much of their computation with classical computing hardware and reserve valuable

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[1] Roy Charles Amara was an American scientist and President of the Institute for the Future who also worked at the Stanford Research Institute (later SRI International).
[2] McKinsey indicates early- and late-stage fault tolerance at 100 and 1,000 logical qubits respective. See: McKinsey & Company, "Quantum Computing: An Emerging Ecosystem and Industry Use Cases," (December 2021).

qubits for the parts of each problem for which they are most necessary. Hybrid approaches represent a way to potentially accelerate the near-term use of quantum computing as they alleviate the need for fully scaled all-quantum systems.

Against the backdrop of the state of QC R&D and its uncertain future, SRI International (SRI) examined the history and performance of nine PPPs established to help accelerate technology development. These PPPs cover a range of science and technology (S&T) areas. Each partnership includes a significant role for government participants. Their success comes from setting clear goals that are understood by all partnership participants, aligning these goals with important government missions, and translating top-level goals into more detailed objectives and workplans. Based on the state of QC R&D and the experience of these partnerships, SRI proposes three PPP models that the federal government should consider adopting to accelerate QC uses. The models are meant to complement each other by addressing different aspects of the QC development challenge.

The most effective way to identify a set of potential near-term QC applications of value to government is through a discovery process that involves cooperation among all stakeholders, from quantum scientists to domain subject matter experts to end users to regulators. Accordingly, the federal government should consider establishing a PPP or leveraging an existing PPP (e.g., QED-C) whose mission is to find possible near-term QC applications by facilitating planned interaction and cooperation among QC hardware and software experts, application domain experts, user communities, and policy and market experts. Such a partnership should be organized thematically around a significant area of public interest, such as climate and sustainability or public health, where there is an emerging critical mass of quantum R&D already underway. The partnership's goals would not be defined in terms of achieving real-world applications in a given number of years. Rather its objective would be to evaluate possible application areas in much more depth than can be done via a survey of the literature, thus identifying strategies to advance the date at which real-world progress can be made.

Looking more narrowly, government-sponsored challenges have demonstrated their effectiveness in accelerating the development of technology intended for use in government mission areas. The iterative approach to competition allows the government to revise timelines and objectives in response to participant progress and improved understanding of what is technologically possible, an attribute suited to QC use case development. The U.S. federal government should consider organizing a QC challenge. The targeted challenge should focus on an area with (a) clear government mission relevance, (b) active interest by the private sector, and (c) a critical mass of current QC research. Several areas described in the near-term applications section meet these criteria. Financial fraud detection stands out given the level of interest on the part of private-sector financial services firms in quantum computing for fraud detection and the enormous amount of real-world data available with which to experiment and develop quantum machine learning (QML) anomaly and fraud detection tools.

In addition to application-focused partnerships, the federal government should consider supporting a PPP focused on addressing the underlying technology development challenges of quantum computing in a manner similar to the Department of Energy's (DOE) Innovation Network for Fusion Energy (INFUSE) program. INFUSE awards are intended to help solve specific challenges related to fusion-enabling technology development and are awarded based on the expected impact of proposed projects on the overall progress of fusion energy R&D. Most of the technical work is performed by DOE laboratories. An INFUSE model for quantum computing would include participation of DOE's Quantum Information Science (QIS) Research Centers and other participants from the private sector and academia and, in effect, would create focused PPPs for each approved project. Such a partnership would not address specific QC applications but the development of enabling technologies in technical areas such as qubit control, error correction, cryogenics, and system scaling, areas with broad, pre-competitive application.

Near-term applications in quantum computing

Anticipating useful applications for quantum computing, even in the near term, is inherently speculative. Congress directed NIST to evaluate the potential for public-private partnerships to develop and deploy near-term, practical applications of quantum computing.[3] SRI initiated this study, in part, to help inform NIST's response to Congress. Although the Congressional request defined "near-term" as one to three years, for purposes of this report it is a relative distinction.

In the context of this report, "useful applications" implies the choice to use quantum computing to solve significant, real-world problems because doing so provides a demonstrably economically superior way to solve those problems. Many recent proof-of-concept experiments in quantum computing indicate that quantum approaches may eventually provide superior approaches to a wide range of commercially and societally important problems. Some of these experiments even suggest that quantum computing may one day be able to solve problems that classical computers will likely never be able to solve. However, there is no known evidence to suggest that quantum computing has demonstrated *economic* superiority yet.

Among the challenges to realizing real-world QC applications is the fact that quantum computing's competitor—classical computing—is constantly getting better. Moore's law continues to make classical computers more powerful, and classical computing algorithm development continues to make more efficient use of that more powerful hardware on a per clock cycle basis. The competition is, accordingly, a moving target, one that has been undergoing incremental refinement for several decades. Quantum computing, on the other hand, is very nascent. This nascency presents a challenge to identifying its future applications. When the transistor was invented in 1947, it would have been impossible to predict that in 2022, a large share of the world's population would be carrying wallet-sized mobile telephony devices in their pockets each of which contain billions of transistors.

Another challenge to identifying near-term QC applications is the disagreement within the QC community regarding the status of the technology. In 2019, Google claimed that its 53-qubit computer took just 200 seconds to perform an arcane task of no practical use that would take 10,000 years to be solved by IBM's Summit supercomputer, a very large classical computer built for the U.S. Department of Energy. IBM countered that Summit could actually perform the task in 2.5 days,[4] for a factor of disagreement of almost 1.5 million.

Another factor contributing to uncertainty regarding the near- and long-term applications of quantum computing is the diversity of approaches to technology development in the industry. Virtually all classical computers rely on the same underlying computation principles; this is not the case for quantum computing. Quantum computing generally includes diverse models for computing (approaches to manipulating qubits to achieve something computationally valuable) and diverse physical approaches to creating qubits.[5] The former includes gate-based quantum computing and quantum annealing. The most

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[3] House Committee on Appropriations, "Report together with Minority Views," Report 117-97, https://www.congress.gov/117/crpt/hrpt97/CRPT-117hrpt97.pdf.
[4] Adrian Cho, "IBM Casts Doubt on Google's Claims of Quantum Supremacy" (23 October 2019), *Science*, https://www.science.org/content/article/ibm-casts-doubt-googles-claims-quantum-supremacy.
[5] There is even disagreement within the industry regarding what constitutes a quantum computer. For example, see BCG, "Why Nobody Can Tell Whether the World's Biggest Quantum Computer Is a Quantum Computer" (2018).

common physical approaches to creating gate-based quantum computers include superconducting, ion-trap, photonic, neutral atom, and silicon spin qubits. The qubits used in D-Wave's quantum annealing computers are created from superconducting loops.[6]

This considerable uncertainty has led many QC experts to question whether it is realistic to expect near-term QC applications, and some have publicly stated that they simply do not know when these applications will emerge.[7] There is also disagreement among experts regarding whether economically useful QC applications are possible at all before considerably more fault tolerant, higher power QC hardware is available,[8] the advent of which is not likely prior to 2030,[9] a date that itself is subject to uncertainty.[10] Nevertheless, several application areas are currently discussed in the QC use case literature that reports on early proof-of-concept experiments with limited datasets or small-scale experiments. Management consulting firms have completed the extensive recent surveys of these near-term use cases and provide the most thorough publicly available coverage of the topic. This section of the report relies on these reports as well as selected technical sources. None of these sources identify clear, economically valuable use cases expected within three years. As McKinsey & Company indicates in its December 2021 report on quantum computing, "the early stage of quantum computing technology and the immaturity of the quantum-computing industry make identifying relevant use cases largely a theoretical exercise."[11]

Identifying potential *nearer*-term use cases, those that may see real-world application relatively sooner, but some time beyond three years, is a less uncertain exercise. This section reviews QC application areas that may provide economical advantage at some point beyond three years but prior to the arrival of fully fault-tolerant quantum computers. In other words, they represent QC applications that would need to demonstrate economic superiority with current NISQ hardware. Review of these applications inform consideration later in this report of quantum-focused public-private partnerships. The phrase "near-term" is used in this report as a relative distinction; it does not refer to something expected within a given timeline.

Categories of computational analyses

Anticipated QC use cases fall into four broad categories of analyses:

- **Optimization**: maximizing such objective functions as efficiency, cost, and distance traveled
- **Simulation**: modeling physical systems, especially those that themselves are quantum mechanical in nature or involve solving differential equations
- **Linear algebra**: matrix diagonalization and related analyses for use with machine learning and artificial intelligence (AI) applications

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[6] D-Wave, "What is Quantum Annealing?" https://docs.dwavesys.com/docs/latest/c_gs_2.html.
[7] Sankar Das Sarma, "Quantum Computing Has a Hype Problem," *MIT Technology Review* (28 March 2022).
[8] In order to correct errors that emerge with single physical qubits, multiple physical qubits are typically used to define a single logical qubit. The number of logical qubits is one measure of the computational capacity of a quantum computer.
[9] McKinsey & Company (2021).
[10] Fault tolerance is not a discrete achievement. Quantum computers will get progressively more tolerant over time. At some point, they may reach a level of error minimization that makes it practical to use them for real-world applications, the way classical computers are used today.
[11] McKinsey & Company (2021).

- **Factorization**: deriving factors for the large integers used in cryptography

Many of the near-term applications identified in the consulting and technical literature make use of quantum optimization and quantum machine learning. Optimization challenges are ubiquitous in real-world service, commercial, industrial, and government contexts. Optimization involves choosing the best (or at least a good) set of parameter values from combinations of those values that can quickly grow into the billions and trillions or more. Machine learning is an application of AI that enables computer systems to learn and improve from experience (i.e., exposure to data) in order to find patterns and make inferences based on the known samples, e.g., to recognize tumors in radiological images based on analyzing the image features of scans with tumors present. Like optimization, ML has a wide and growing range of applications.

While optimization and QML represent the most frequent use for quantum computing currently being explored, there is active research in all four computational areas listed above. This work is ongoing in a variety of sectors and for numerous QC application areas. While it is impossible to forecast what QC applications are likely to lead to real world use at any point in the future, there is a critical mass of interest and investment in several areas. These application areas are described below.

Pharmaceuticals

Quantum annealers, which rely on quantum mechanical behavior but not on quantum gate structures for computation, are suited to solve optimization problems.[12] GlaxoSmithKline recently announced that quantum annealing machines made by D-Wave can compete with classical computers for codon optimization in the context of research on gene expression and development of recombinant protein therapies.[13] GlaxoSmithKline found that gate-based quantum computers could not yet compete with classical computers for this type of analysis but believes that larger fault tolerant gate-based quantum computers could compete if successfully developed. The type of optimization analysis performed by GlaxoSmithKline is typical of the type of optimization problem that quantum annealers are designed to tackle, those for which combinatorics are central.

Similar work is being done by Menten AI, a drug design company that develops machine learning and QC methods to accelerate drug discovery. The conformational variation of large organic molecules grows exponentially with molecule size, challenging even the most powerful classical computers running the most efficient algorithms. Better optimization would allow for greater understanding of how drugs interact with proteins, reducing reliance on trial-and-error approaches to drug design and reliance on X-ray and nuclear magnetic resonance (NMR) imaging to understand molecular behavior.[14] Menten mapped a protein design problem to a D-Wave quantum annealer to find amino acid side chain identities and conformations to stabilize a fixed protein backbone. Menten designed molecules comparable to those produced by widely used classical protein design approaches.[15]

[12] As an indication of the level of disagreement among experts regarding the state and future of quantum computing, there has been considerable debate as to whether quantum annealing is, in fact, quantum computing.
[13] Daphne Leprince-Ringuet, "Quantum Computing: Quantum Annealing Versus Gate-Based Quantum Computers" (11 March 2021), ZDNet.
[14] McKinsey & Company (2021).
[15] VK Mulligan, et al., "Designing Peptides on a Quantum Computer"(11 March 2020), bioRxiv, https://doi.org/10.1101/752485.

Other areas of possible near-term use of quantum computing in pharmaceutical R&D include optimization of clinical trials and creation of synthetic data,[16] as well as transplant donor matching.[17] Clinical trials already benefit from application of classical AI. Quantum computing could help optimize patient identification and stratification into subgroups and in trial site selection. Quantum annealing has been used to simulate optimal matching of donated kidneys to patients needing kidneys using a randomly generated dataset.[18]

Chemicals and materials

The potential use of quantum computing in chemical and materials development is closely related to its prospective uses in pharmaceutical R&D, namely, its potential in reducing some of the trial-and-error effort associated with molecule design.[19] Classical approaches to computational chemistry are in widespread use in estimating chemical properties. QC approaches could help with the design of small molecules, specifically in the prediction of their properties via quantum mechanical simulation. Such progress could accelerate chemical design for a very wide range of applications.

Other potential nearer-term areas of application of quantum computing in chemicals and materials include production process optimization and supply chain optimization.[20] Chemical production relies extensively on the use of catalysts, which make chemical production more efficient but also account for a large share of the chemical production cost chain. Even modest improvement in catalyst performance could have an enormous impact. Prototype QC tools have been developed to help chemical companies understand the properties of catalysts by simulating subatomic interactions in chemical reactions.[21] QML is one of the primary quantum computing tools being used for molecular modeling in both pharmaceutical and materials design.[22] Supply chain challenges are similar across all industries that rely on diverse production inputs with multiple and varying sources, prices, availabilities, and mix of substitutes for inputs. Quantum computing's potential to address these general supply chain challenges are described in the section below on logistics, supply chain management, traffic, and route management.

Batteries

Batteries are becoming an ever more important part of the energy economy. The trend is driven in large part by the evolution of vehicle propulsion systems away from internal combustion engines toward battery power, though an increase in battery-powered devices of all kinds is contributing to the need for more efficient batteries. Use of quantum computers for battery R&D is essentially a subset of its use in chemical R&D. Quantum computing is being explored to help design more efficient vehicle batteries by

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[16] McKinsey & Company (2021).
[17] Center For Data Innovation, "Why the United States Needs to Support Near-Term Quantum Computing Applications" (2021).
[18] Accenture, "Quantum Computing with D-Wave" (September 2019).
[19] McKinsey & Company (2021).
[20] McKinsey & Company (2021).
[21] Riverlane, "Designing Better Catalysts with Quantum Computers" (22 November 2021), https://www.riverlane.com/news/2021/11/designing-better-catalysts-with-quantum-computers/.
[22] Quantum Insider, "Quantum Machine Learning Is the Next Big Thing" (28 May 2020), https://thequantuminsider.com/2020/05/28/quantum-machine-learning-is-the-next-big-thing/.

simulating matter at the atomic level.[23] Related research is investigating the application of quantum computers to boost the fidelity of battery simulations by using quantum algorithms to solve partial differential equations governing simulation of lithium-ion battery cells.[24]

Manufacturing and warehousing

While manufacturing's share of total employment has been declining for decades, its share of total value contribution to the economy in real terms has remained steady over most of that time at about 12 percent of gross domestic product. Over this time, manufacturing processes and manufactured products have, on average, grown significantly more complicated, leading to an enormous number and range of opportunities for optimization. Optimization in manufacturing has received considerable attention from classical computer algorithm developers and is now attracting similar effort from quantum algorithm developers.

Fujitsu, for example, has partnered with a large automotive manufacturer to address optimization challenges associated with job shop scheduling and positioning for chassis welding equipment. Polyvinyl chloride (PVC) seam sealing is one of the most expensive steps in car production, contributing an average of 40 percent of the total manufacturing costs.[25] Seam sealing robots face an extraordinarily large number of possible combinations of welding maneuvers, the sort of large-scale combinatorial problems that quantum annealing computers can address. Using an 8192-bit digital annealer, Fujitsu's partner was able to map optimal welder roundtrips for a limited number of seem welders.[26] Fujitsu has a similar annealing approach to optimize its own warehouse operations.[27]

Auto manufacturer paint shop represents another application of quantum computing currently being explored. Changing colors requires cleaning and changing spray robots and so auto manufacturers are eager to minimize color changes at the end of the assembly line. The problem is deceptively challenging in the context of a manufacturer that produces multiple car models, each of which can be painted in a range of different colors. Volkswagen demonstrated use of a D-Wave quantum annealer to address the problem.[28]

Logistics, supply chain management, traffic, and route management

Supply chain management in manufacturing involves real-time management of the upstream logistics related to parts and materials suppliers and downstream logistics related to wholesalers, distributors, retailers, and customers. BMW is exploring the use of quantum computing to optimize the company's supply chains for automotive manufacturing, partnering with Honeywell (who supplied the quantum hardware) and Entropica Labs, a Singapore-based startup that develops QC software and algorithms.[29]

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[23] Forbes, "Can Quantum Battery Research Extend Electric Vehicle Range? IonQ And Hyundai Intend to Find Out" (9 February 2022).
[24] George Leopold, "Modeling Battery Designs via Quantum Computers" (12 May 2021), *EE|Times*.
[25] Fujitsu, "Manufacturing Gets Ready for Quantum Computing" (2019), https://www.fujitsu.com/global/imagesgig5/Digital_Annealer_Manufacturing.pdf.
[26] Fujitsu, "The Power of Quantum-Inspired Computing: Journey of Digital Annealer" (April 2019), https://techcommunity.ts.fujitsu.com/en/solutions-2/d/uid-ef37e3d6-ebc6-1fe6-6ad5-75dcdb3ecafa.html.
[27] Fujitsu (2019).
[28] Center for Data Innovation, "Why the United States Needs to Support Near-Term Quantum Computing Applications" (2021).
[29] ZDNet, "BMW Explores Quantum Computing to Boost Supply Chain Efficiencies" (27 January 2021).

In related work, Fenix Marine Services and SavantX, an AI developer, used D-Wave hardware to develop the Hyper Optimization Nodal Efficiency (HONE) optimization tool to optimize scheduling, appointments, in-terminal container handling for trucking companies, and other port optimization challenges at the Port of Los Angeles.[30]

A wide range of possible QC applications center on the challenges of optimizing the routes taken by vehicles, both autonomous and human controlled. The number of routes between nodes in a transportation network increases by the factorial of the number of nodes, which is faster than exponential growth, creating the type of constrained optimization challenges quantum computing is well suited to potentially address. These challenges are versions of the famous traveling salesman problem. Traffic and route management challenges are ubiquitous in the modern economy and play a role in numerous government service and mission areas ranging from healthcare delivery to national defense. Volkswagen has partnered with public transport provider CARRIS in Lisbon, Portugal to use quantum computing to optimize bus routes. The pilot project uses D-Wave hardware. German software developer Hexad developed navigation software for the project, which shows bus drivers optimized routes as they drive. The PTV Group, which specializes in data analytics, provided the necessary data for movement flow analysis in a city model developed for this project.[31]

At the intersection of traffic routing and manufacturing, DENSO Corporation, a supplier of advanced automotive technology for automakers, is exploring the use of quantum computing to optimize the routes of automated guided vehicles (AGVs) that move materials within factories. AGV congestion is a common problem in areas of high traffic on the factory floor. Using quantum annealing hardware made by D-Wave, DENSO has demonstrated a 15 percent reduction in AGV traffic congestion, with associated increases in productivity and reduction in costs.[32] Groovenauts, a cloud-services company, used quantum annealing to reduce carbon dioxide emissions from a group of 26 buildings owned or managed by Mitsubishi in the Marunouchi area of Tokyo. The quantum algorithms were used to find optimal collection routes by waste collection vehicles, leading to a 57 percent reduction in greenhouse gas emissions and a 59 percent reduction in the number of needed waste collection vehicles.[33]

Financial fraud detection

Finance represents a very active area of research for quantum computing. Some applications in finance are not expected prior to the advent of more fault tolerant quantum computers, and some involve analytical challenges in areas such as trading and risk management that are of greater interest to the private sector. Fraud detection, an area receiving significant attention, represents an area within this category of QC application that has clear relevance to the public sector. Both gate-based QC companies such as IBM,[34] as well as quantum annealing companies such as D-Wave,[35] have identified fraud detection as expected use cases for quantum computing. In the case of D-Wave, the company sees fraud detection as a potential area for a hybrid framework that uses both classical and quantum systems in

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[30] Quantum Insider, "SavantX, D-Wave Collaborate on Quantum Algorithms to Tackle Supply Chain Problems at U.S.'s Busiest Port" (8 January 2022), https://thequantuminsider.com/2022/01/08/savantx-d-wave-collaborate-on-quantum-algorithms-to-tackle-supply-chain-problems-at-u-s-s-busiest-port/.
[31] Volkswagen News Group, "Volkswagen Optimizes Traffic Flow with Quantum Computers" (31 October 2019).
[32] Center for Data Innovation (2021).
[33] Center for Data Innovation (2021).
[34] IBM, "Exploring Quantum Computing Use Cases for Financial Services" (2019).
[35] D-Wave, "Quantum in Financial Services: The Future is Now" (2021).

parallel to solve problems. Fraud detection has obvious applications in financial regulation and law enforcement and could have a large impact in these areas as quantum technology matures.

PayPal has already begun exploring the use of quantum machine learning for fraud detection. The payments company has partnered with IBM on research using quantum computers to sift through large datasets in search of indicators of fraudulent behavior. The enormous amount of archived data available for computation experimentation represents an advantage to exploring quantum for fraud detection. PayPal indicates that their early research demonstrates that quantum computing can be better than classical approaches at finding patterns in data that may be indicative of fraudulent behavior but acknowledges that the research is still in its early stages.[36]

Use of hybrid approaches

Many of the use cases described in the previous sections rely on hybrid quantum-classical approaches to computation. Hybrid approaches subdivide computational problems into portions that can be done efficiently with classical computing hardware and use QC hardware only for those portions that cannot be solved classically. Hybrid approaches thus reserve the valuable asset—the quantum processing capability of qubits—for those parts of a problem for which it is most necessary. Until quantum hardware matures, hybrid approaches represent a way to potentially accelerate the near-term use of quantum computing.[37] The approach alleviates the need for all-quantum systems in order to attempt to address real world challenges with quantum computing. It also provides a way for end users to incrementally migrate their processes to include quantum computing. Originally pursued by quantum annealing companies, the large gate-based quantum system developers are now developing hybrid platforms for use with their quantum hardware, including IBM, Microsoft, and IonQ.[38] Hybrid approaches have been highlighted as mechanism for accelerating government QC use cases in areas such as route optimization (e.g., for emergency response), supply chain (e.g., for public port management like that done at the Port of Los Angeles), and sustainability (e.g., through carbon reduction via more efficient vehicle use).[39]

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[36] Business Insider, "Inside Paypal's Partnership with IBM to Use Quantum Computing to Improve How It Detects Fraud and Underwrites" (7 January 2022).
[37] Medium, "Application-Specific Quantum Hardware is the Most Promising Approach for Early Practical Applications" (8 February 2022).
[38] Forbes, "The Quantum Revolution Is Here, Its Name is Hybrid" (29 April 2022).
[39] techUK, "Quantum Commercialisation: Positioning the UK for success" (24 May 2022).

Public-private partnership case studies

This section reviews the history and performance of ten public-private partnerships that cover a range of S&T areas. All but two are ongoing partnerships. The Defense Advanced Research Projects Agency (DARPA) Grand Challenge for autonomous vehicles was completed over the course of two competitions in 2004 to 2005. Each partnership includes goals rooted in scientific or technological advancement. They were chosen for review based on their relevance to how QC technology and its applications can be accelerated and because each includes a significant role for government participants. Partnerships in which the role of government is limited largely to funding R&D were excluded.

Some high-profile partnerships were excluded because their lessons for contemporary QC application development are limited. The Manhattan Project, for example, was excluded for several reasons, despite being among the best-known government led S&T partnerships in history. First, the ecosystem for new technology commercialization in the United States is vastly different in 2022 than it was in the early 1940s. Second, the Manhattan Project was unprecedented in scope and size, with a budget in excess of $23 billion in 2022 dollars. Finally, it involved a collection of many of the greatest scientists of the twentieth century— Richard Feynman, J. Robert Oppenheimer, and Enrico Fermi among them—a collaboration unlikely ever to be repeated.

Similarly, Operation Warp Speed (OWS), a much more contemporary partnership, was excluded because this was primarily an interagency partnership that brought the biomedical and public health expertise of the U.S. Department of Health and Human Services together with the logistical expertise of the U.S. Department of Defense to coordinate federal efforts to accelerate the development, acquisition, and distribution of COVID-19 countermeasures. OWS's implementation of a successful national vaccination program was the result of precise coordination among all stakeholders and offers significant insight into how the government can best contribute to large logistical challenges facing the nation. OWS's support for vaccine development at private pharmaceutical and biotechnology firms, however, came primarily through advanced purchase contracts and funding to expand manufacturing capacity. Since most of the key scientific ideas behind the seven COVID-19 vaccine candidates supported by OWS predated the pandemic, OWS did not contribute to new scientific breakthroughs. As a result, OWS does not have notable features that could serve as a model for advancing applications for quantum computing.

Also excluded from this report is discussion of current PPPs in the area of quantum computing. Several such partnerships exist.[40] These include entities such as the Quantum Economic Development Consortium (QED-C), which convenes 200+ international representatives from the public and private sectors to advance quantum science and technology and their support structures (e.g., standards, workforce, and enabling technologies) in a number of areas, of which quantum computing is one. Similarly, Quantum Delta NL aims to position the Netherlands as a leading ecosystem in quantum technologies, specifically: quantum networks, quantum sensing applications, and quantum computing and simulation. The goal of the case studies is to consider lessons from outside of the QC space on how technology application can be accelerated through public-private partnerships. These lessons are summarized following the case descriptions.

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[40] QED-C. *Toward a Resilient Quantum Computing Supply Chain: Response to the American COMPETE Act*. Arlington, VA, April 2022. https://quantumconsortium.org/COMPETE/.

NASA Commercial Crew Program

Technology Domain: Propulsion, space vehicles

Region: USA

Participants (Public):

- National Aeronautics and Space Administration (NASA)

Participants (Private):

- Boeing
- SpaceX

Motivation and goals

The primary goal of NASA's Commercial Crew Program (CCP) is to facilitate the development of safe, reliable, and cost-effective human transportation to and from the International Space Station (ISS) from the United States. The resulting spacecraft and launch systems capable of carrying astronauts to low-Earth orbit and the ISS provide expanded utility, additional research time, and broader opportunities for discovery on the orbiting laboratory.[41] This PPP was formed so that partner entities—currently Boeing and SpaceX—can put forth their best design ideas and most efficient and effective manufacturing and operating techniques in developing space transportation that conforms with NASA's safety requirements. As commercial companies focus on providing human transportation services to and from low-Earth orbit, NASA is freed up to focus on building spacecraft and rockets for deep space missions.

Operating model

In the history of the U.S. Space Shuttle Program and U.S. involvement in the ISS, NASA had always operated one way: the agency identified a need for a crew transportation system and then its engineers and specialists oversaw all aspects of spacecraft development, support systems, and operating plans. A commercial aerospace contractor would build the system per NASA's specifications, but NASA would be heavily involved and oversee processing, testing, launching, and operating the crew system to ensure safety and reliability. All hardware and infrastructure were owned by NASA.

With CCP, NASA still identified the need for a crew transportation system, but it developed broad requirements to ensure crew safety and now lets select private industry partners execute on those requirements as they see fit. In 2010 NASA began partnering with a number of companies in its initiative to enable private industry to take on the task of providing routine access to space. Most companies received funding from NASA, but several were 'unfunded' and only received NASA's review and expert feedback on overall concepts and designs, systems requirements, launch vehicle compatibility, testing and integration plans, and operational and facilities plans. Over time, the pool of private partners dwindled to two as milestones were met (or not met). Now, NASA's engineers and aerospace specialists work closely with the remaining commercial company partners SpaceX and Boeing, offering insight, expertise, and available resources, but the companies own and operate their own hardware and

[41] NASA, "Commercial Crew Program Overview" (27 July 2021), https://www.nasa.gov/content/commercial-crew-program-overview.

infrastructure.

Accomplishments

In November 2020—nine years after CCP was initiated—the SpaceX Falcon 9 rocket launched the Crew Dragon spacecraft and NASA astronauts into orbit to begin a six-month science mission on the ISS. This was the first of six crewed missions that NASA and SpaceX will fly as part of the CCP, and the partnership is now on its fourth mission.[42] Meanwhile, NASA continues to work with Boeing on testing its uncrewed CST-100 Starliner spacecraft in preparation of NASA certification and future crewed missions.

Success factors

The first factor that has led the CCP to success is its phased approach with goals and milestones to guide proof of concept. NASA arrived at trusting SpaceX and Boeing as partners via a phased approach through which the companies had to prove themselves worthy of receiving continued government funding along the way.

Agency-facilitated partner validation has also proven instrumental. NASA helped finance the development work of domestic companies through the following mechanisms[43]

- Space Act Agreements to support industry partners in developing crew transportation capabilities and in performing tests to verify, validate, and mature integrated designs
  - Commercial Crew Development Round 1 (CCDev1)
  - Commercial Crew Development Round 2 (CCDev2)
  - Commercial Crew Integrated Capability (CCiCap)
- Contracts to ensure the selected commercial transportation systems meet NASA's safety and performance requirements for transporting humans into (and back from) space
  - Certification Products Contracts (CPC) – certification plan development
  - Commercial Crew Transportation Capability (CCtCap) – certification plan implementation

Finally, a significant government investment was made to see the PPP through. Roughly $8.4 billion was provided to private partners, which is not atypical for the area of space travel; this funding ultimately helped to shape the capability offerings of the companies best aligned with CCP's mission. Table 1 below shows how money was allocated among partners, and through which funding mechanisms.

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[42] Jason Costa, "NASA's SpaceX Crew-4 Underway as Freedom Journeys to Station" (27 April 2022), NASA, https://blogs.nasa.gov/commercialcrew/category/spacex/.
[43] NASA, "Commercial Crew Program – Essentials" (14 August 2019), https://www.nasa.gov/content/commercial-crew-program-the-essentials.

Table 1: Funding allocation among NASA CCP participants over time

	CCDev1 (2010)	CCDev2 (Apr 2011)	CCiCap (Aug 2012)	CPC (Dec 2012)	CCtCap (Sept 2014)
Alliant Techsystems		unfunded			
Blue Origin	$3.7M	$22M	unfunded		
Boeing	$18M	$112.9M	$460M	$10M	$4.2B
Excalibur Almaz Inc.		unfunded			
Paragon Space Development Corp.	$1.4M				
Sierra Nevada Corporation	$20M	$105.6M	$212.5M	$10M	
SpaceX		$75M	$440M	$9.6M	$2.6B
United Launch Alliance	$6.7M				
Total	~$50M	~$316M	~$1.1B	~$30M	~$6.8B

National Spectrum Consortium (NSC)

Technology Domain: Electromagnetic spectrum technologies

Region: USA

Participants (Public):

- Under Secretary of Defense for Research and Engineering
- Test Resource Management Center, U.S Department of Defense
- Under Secretary of Defense for Personnel and Readiness

Participants (Private):

- 129 large businesses
- 227 small businesses[44]

Participants (Non-Profit):

- 23 non-profit organizations

Participants (Academic):

- 28 academic institutions

Motivation and goals

The NSC is a research and development organization that incubates new technologies to expand the way that the electromagnetic spectrum is utilized. The NSC provides the U.S. Government with direct access to over 440 members of U.S. industry and academia who work with systems, sub-systems, components, and the enabling technologies related to the use of the electromagnetic spectrum or the information that rides on it. Through collaboration among industry partners, academia, and government agencies, NSC provides a unified voice for effectively articulating the strategically important role that electromagnetic spectrum technologies play in government and industry systems. They also provide the government with insights that enhance, inform, and sustain U.S. technical leadership on advanced technologies that expand access to, increase the control of, and make use of the data that flow across the electromagnetic spectrum to ensure U.S. economic and security interests.

NSC started in August 2014 with a five-year, $1.25 billion ceiling, Section 815 Prototype Other Transaction Agreement (OTA) with the Office of the Secretary of Defense (OSD). The OSD allows all DOD organizations (e.g., services, agencies, systems commands, and combatant commands) to use the OTA for spectrum-related collaborative purposes or competitive R&D project solutions. This OTA with DOD can also be used in support of other federal agencies with Statutory Other Transaction Authority; or if desired, other federal agencies can contract directly with the NSC using other contract instruments or their own Other Transaction Authority.

[44] Small business criteria for federal contracting can be found at: https://www.sba.gov/document/support-table-size-standards.

Objectives of the NSC include:

- Rapidly maturing technologies that assist in improved electromagnetic spectrum awareness, sharing, and use
- Experimentation to demonstrate how technology can be employed in increasingly contested and congested environments
- Technology analysis to inform DOD requirements and policy considerations

NSC members develop prototypes in spectrum and spectrum-using capabilities. Membership spans the continuum of basic research through large-scale production organizations, enabling the formation of purpose-built teams tailored to the development phase(s) of most interest to DOD sponsors.

Government entities can also engage with NSC members on technical or policy questions that fall within the consortium's domain through written responses, virtual interactive sessions, or in-person exchanges, such as:

- Market research discussions to provide deeper insight into the state of the art in a given technical area
- Brainstorming around potential technical solutions for a given problem set
- Vetting of draft requirements, policy documents, or other products that could benefit from multiple technical perspectives across industry, academia, and nonprofits
- Member perspectives on an existing policy or analytic document
- Technical approaches to achieve or inform operational concepts

Operating model

The NSC relies on OTAs to quickly bring innovative research and prototypes to government clients. The use of an OTA to govern consortium membership allows the government and industry to communicate relatively openly throughout a project's lifecycle, from requirement generation to the proposal stage and beyond. In this way, the government can clearly articulate its needs for cutting-edge technologies.

The OTA provides an overarching contractual arrangement that members agree to upon joining the consortium. This allows for greater speed when the government contracts with consortia members on individual project awards, enabling solutions to get to the end users sooner. The consortia's diverse membership of technology supplies of all sizes allows the government to cast a wider net when searching for ideas and innovations. The NSC's operating model promotes competition among large R&D companies that routinely support the government, academic institutions, and small or commercially focused suppliers.

A government organization that wishes to engage the NSC on a problem or requirement follows these steps:

- Define or refine the requirement to confirm it fits within the scope of the OTA.
- Work with the Contracting Office to draft Statement of Objectives/Statement of Work.
- Hold Industry Day discussion for NSC members.
- Release Request for Prototype Proposals.
- Receive proposals from NSC member teams, which can include non-members as subcontractors.
- Evaluate proposals and select source.
- Negotiate final award agreements.

- Oversee execution.

The entire NSC membership can compete for Request for Prototype Proposals. If the consortium does not include organizations that the government is interested in reaching, the NSC will recruit them.

Accomplishments

Since 2016, the NSC has awarded 111 projects with $1.2 billion in funding. Awards have ranged from $100,000 to over $50 million. Award recipients have included both traditional and non-traditional DOD performers, as well as large, small, non-profit, and academic organizations.

Success factors

Using an OTA to engage performers in this program gives the NSC significant flexibility in its operations. As evidenced by the membership and award information, NSC can engage a wide variety of organizations in many types and sizes of projects.

Manufacturing USA

Technology Domain: Manufacturing

Region: USA

Participants (Public):

- U.S. Department of Commerce
- U.S. Department of Defense
- U.S. Department of Energy
- 6 additional non-sponsoring partner federal agencies
- 16 public-private manufacturing innovation institutes
- Federal labs
- State and local governments

Participants (Private):

- ~1,200 manufacturers, of which ~800 are small- or medium-sized manufacturers

Participants (Non-Profit):

- ~300 non-profit organizations

Participants (Academic):

- ~500 academic institutions

Motivation and goals

Since its founding in 2014, the Manufacturing USA program has brought together over 2,300 member organizations, including businesses, academic institutions, and local government agencies, to drive innovation in the manufacturing industry. This network of public-private partnerships focuses on building future manufacturing capabilities by developing and testing new technology and providing training opportunities to build the workforce necessary for a strong domestic manufacturing industry. Each of its 16 manufacturing innovation institutes, which are located across the country, focuses on one of five fields:

- Electronics
- Materials
- Energy/environment
- Digital/automation
- Bio-manufacturing

Operating model

The Manufacturing USA program is a network of 16 manufacturing innovation institutes. Each institute is funded by one of the three federal agencies that oversee the program and managed jointly by the sponsoring agency and a non-profit organization or university with expertise in the specific field.

Each institute is a public-private partnership that brings together members from industry, academia, and government. The institutes connect their members to resources and proprietary data, support collaboration between members, and provide vision and leadership. As part of its formation, each institute convened stakeholders from across sectors for workshops aimed at refining the scope of the institute, creating a roadmap, and selecting topics for future projects. Many institutions update these programmatic priorities regularly through membership convenings.

In addition to issuing project calls based on ideas laid out in an institute's roadmap, some institutes periodically accept white paper submissions nominating new project topic ideas. Institutes typically require approval from the sponsoring federal agency for an open project call. Projects fall into one of three categories: roadmap projects that develop new capabilities aligned with an institute's goals, application projects that use and apply new capabilities, or education and workforce development projects that focus on increasing training opportunities and awareness of careers in the particular field.

Institutes fund projects by issuing requests for proposals (RFPs), typically once a year. Proposers do not need to be members of the institute at the time of project submission, but they do need to be a member by the time the award becomes effective. Award recipients are most commonly either a private company or a higher education institution, although frequently awards are granted to partnerships of members from both sectors. Awards typically range between $50,000 and $5 million, depending on the type of project, and require a cost-share by the grantee, often 50 percent; project duration can vary greatly.

Members of an innovation institution, who are independent of teams submitting proposals, have the opportunity to participate in deciding which projects to fund, alongside employees of the sponsoring federal agency. Though it varies by institute and RFP, proposals are evaluated along criteria such as technical feasibility, alignment with the roadmap, and benefit to other institutional members.

Accomplishments

Since the Manufacturing USA program was established in 2014, $3.1 billion, including $1.6 billion in private-sector support, has been invested in connecting 2,300 stakeholders across the manufacturing industry. Over 1,600 R&D projects have been conducted, which have contributed to 400 patents and license agreements and 270 technological advancements.

Recent achievements of the program include developing and manufacturing a new material for use in surgical masks and N95 respirators to address the COVID-19 pandemic, hosting a boot camp on using lab equipment to test passive photonic chips, and developing career exploration materials for students and educators. The PowerAmerica innovation institute helped establish a new semiconductor foundry, helping to address the domestic microchip shortage. The Institute for Advanced Composites Manufacturing Innovation sponsored a project that has developed a new thermoplastic for use in wind blades that will not only reduce costs and increase efficiency in wind turbine development but also enable more automation in production.

Success factors

Establishing multiple public-private partnerships, each focused on a specific industry in manufacturing, has enabled the Manufacturing USA program to both engage a broader membership and have more tangible accomplishments for industry. Additionally, the roadmaps that each institute uses to guide essentially all activities has helped them to hone their scope and readily define priorities. Lastly, the benefits that institution members receive, such as access to intellectual property and the governing board, make member recruitment much easier.

National Cybersecurity Center of Excellence

Technology Domain: Applied Cybersecurity

Region: USA

Participants (Public):

- National Institute of Standards and Technology
- U.S. Department of Homeland Security
- U.S. Airforce Research Laboratory
- U.S. Coast Guard
- U.S. Department of Transportation

Participants (Private):

- 30+ U.S. companies through the National Cybersecurity Excellence Partnership

Participants (Academic):

- Students, faculty, researchers, and administrators from K-12 and higher education communities through the Academic Engagement Community of Interest

Motivation and goals

The National Cybersecurity Center of Excellence (NCCoE), run by the National Institute of Standards and Technology (NIST), brings together government agencies, industry organizations, and academic institutions to collaborate on cybersecurity challenges and protect the nation's critical infrastructure. The collaborations create modular, easily adaptable cybersecurity solutions that demonstrate how to address pressing private-sector cybersecurity problems using commercially available technology. Through the production of standards-based, cost-effective, repeatable, and scalable cybersecurity solutions that address real business needs, the NCCoE aims to accelerate the adoption of secure technologies.

Operating model

NCCoE is part of the Applied Cybersecurity Division of NIST's Information Technology Laboratory. The MITRE Corporation provides operational support for the NCCoE through the National Cybersecurity federally funded research and development center (NCF). The NCCoE engages with the private sector, academia, and other government agencies through several avenues.

NCCoE hosts several communities of interest (COIs) through which public- and private-sector organizations share business insights, technical expertise, challenges, and perspectives. NCCoE relies on the COIs to identify and define problems that NCCoE should address. The NCCoE currently sponsors six sector-specific COIs and ten technology-specific COIs. Involvement in the COIs is voluntary. Most COIs meet virtually on a monthly or quarterly basis. Some COIs communicate through email channels more often to ask for feedback on topics of interest or draft guidance under development.

The primary activity of the NCCoE is the development and execution of projects that design, build, deploy, and document standards-based cybersecurity solutions for broad adoption in the private sector.

Each NCCoE project is led by a NIST Principal Investigator (PI). The PI provides oversight for the development of the project and manages a team of subject matter experts and the NCF operational support.

For each project, NCCoE works with industry to generate a technical description and scope of work for addressing a pressing cybersecurity challenge. During this phase, NCCoE solicits public comment on the draft project description to ensure that the project will be as broadly applicable as possible. At the end of this phase, NCCoE publishes a final version of the scope of work that outlines the cybersecurity challenge and a draft architecture on its website.

In the second phase, NCCoE assembles a team of industry organizations, government agencies, and academic institutions to address the scope of work. NCCoE releases a Federal Register Notice (FRN) that announces the collaboration opportunity and defines the desired capabilities of the team members. Potential team members are invited to respond to the FRN with a Letter of Interest (LOI). NCCoE accepts LOIs on a first-come basis. Collaborators that join the build team sign a Cooperative Research and Development Agreement (CRADA) with NCCoE to provide commercially available products and expertise to the project.

In the final phase, the NCCoE team builds a practical, usable, repeatable solution to address the cybersecurity challenge outlined in the statement of work. Industry collaborators provide support to install and configure their technologies. They also provide support throughout the build to address issues such as interoperability. As part of the development, the reference architecture is finalized. NCCoE documents the example solution in the NIST Special Publication 1800 series, which maps capabilities to the NIST Cyber Security Framework and details the steps needed for another entity to recreate the example solution.

Other federal agencies and some state governments, municipal governments, and not-for-profit organizations can collaborate with NIST to access the facilities, technologies, and expertise of the NCCoE. NCCoE engages the NCF to work with other government organizations on their project proposals. Approved projects from other government organizations receive research, development, engineering, and technical support from NCCoE, such as:

- Frameworks and implementation strategies to encourage and expedite adoption of effective cybersecurity controls and mechanisms;
- Collaboration across government, industry, and academia to accelerate effective innovation;
- Systems engineering to accelerate adoption of cybersecurity technologies; and
- Support for technology transfer of cybersecurity solutions.

In addition to contributing to individual projects, the NCCoE forms long-term relationships with industry organizations through the National Cybersecurity Excellence Partnership (NCEP) program. As part of the NCEP program, industry organizations pledge to contribute physical infrastructure such as hardware and software components; intellectual knowledge including best practices and lessons learned; or guest researchers to work side by side with federal staff in NCCoE’s test environments. NCEP organizations are accepted based on the feasibility of their proposed collaboration with NCCoE, their relevance to NCCoE’s strategy, and the potential to advance cybersecurity through their partnership. Qualified companies are invited to join a memorandum of understanding with NIST and NCCoE.

Accomplishments

NCCoE has successfully produced many cybersecurity solutions over the past decade.

One example is security for wireless infusion pumps. Designed to enhance patient care, wireless infusion pumps connect to a variety of systems, networks, and other devices. Through one of its cybersecurity projects, NCCoE demonstrated an approach that healthcare providers could use to enhance the security of the pumps. NCCoE collaborated with healthcare providers, information technology (IT) companies, and device manufacturers to develop cybersecurity guidance that would help strengthen the security of the wireless infusion pump ecosystem within healthcare facilities. The final NCCoE guidance is based on commercial off-the-shelf technologies that meet industry standards, as well as existing NIST/industry guidance and best practices. *Securing Wireless Infusion Pumps in Healthcare Delivery Organizations*, NIST Special Publication 1800-8, shows how biomedical, networking, cybersecurity and IT professionals can configure and deploy wireless infusion pumps to reduce cybersecurity risk. NCCoE's work has led several wireless infusion pump manufacturers to begin incorporating increased security capabilities into the next generation of pumps.

Successful collaborations with other government organizations have included:

- **U.S. Department of Homeland Security – Continuous Diagnostics and Mitigation Lab (CDM)**
  NCCoE provided technical expertise to assist the CDM program with developing, designing, implementing, and maintaining a dashboard to help federal agencies produce customized reports containing critical cybersecurity risks. The tool also consolidates information from each agency's dashboard to create a federal dashboard, providing a whole-of-government overview of its cybersecurity status across all civilian agencies.
- **U.S. Coast Guard – Cybersecurity Framework Profiles**
  With the help of NCCoE, the U.S. Coast Guard (USCG) collaborated with critical infrastructure subsectors that play a role in the Maritime Transportation System to develop voluntary Cybersecurity Framework Profiles (CFPs). The resulting USCG Maritime Profile, based on the NIST Cybersecurity Framework, addresses and helps industry mitigate risks in the joint mission areas of Maritime Bulk Liquids Transfer, Offshore Operations, and Passenger Vessel Operations. These CFPs identify and prioritize the subset of Cybersecurity Framework Subcategories that support operational priorities in each context, while giving organizations the flexibility to address subcategories in a way that makes the most sense for their unique risk posture.
- **U.S. Department of Transportation – Cybersecurity Framework Profile and Privacy Risk Assessment of Connected Vehicles**
  To support the deployment of connected vehicles (CVs) across the United States, NCCoE helped the U.S. Department of Transportation create the Cybersecurity Framework Profile and Privacy Risk Assessment Methodology (PRAM) for Connected Vehicle Environments (CVE). This project came out of the Intelligent Transportation System (ITS) Cybersecurity Research Program, which supports ITS deployers by conducting research that adopts or adapts implementation practices from other industries or develops new approaches specific to transportation when needed. The CVE Cybersecurity Framework Profile is being expanded to address the full scope of ITSs.

Success factors

NCCoE attributes its success in creating practical cybersecurity solutions to three key elements: collaboration, documentation, and advocacy and education. NCCoE ensures each of these elements is present in every phase of its projects by:

- Engaging in regular, robust collaboration with experts and innovators from various sectors in addition to the broader technology community to help identify and address businesses' most pressing cybersecurity challenges;
- Documenting its work across media such as the NIST Special Publication 1800 series, industry-specific cybersecurity papers, videos, and interactive guides, as well as mapping capabilities to the NIST Cybersecurity Framework and detailing the steps needed for another entity to recreate example solutions in part or in full; and
- Promoting what it does and how it does it, and teaching others ways to improve their cybersecurity posture.

Innovation Network for Fusion Energy

Technology Domain: Fusion Energy

Region: USA

Participants (Public):

- Ames Laboratory
- Argonne National Laboratory
- Brookhaven National Laboratory
- Fermi National Accelerator Laboratory
- Idaho National Laboratory
- Lawrence Berkeley National Laboratory
- Lawrence Livermore National Laboratory
- Los Alamos National Laboratory
- National Energy Technology Laboratory
- National Renewable Energy Laboratory
- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory
- Princeton Plasma Physics Laboratory
- Sandia National Laboratories
- Savannah River National Laboratory
- SLAC National Accelerator Laboratory
- Thomas Jefferson National Accelerator Facility

Participants (Private):

- 17+ fusion energy companies since 2019

Motivation and goals

The Innovation Network for Fusion Energy (INFUSE) is a public-private partnership sponsored by the Fusion Energy Sciences (FES) program in the DOE Office of Science that gives private-sector fusion energy companies access to the technical and financial support necessary to move fusion energy technologies forward by leveraging the unique capabilities present in the DOE National Laboratories. INFUSE streamlines the process by which companies access the fusion expertise and capabilities of ten DOE laboratories. The fusion capabilities and expertise currently available to companies include:

- Enabling Fusion Technologies
- Materials Science
- Plasma and Engineering Diagnostics
- Modeling and Simulation
- Experimental Capabilities

Operating model

INFUSE aids companies through Request for Assistance (RFA) partnership awards that grant access to unique capabilities at DOE laboratories. RFA awards provide funding directly to participating DOE laboratories to help eligible private-sector companies overcome specific critical scientific and technical challenges to accelerate the development of cost-effective fusion energy systems. The awards are not intended to help companies with commercialization efforts nor provide access to research services, expertise, or equipment that is readily available elsewhere.

INFUSE RFA partner awards are available to U.S.-based private organizations with U.S. ownership and U.S.-based private organizations with foreign ownership as long as the organization's participation in INFUSE is in U.S. economic interests. An organization may submit up to five RFAs to a single RFA call across any of the capability areas listed above. RFA calls are managed by a consortium of FES-funded laboratories led by Oak Ridge National Laboratory (ORNL) and Princeton Plasma Physics Laboratory (PPPL). ORNL and PPPL organize the RFA review process to assess the value of the work from the applicant's perspective and the impact to fusion research overall. ORNL and PPPL submit the results to FES for final selection. Competitive selection follows DOE Office of Science review criteria.

Most requests are for single year awards between $50,000 and $200,000, however, the program allows for awards up to $500,000 in total value and/or a duration of 24 months for work deemed to be of critical value to the applicant. DOE requires a 20 percent cost share from successful applicants for each RFA, which can come in the form of cash, equipment, or in-kind contributions. The cost share is calculated based on the full project cost (the sum of the government share and the private partner share). Upon award, RFA applicants must accept either the DOE-Standard Cooperative Research and Development Agreements (CRADAs) (for large businesses and those with foreign influence) or the INFUSE Small Business Award CRADA (for small business/non-profit awardees with no foreign influence), which govern intellectual property and other terms related to working with DOE laboratories. Factors including but not limited to, the scope of work of the application and the applicant's foreign affiliations/ownership, may lead to the negotiated use of alternate CRADA provisions. The FES program is committed to reducing the processing time needed for laboratory partnership awards so that the terms and conditions in the INFUSE Small Business Award CRADA or DOE-Standard CRADA are not negotiated except in extreme cases and only at DOE's discretion.

All work on INFUSE awards must be performed in the United States. Products that make use of intellectual property developed under the INFUSE program must be substantially manufactured in the United States. Applicants are the sole recipient of technology transferred to them as a result of work completed under awards in the INFUSE program. Any transfer of technology or data to foreign entities requires specific authorization under federal export control laws and regulations.

Accomplishments

This INFUSE program started in FY 2019 and has completed six rounds of funding since its inception. The first projects wrapped up in the first half of 2021. As such, the program has little information available on the outcomes of the projects and their impacts on the private-sector fusion energy companies. The INFUSE program has had six RFA calls. Each call has resulted in 8-12 awards. Through the INFUSE program, the DOE National Laboratories have partnered with at least 17 private-sector fusion energy companies. The partnerships between private-sector fusion energy companies and DOE labs have resulted in at least two publications being accepted by leading plasma physics journals, with more in progress. Additionally, one participating company credits its INFUSE award with helping to secure additional private-sector funding.

Success factors

Providing access to the DOE labs gives private-sector companies the opportunity to advance the development of their fusion energy products with expertise and technologies to which they would not otherwise have access. This approach to federal support guarantees that the government is contributing to this sector in a manner that only the government can. In this way, the INFUSE program has the potential to significantly advance the state of fusion energy technology.

Accelerating Medicines Partnership® (AMP®)

Technology Domain: Biopharmaceuticals

Region: USA

Participants (Public):

- National Institutes of Health (NIH)
- U.S. Food and Drug Administration (FDA)
- European Medicines Agency

Participants (Private):

- 27 pharmaceutical companies

Participants (Non-Profit):

- 27 non-profit organizations, including PPP leadership by Foundation for the NIH (FNIH)

Motivation and goals

The Accelerating Medicines Partnership® (AMP®) was launched in 2014 as a public-private partnership between the NIH, the FDA, multiple biopharmaceutical and life sciences companies, non-profit entities, and other organizations. It aims to compress timelines, reduce costs, and increase success rates of new targeted therapies for some of the most significant diseases (such as Alzheimer's disease and autoimmune and immune-mediated diseases). Specifically, it seeks to better understand biological pathways and validate information that could be relevant for the development of multiple therapeutics.[45]

Operating model

The novelty of this PPP is that it brings together the public and private sectors to share open science practices and resources and accelerate the discovery of new drug targets, biomarkers, and disease subtypes. The partnership is managed by FNIH but leverages people and resources from NIH, private companies, and non-profit entities.

Five programs were established at the onset of AMP (with two added later) based on the NIH's strategic decision to bolster funding and pursue safe and effective treatments for major diseases that affect a large number of people. The lack of treatments signaled a need to change how the academic, biopharmaceutical, and government sectors collaborate to expedite therapeutic development. Thus, FNIH was tasked with leading the partnership among NIH (the primary funder), private companies, and non-profit entities and managing the steering committees for each of the now seven programs. Each steering committee has representation from the public and private partners participating in their related program, and they meet regularly to review ongoing progress and milestones. The steering committees are ultimately directed by an AMP Executive Committee comprised of representatives from NIH,

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[45] NIH, "Accelerating Medicines Partnership® Overview," https://www.nih.gov/research-training/accelerating-medicines-partnership-amp#overview.

participating industry leaders, the FDA, the European Medicines Agency, and non-profit organizations.[46] For each of the programs, at least two phases are involved: one that involves understanding disease drivers and identifying/validating biomarkers, and a second that involves proof-of-concept trials. In addition to NIH funding, FNIH helps to secure private sector partner contributions. So far, $768 million has been spread among the programs, with at least half of each program's funding provided by a relevant entity within NIH, and the rest provided by private-sector partner contributions (including in-kind contributions via equipment, facilities, etc.).

Accomplishments

As of 2019, it was announced that $360 million had been spent by AMP to develop "tools to speed up drug discovery for rheumatoid arthritis, lupus, diabetes, Alzheimer's disease, and Parkinson's disease."[47] However, the timeline for AMP programs to achieve results extends through 2027. The six existing programs and their objectives are:

- Alzheimer's disease (AD 1.0 Biomarkers in Clinical Trials and AD 2.0)
  - Enable precision medicine research for Alzheimer's disease through deep and longitudinal molecular analyses across diverse populations.
- Common Metabolic Diseases (CMD)
  - Analyze large-scale genetic and genomic data to ultimately therapeutically address multiple metabolic diseases that share common pathogenic drivers and overlapping molecular pathways.
  - Build upon Type 2 Diabetes (T2D) program.
- Autoimmune and Immune-Mediated Diseases (AIM)
  - Accelerate identification and validation of specific drug targets in autoimmune diseases that may share immune and inflammatory pathways.
  - Build upon Rheumatoid Arthritis, Systemic Lupus Erythematosus (RA/SLE) program.
- Parkinson's disease (PD)
  - Generate and combine data from thousands of PD patients across studies, to identify biomarker tools that will be informative to clinical trials of novel treatments.
- Schizophrenia (SCZ)
  - Validate biomarkers needed to identify people at risk for schizophrenia.
- Bespoke Gene Therapy Consortium (BGTC)
  - Foster development of gene therapies intended to treat rare genetic diseases, which affect populations too small for viable commercial development.

A visualization of the programs' intended timeframes is shown in Figure 1 below.

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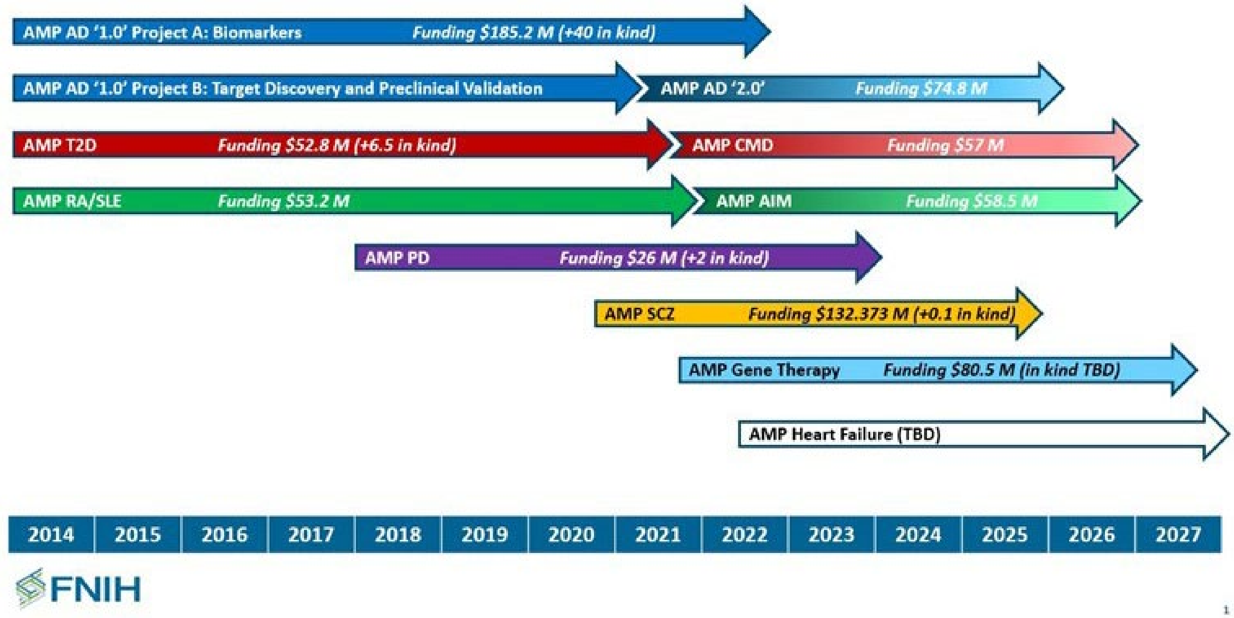
[46] FNIH, "Governance and Resources," https://fnih.org/our-programs/amp/governance.
[47] Elie Dolgin, "Massive NIH–Industry Project Opens Portals to Target Validation" (1 March 2019), *Nature*, https://www.nature.com/articles/d41573-019-00033-8.

Figure 1: Timeline for AMP programs



Success factors

Data and information sharing that allows stakeholders across sectors to jointly advance disease research is a key factor in the success of AMP. For instance, the high-quality and novel data generated during the first AMP Alzheimer's program was made public through a centralized data infrastructure and data-sharing platform: the AD Knowledge Portal, and the portal-linked, open-source platform Agora. The wide availability of these data has led to new insights into disease processes, with more than 3,000 researchers around the world from academic, biotechnology, and pharmaceutical industry sectors using these data in research on Alzheimer's and related dementias.[48] This unprecedented level of public-private disease-specific data collection and sharing is proving invaluable for the other AMP programs as well.

Partnership for Accelerating Cancer Therapies (PACT)

Technology Domain: Biopharmaceuticals

Region: USA

Participants (Public):

- National Cancer Institute (NCI)
- National Institutes of Health (NIH)
- U.S. Food and Drug Administration (FDA)

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[48] NIH, "NIH Invests in Next Iteration of Public-Private Partnership to Advance Precision Medicine Research for Alzheimer's Disease" (2 March 2021), https://www.nih.gov/news-events/news-releases/nih-invests-next-iteration-public-private-partnership-advance-precision-medicine-research-alzheimers-disease.

Participants (Private):

- AbbVie, Inc
- Amgen, Inc
- Boehringer-Ingelheim Pharma GmbH & Co. KG
- Bristol-Myers Squibb Company
- Celgene Corporation
- Genentech, Inc.
- Gilead Sciences, Inc.
- GlaxoSmithKline plc
- Janssen Research & Development LLC
- Novartis Institutes for BioMedical Research, Inc.
- Sanofi
- Pfizer, Inc.

Participants (Non-Profit):

- Foundation for the NIH (FNIH)

Motivation and goals

In February 2018, the NIH, FNIH, and 12 pharmaceutical companies launched the Partnership for Accelerating Cancer Therapies (PACT): a five-year public-private research collaboration. This PPP, part of the Cancer Moonshot Research Initiatives,[49] aims to identify, develop, and validate biomarkers to advance new therapies and treatments that activate the immune system to attack cancer.

Immunotherapies have been effective in treating certain cancers, but they do not work for all patients. Biopharmaceutical companies have invested in these therapies, hoping to provide alternative options to patients for whom traditional cancer therapies do not work. To maximize those who could benefit from immunotherapies, development and standardization of biomarkers is being pursued to understand how immunotherapies work and predict patient responses to treatment.

PACT has the following core goals:[50]

- Provide a set of basic biomarker modules for uniform clinical application.
- Establish a network of labs to coordinate, conduct, validate and standardize biomarker assays (tests).
- Fund development of standardized biomarkers for immune profiling and exploratory biomarker assays.
- Incorporate biomarkers and data collection standards into clinical trials and coordinate adoption of these biomarkers and standards across the immuno-oncology community.
- Create a database integrating biomarker and clinical data to enable pre-competitive correlative biomarker analyses.

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[49] In 2016, then-Vice President Joe Biden launched the Cancer Moonshot with three goals: to accelerate scientific discovery in cancer, to foster greater collaboration, and to improve the sharing of data.
[50] FNIH, "Partnership for Accelerating Cancer Therapies (PACT)," https://fnih.org/our-programs/partnership-accelerating-cancer-therapies-pact.

- Facilitate information sharing across government, academia, and industry to better coordinate clinical efforts, align investigative approaches, eliminate duplicative efforts, and support execution of more high-quality trials.

Operating model

Similar to AMP, NIH initiated PACT along with FNIH and leading pharmaceutical companies to serve as a pre-competitive research partnership. PACT partners from public and private sectors are funding and conducting research and development to standardize biomarker tests so they can be used effectively in clinical trials conducted anywhere in the cancer field. PACT also provides scientific coordination by sharing results and information across the immune-oncology field and aligning investigative approaches.

PACT has established protocols for its private partners to perform systematic clinical testing of biomarkers to advance understanding of cancer treatment response and resistance to immunotherapies. The research is also leading to the integration of immune and other related oncology biomarkers into clinical trials. This approach helps ensure that data are generated consistently and can be reproduced and compared across trials. PACT also facilitates information sharing between public and private sectors to ensure consistency and efficiency in clinical approaches and to achieve more high-quality trials.

FNIH manages the partnership, with the FDA serving in an advisory role. A total of $220 million has been contributed toward this effort, with a $160 million investment by NCI to develop Cancer Immune Monitoring and Analysis Centers (CIMACs) and to establish the Cancer Immunologic Data Commons (CIDC), a centralized database. This money also supports immunotherapy trials conducted by PACT's private-sector partners. FNIH has raised an additional $60 million among industry partners to supplement NIH funding.[51] Even after the five-year dedicated funding for PACT ends, the CIMACs and CIDC will live on for the benefit of future cancer researchers, fulfilling the partnership's goal to standardize cancer data collection, centralize cancer data and analyses, and share cancer data and information among as many relevant stakeholders as possible, especially to improve clinical trials. Douglas R. Lowy, MD, Acting Director of NCI notes that "this partnership, and the data the partners have committed to making publicly accessible to the broader research community, will facilitate our continued progress in helping to find the cancer treatments that benefit the greatest number of patients."

Accomplishments

PACT is on track to have an impact within its original five-year plan. Work is still underway for the partnership to achieve its goals and milestones but there is clear progress. PACT is currently at the point of soliciting clinical trials to provide biospecimens for exploratory deep immunoprofiling analysis. Data from this immunoprofiling, along with clinical trial data, will be placed into the centralized database and can be used to validate existing biomarkers to develop newly validated biomarkers. Development and validation of these biomarkers will allow the immuno-oncology field to more accurately pair patients with novel immunotherapies.

In late 2021, three years after PACT was initiated, PACT awarded a grant to Oxford BioDynamics to finish

[51] David Wholley, "The Role of Public-Private Partnerships in the Cancer Moonshot: How PACT Can Transform Cancer Immunotherapy Clinical Trials" (21 September 2018), FNIH, https://fnih.org/news/announcements/role-public-private-partnerships-cancer-moonshot-how-pact-can-transform-cancer.

developing their novel EpiSwitch® diagnostic platform to accurately predict a patient's response to Immune Checkpoint Inhibitors (ICIs) from a routine blood sample. In contrast, existing modes of testing patient response to immunotherapies could not predict reactions without requiring invasive biopsies. The two-year $910,000 PACT grant is meant to fund the finalization and use of this technology in the analysis of primary and acquired resistance to ICI in several PACT-led trials. As Dr. Stacey Adam at FNIH noted, the diagnostic platform can ultimately allow "for better assignment of patients to specific immunotherapies to treat their cancer."[52]

Success factors

PACT has had a clear, specific purview with achievable goals. Furthermore, the goals focus on an array of coordinated outputs: establishing standardized biomarkers, biomarker tests, and clinical trials; enforcing these standards among immuno-oncology stakeholders; creating a centralized data repository for biomarker and clinical data; and promoting the sharing of information within the immune-oncology community to minimize inconsistency and redundancy.

While PACT is similar in structure to AMP, which is also led by FNIH and involves many of the same industry partners, its focus is narrower, and it does not involve sub-programs—thus making it inherently less complex. The partnership's recent solicitation for clinical trials suggests that it is moving through its goals and is at the point of incorporating biomarkers and data collection standards into selected clinical trials. This is due in part to the group of private-sector partners who all have a stake in seeing immunotherapies succeed as quickly as possible.

DARPA Grand Challenge

Technology Domain: Vehicle autonomy

Region: USA

Participants: (Private, 2004 Challenge)

- Elbit, Ltd
- Digital Auto Drive
- The Golem Group
- Oshkosh Truck Corporation
- SciAutonics
- ENSCO, Inc
- Axion Racing
- TerraHawk

Participants: (Academic, 2004 Challenge)

- Carnegie Mellon

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[52] Business Wire, "Oxford BioDynamics Awarded US FNIH Grant to Apply EpiSwitch® Immune Health Test for Improved Prediction of Patient Response to Immune Checkpoint Inhibitor (ICI) Cancer Therapies" (31 August 2021), https://www.businesswire.com/news/home/20210831005447/en/Oxford-BioDynamics-Awarded-US-FNIH-Grant-to-Apply-EpiSwitch%C2%AE-Immune-Health-Test-for-Improved-Prediction-of-Patient-Response-to-Immune-Checkpoint-Inhibitor-ICI-Cancer-Therapies.

- Caltech
- University of Florida
- University of Berkeley
- Virginia Tech
- University of Louisiana
- Palos Verdes High School

Motivation and goals

Autonomous vehicles have long been viewed as a potential substitute for the use of soldiers in hazardous military operations. In 2004, DARPA launched the first autonomous vehicle competition to accelerate development of the technological foundations for autonomous vehicles, with the long-term goal of being able to use autonomous vehicles for hazardous miliary operations such as supply convoys.[53] The foundational technologies for vehicle autonomy—machine vision, artificial intelligence, sensors, radar, and others—existed prior to the DARPA challenge but concerted effort to refine and integrate these technologies into fully autonomous vehicles was limited and not a primary focus of commercial vehicle makers. DARPA hoped the challenge would have the twofold effect of accelerating autonomous technology development and generating interest within industry and technical circles in the use of autonomous vehicles for defense and in the broader economy.

Operating model

The DARPA Grand Challenge included three key operating features: (1) announcement and information sharing with potential competitors to generate participant interest, (2) down selection of competitors via increasing levels of evaluation of the potential benefits of competitor vehicles, and (3) repetition of the final competition based on initial success.

DARPA announced the Grand Challenge in the summer 2002.[54] Using its prize authority, DARPA announced it would award $1 million to the first team whose vehicle completed the planned competition route. In February 2003, DARPA held a competitors' conference in Los Angeles to officially announce the challenge and provide details for the competition, including route conditions expected to be encountered by competing vehicles and the expectations for performance.[55] Teams interested in competing were required to submit applications and technical papers detailing their proposed vehicles. DARPA evaluated each paper to assess its compliance with contest rules and the degree to which the proposed autonomous vehicle technology would be of interest to the Department of Defense (DOD). Teams were further down selected through a physical Qualification, Inspection, and Demonstration (QID) process to ensure that each vehicle complied with all competition rules and was safe to operate. In March of 2004, DARPA announced the final 15 teams that had qualified for the challenge.[56]

The actual challenge required an unmanned autonomous vehicle to travel at tactically relevant speeds over distance. The winner would be the first team that demonstrated a fully autonomous, unmanned ground vehicle capable of traveling across terrain similar to that encountered by U.S. forces in overseas

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[53] DARPA, "The DARPA Grand Challenge: Ten Years Later" (13 March 2014), https://www.darpa.mil/news-events/2014-03-13.
[54] R. Behringer, "The DARPA Grand Challenge – Autonomous Ground Vehicles in the Desert," *5th IFAC/EURON Symposium on Intelligent Autonomous Vehicles*, (5-7 July 2004).
[55] DARPA, "Grand Challenge 2004 Final Report" (30 July 2004).
[56] Ibid.

operations. The course was a total of 142 miles in desert terrain.[57] Competitors also had to complete the course in under 10 hours to be eligible for the prize.

None of the participants of the 2004 competition completed the course. The farthest any of the teams traveled was 7.4 miles, achieved by the Carnegie Mellon Red Team vehicle, less than five percent off the full length of the course.[58] Though none of the teams finished the 2004 challenge, the results were promising, and the first competition provided an invaluable learning environment for competing teams. DARPA decided to hold a second challenge in October of 2005. Five vehicles representing four teams completed this second challenge. Four of these completed the challenge withing the 10-hour time limit. In 2007, DARPA repeated the challenge again, this time focusing on autonomy within populated urban environments, requiring entrant vehicles to obey state driving laws and including other, more restrictive rules not present in the 2004 and 2005 challenges. For the 2007 challenge, officially called the DARPA Urban Challenge, DARPA provided $1 million in development funding to selected participants.[59] Many of the teams in the 2007 challenge consisted of joint university-industry partnerships, such as the winning Tartan Racing team, a collaboration between Carnegie Mellon University and General Motors Corporation.

Accomplishments

The DARPA Grand Challenge is credited with spurring research into autonomous vehicles.[60] In the early part of the 21st century, as the challenge was being conceived and run, driverless vehicles were considered the domain of science fiction.[61] Eighteen years after the first DARPA Challenge, commercial interest in autonomous commercial vehicles is universal among major automobile manufacturers, and autonomous or partially autonomous vehicles are widely available to consumers. Non-passenger vehicles ranging from delivery robots to autonomous vehicles in factories are also making use of the technology whose inspiration can be traced, directly or indirectly, to the original DARPA challenges. Ironically, although some later challenge participants continued to develop autonomous technology for defense applications,[62] the effect of the Grand Challenge on adoption of autonomous vehicles by the military is less compelling.[63]

The success of the challenge in spurring innovation led to new DARPA challenges. In addition to the 2007 challenge focused on vehicle autonomy in urban areas, the agency would go on to fund challenges in such diverse areas as communications, robotics, cybersecurity, and subterranean technology.[64]

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[57] Ibid.
[58] Wikipedia, "DARPA Grand Challenge (2004)," https://en.wikipedia.org/wiki/DARPA_Grand_Challenge_(2004).
[59] Wikipedia, "DARPA Grand Challenge (2007)," https://en.wikipedia.org/wiki/DARPA_Grand_Challenge_(2007).
[60] CSIA, "National Security Implications of Leadership in Autonomous Vehicles" (June 2021).
[61] *Wired*, "Inside the Races That Jump-Started the Self-Driving Car" (10 November 2017).
[62] TORC Robotics, one of the six finishers of the Urban Challenge, continued to develop utility-vehicle-scale autonomous capabilities for Marine Corps platforms. DARPA, "The DARPA Grand Challenge: Ten Years Later" (13 March 2014), https://www.darpa.mil/news-events/2014-03-13.
[63] Global Defense Technology, "The Long Road to Autonomy" (July 2019) https://defence.nridigital.com/global_defence_technology_jul19/darpa_s_grand_challenge_at_15_how_far_have_autonomous_military_vehicles_come
[64] DARPA, "Prize Challenges," https://www.darpa.mil/work-with-us/public/prizes.

Success factors

A number of factors contributed to the success of DARPA's challenges. DARPA selected an area in which the underlying technologies were reasonably mature but had not been systematically applied to the use case of vehicle autonomy. To help ensure interest in the competition, DARPA provided a significant prize—$1 million for the first competition—and invested effort in participant education and recruitment. The competition itself relied on a multi-stage review of entrants, helping to ensure that those participating in actual races were the most likely to succeed. Finally, DARPA set difficult but achievable technical goals for the program and let competition outcomes guide how the program proceeded. When no competitors completed more than five percent of the course in 2004, DARPA reran the competition in 2005, and then in 2007 introduced a new but related autonomous vehicle challenge. As with all DARPA sponsored R&D, the Grand Challenge specified the goal and not the approach, leaving the solution ideas up to creativity of individual participant teams.

National Science Foundation Convergence Accelerator

Technology Domain: Various (R&D)

Region: USA

Participants (Public):

- National Science Foundation
- U.S. Department of Defense

Participants (Private):

- About 50 companies within the first three years of the program

Participants (Non-Profit):

- About 30 non-profits within the first three years of the program

Participants (Academic):

- About 150 higher education institutions within the first three years of the program

Motivation and goals

The Convergence Accelerator (CA) is a program sponsored by the National Science Foundation's (NSF) Technology, Innovation and Partnerships Directorate intended to capitalize on research and discovery by funding projects to solve large societal challenges. The focus of the program is to build on foundational research in a way that has impact on society at scale. Grantees come from all sectors to collaborate, receive mentoring, and build partnerships so they can turn R&D into a user-inspired prototype that can achieve real societal impact.

Over the first three years of the program, projects have been focused on finding solutions relevant to one of six broad challenge areas that lie at the intersection of societal need and advanced technology:

- Open knowledge networks
- AI and the future of work
- Quantum technology
- AI-driven innovation via data and model sharing
- Networked blue economy
- Trust and authenticity in communication systems

For the first time in this program, one upcoming track for the 2022 cohort is being co-sponsored by the U.S. Department of Defense (DOD).

Operating model

Each year, the CA program issues a Dear Colleague Letter/Request for Information to the public soliciting ideas for national-scale societal changes for consideration as track topics. Proposals are received from all sectors, though proposers do not necessarily intend to submit a CA research project proposal later. Following a formal proposal review process, selected track topic proposers are given a grant, typically less than $100,000, to facilitate a workshop to foment discussion among stakeholders from different sectors and disciplines and to refine the topic idea. From those workshops, track topics for the following year's cohort are chosen by CA program staff. For the first three years of the program, there were two track topics selected annually; for the program's upcoming fourth year, there are four, including one sponsored jointly with DOD.

NSF then solicits proposals from teams across sectors to conduct research aligned with one of the tracks. There are two phases to the program. For Phase 1, NSF awards nine-month grants of $750,000 per team. While grantees can come from all sectors, the overwhelming majority of principal investigators are from higher education. Still, many teams involve secondary institutions or subcontractors, which are often from the private or non-profit sectors.

During Phase 1, teams meet regularly to share ideas and receive training on identifying end users and end user needs and on understanding how their research output can be oriented toward significant societal impact. Additionally, teams regularly meet with and receive guidance from program directors and coaches with a depth of expertise in industry and venture capital. At the end of Phase 1, teams present their project accomplishments at an expo where they connect with stakeholders from different sectors, who may be future partners, funders, or users.

Teams that complete Phase 1 are then eligible to apply for a Phase 2 grant. These two-year grants are typically for about $5 million, which is the maximum amount that can be requested. At this stage, teams are required to have formed partnerships, primarily from industry and government groups, that will play a specific role in transitioning research into a practical deliverable that will lead to sustained societal impact. Teams are initially given funding for the first year of Phase 2, with the second year's funding released pending an assessment of performance.

Accomplishments

Since welcoming its first cohort in 2019, the CA program has awarded grants for six different tracks. Each track has awarded 10-25 grants for Phase 1 teams and about five grants for Phase 2 teams. The first cohort will finish in September 2022, so there is no quantifiable data yet on the impact of this program, but it is expected to have successfully brought together many academic researchers, venture capitalists, and industry experts in the quest to develop a product with a real-world impact on a broad societal challenge. Projects in the works for the Quantum Technology track include an integrated photonic control engine that will be useful in miniaturizing quantum computers and interconnects to connect quantum computers located several kilometers apart.

Success factors

The CA program's unique approach to supporting convergent research has developed many new partnerships between academic institutions, nonprofits, state and local governments, and private companies. Not only are many of the teams composed of multi-sector institutions but also the teams benefit from the expertise of program directors and coaches who collectively have decades of experience working in industry, managing other federal business development programs, and fostering partnerships. Additionally, the principle of coopetition between teams is tantamount to the program's expected success in developing innovative, use-inspired tools aimed at solving some of the greatest challenges humans face.

Lastly, the focus on building upon foundational research in a way that has impact on society at scale is somewhat novel for NSF-funded projects. Many academic researchers are less familiar with conducting this kind of translational research, making CA participation an especially valuable opportunity for them to work with industry leaders who have commercial experience.

COVID-19 High Performance Computing Consortium

Technology Domain: High Performance Computing for Public Health

Region: USA

Participants (Public):

- NASA
- National Science Foundation (NSF)
- Department of Energy (DOE) National Labs
    - Argonne National Laboratory
    - Lawrence Livermore National Laboratory
    - Los Alamos National Laboratory
    - Oak Ridge National Laboratory
    - Lawrence Berkeley National Laboratory
    - Sandia National Laboratories
    - Idaho National Laboratory

Participants (Private):

- IBM
- Amazon Web Services
- AMD
- DE Shaw Research
- Dell Technologies
- Google Cloud
- Hewlett Packard Enterprise
- Microsoft
- NVIDIA
- Intel

Participants (Academic):

- 14 U.S. research universities
- Three European research centers
- Two governmental research agencies in Asia

Motivation and goals

To combat COVID-19 and its adverse public health impacts, the White House Office of Science and Technology Policy (OSTP) created the COVID-19 High Performance Computing (HPC) Consortium in March 2020 in less than a week with no formal legal agreements.[65] The consortium gave COVID-19 researchers from academia, nonprofits, and industry access to computing resources, including super computers, to accelerate scientific advances for combating the virus. Researchers did not need to be affiliated with consortium members to apply for resources. Consortium members spanned industry,

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[65] Jim Brase, et al., "The COVID-19 High-Performance Computing Consortium," *Computing in Science & Engineering* (January/February 2022), [The COVID-19 High-Performance Computing Consortium (computer.org)]

federal agencies, national laboratories, and academia, all of which contributed significant computer resources, services, and skills to the effort.[66] Consortium members provided high performance computing resources up to and including supercomputers. The PPP was formed to serve a highly specialized need quickly by mobilizing resources to meet that need. The consortium is now in the process of being sunsetted, and as of May 1, 2022, is no longer accepting requests for computing resources and services to support the pandemic response.[67]

Operating model

The HPC Consortium was formed with remarkable speed, reflecting the urgency of its task. From preliminary discussion to the start of the first project took 15 days (Figure 2). The PPP was able to get off the ground quickly because of the preexisting relationships among the founding members. Additionally, the consortium was created without formal agreements between members. Even though there were no formal agreements between consortium members, the consortium was able to create an effective governance model.[68] According to James Brase, "Essentially, all potential members agreed to a simple statement of intent that they would provide their computing facilities' capabilities and expertise at no cost to COVID-19 researchers, that all parties in this effort would be participating at risk and without liability to each other, and without any intent to influence or otherwise restrict one another."[69]

The inspiration for the partnership came in March 2020, when IBM proposed organizing the HPC community to accelerate progress and understanding in the fight against COVID-19 by connecting researchers with organizations that had substantial computing capabilities and resources.[70] The White House OSTP, DOE, and NSF were quick to support the proposal. The groundwork was laid in the following days. On March 17, 2020, DOE was tasked by OSTP with the creation of the consortium. To handle the high volume of proposals, they leveraged XSEDE's (Extreme Science and Engineering Discovery Environment) Resources Allocation System (XRAS) to serve as the access point for the proposals because it handled nearly 2,000 application requests annually. By March 22, 2020, XSEDE implemented a complete proposal submission and review process, supported by the XRAS service, which was ready to accept proposal submissions. The launch was announced by the President on March 22, 2020.[71]

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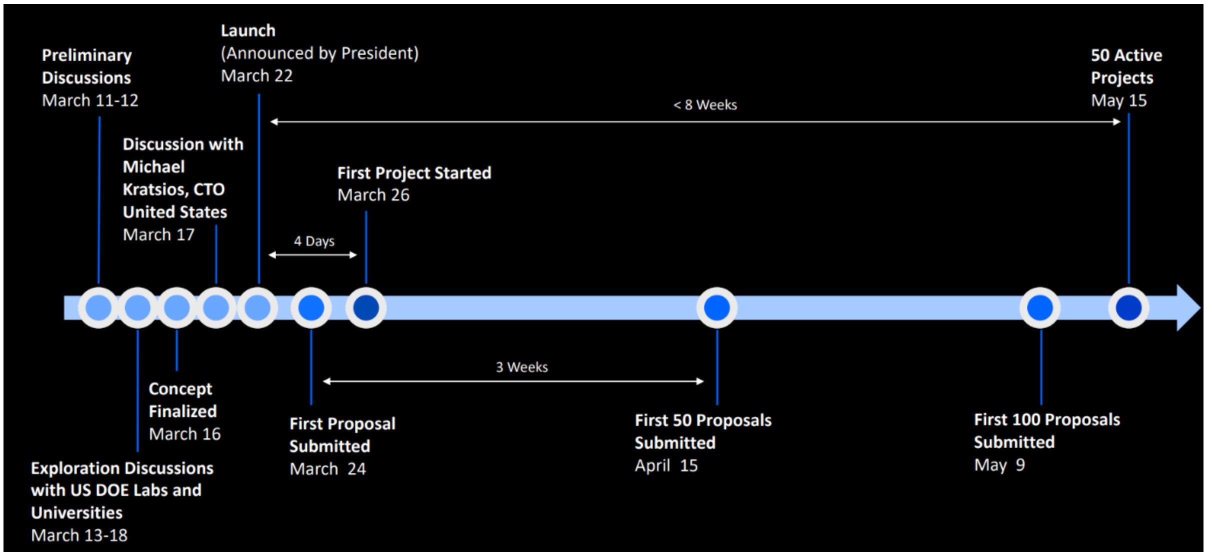
[66] COVID-19 HPC Consortium, "Who We Are," Who We Are | COVID-19 HPC Consortium (covid19-hpc-consortium.org)
[67] COVID-19 HPC Consortium, "Announcement: The Consortium Is No Longer Accepting Proposals" (1 May 2022), https://covid19-hpc-consortium.org/blog/announcement-covid-19-hpc-consortium-is-no-longer-accepting-requests.
[68] Brase, et al. (January/February 2022).
[69] James Brase, et al, "The Full Story of the COVID-19 High Performance Computing Consortium ", *COVID-19-HPC Consortium* (March 2022) News & Press | COVID-19 HPC Consortium (covid19-hpc-consortium.org)
[70] Brase, et al. (January/February 2022).
[71] Brase, et al. (March 2022).

Figure 2: Timeline of HPC Consortium (2020)[72]



The HPC Consortium created an Executive Board composed of a subset of founding members. The Executive Board initially met weekly, later monthly, to review progress, approve recommendations for new members and affiliates, and provide guidance on future directions and activities of the consortium. There were two committees below the Executive Board. The first was the Science and Computing Executive Committee, consisting of individuals from IBM, DOE, NSF, Lawrence Livermore National Laboratory (LLNL), and the National Center for Supercomputing Applications (NCSA). It was responsible for day-to-day operations of the consortium including overseeing proposal review and the computer matching process, as well as tracking project progress.[73] The other was the Membership Committee, which reviewed requests for organizations and individuals to become members or affiliates of the consortium.

Research proposals were submitted through a dedicated XSEDE webpage and were required to have the following sections:[74]

- Scientific/technical goal that provides near-term benefits (<6 months)
- Estimates of compute, storage, and other resources
- Support needs
- Team preparedness

Upon submission, research proposals were reviewed by the Scientific Review Subcommittee, a part of the Science and Computing Executive Committee, composed of subject matter experts, who evaluated proposals based on the following criteria:[75]

- Potential benefits to the COVID-19 response

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[72] Oak Ridge National Laboratory, "The COVID-19 High-Performance Computing Consortium on Summit" (September 2021), [ASCAC-Covid_Messer_ASCAC_202109.pdf (osti.gov)]
[73] Brase, et al. (January/February 2022).
[74] XSEDE, "HPC Resources Available to Fight COVID-19" (6 May 2022), [COVID-19 HPC Consortium - XSEDE]
[75] Brase, et al. (March 2022).

- Feasibility of the technical approach
- Need for high-performance computing
- High-performance computing knowledge and experience of the proposing team
- Estimated computing resource requirements

After review by the Scientific Review Subcommittee, requests were then sent to OSTP for additional vetting, with the Science and Computing Executive Committee making final recommendations to the Executive Board for approval. When a research proposal was accepted, the Computing Matching Subcommittee, a part of the Science and Computing Executive Committee, matched the computing needs of the proposal to consortium members with appropriate available resources.

Accomplishments

Since its creation, the COVID-19 HPC Consortium has supported 115 projects covering technical areas from understanding SARS-CoV-2 to optimizing medical supply chains and resource allocation.[76] By the end of the 2021 calendar year, the projects funded by the HPC Consortium led to more than 70 publications, datasets, and other products.

As an example, the consortium provided computation assistance to a project that modeled urban transportation systems for a return to operations. This project modeled the New York City metropolitan area travel patterns before and during the pandemic then used those data to predict trends after travel restrictions lifted. This information was then conveyed to the New York Metropolitan Transportation Authority. This project focused on applying transportation system modeling resources developed at Lawrence Berkeley National Lab. The project used the BEAM (Behavior, Energy, Autonomy, Mobility) model, which simulated private car travel, all transit modes, non-motorized travel, ride-hailing, and multimodal trips.[77]

The consortium also supported analysis of how SARS-CoV-2 binds to various substrates. Researchers at Stony Brook University worked with XSEDE, an organization under the NSF. The objective of the project was to help prevent the spread of COVID-19 and save lives by developing more efficient personal protective equipment. The research team sought to analyze the effects of saline concentrations on COVID-19's spike-protein. Prior to the help of the consortium, the project was running into computational limits with its software because the team was trying to do microsecond modeling. Although the project showed no denaturing of the protein as saline concentrations increased, it identified differences in the residues that required further investigation.[78]

The consortium facilitated the partnership between the University of Notre Dame, Los Alamos National Laboratory (LANL), and Microsoft to analyze and enhance CORD-19 and additional coronavirus-related datasets; upon completion, this analysis was redistributed for further scholarly analysis.[79] Before the

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[76] Brase, et al. (January/February 2022).
[77] COVID-19 HPC Consortium, "Modeling and Simulation of Urban Transportation Systems for Return to Operations" (6 May 2021), Modeling and simulation of urban transportation systems for return to operations | COVID-19 HPC Consortium (covid19-hpc-consortium.org)
[78] COVID-19 HPC Consortium, "The Analysis of Binding SARS-CoV-2 to Various Substrates" (28 May 2021), The Analysis of Binding SARS-CoV-2 to Various Substrates | COVID-19 HPC Consortium (covid19-hpc-consortium.org)
[79] COVID-19 HPC Consortium, "Analyzing and Enhancing CORD-19 and Additional Coronavirus-Related Data Sets" (3 June 2021), Analyzing and enhancing CORD-19 and additional Coronavirus-related data sets | COVID-19 HPC Consortium (covid19-hpc-consortium.org)

partnership, the datasets necessitated advanced text and data mining skills in order to be truly exploited. After partnering with Microsoft and using their Azure platform, the University of Notre Dame researchers were able to create more focused and digestible subsets of COVID-19 data. The project commenced on June 1, 2021, and would have concluded around August 31, 2021, however, additional computing resources from LANL and Microsoft allowed for the completion of this project in less than a month.[80] Access to these additional resources not only improved the quality of the final product, but also shortened the time to dissemination.

Success factors

Access to the HPC Consortium's computational resources was essential to the timely completion of COVID-19-related research. The consortium's specialized computational resources were not traditionally accessible to most researchers. Industry participants were able to overcome their natural competitive tendencies and cooperate to jointly provide these resources because of the urgent nature of the global pandemic crises. Also critical to the success of this program was that the HPC services could be applied for and granted quickly.[81] Figure 2 shows that it only took four days from when the partnership was announced, to the start of the first project. The consortium's remarkably lean governance model, made possible by members' agreement to work together for the common good, allowed it to be set up quickly and operate nimbly.

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[80] Ibid.
[81] Oak Ridge National Laboratory, (2021).

Public-private partnership case summary and lessons

The preceding case studies highlight several success factors for PPPs focused on technology acceleration. Each has clear goals that are understood by all participants and aligned to a single, important government mission—such as public health, national defense, or sustainability—for which government participation and investment are essential. Partnerships translate their big picture public mission orientation into a set of specific objectives that are typically narrowly defined but ambitious. Any quantum-focused partnerships should similarly have clear goals connected to government priorities that are translated to specific objectives. If the government wishes to address multiple goals via QC partnerships, it will need to establish multiple partnerships. No single partnership can be all things to all stakeholders.

In addition to clear goals, the participants in each partnership share a common understanding of how the relevant body of underlying scientific and technical knowledge will be used to address partnership goals. And in all cases, the role of government participants is clear. Government provides the core program management for all partnerships and depending on partnership goals and operating model, may play other roles as well, including funder, researcher, and end user representative. Whatever the government role, it is always aligned with partnership objectives. For example, a partnership focused on identifying near-term government use cases for quantum computing must include government end users in partnership R&D. Partnerships that rely on unique government capabilities, such as those that exist at DOE's National QIS research centers, must include those entities in all partnership planning and governance.

Table 2 below summarizes the cases and highlights specific lessons relevant to a QC PPP.

Table 2: Summary of case studies and lessons for QC PPP

PPP	Primary goal	Government mission	Government role	Lessons learned for potential QC PPP
NASA Commercial Crew Program	Facilitate development of safe, reliable, and cost-effective human transportation between U.S. and International Space Station (ISS)	Aerospace	▪ Funder ▪ Program manager	▪ Pre-identify practical applications / targeted outcomes to ensure clear, precise PPP goals ▪ Break overarching goals into sequential objectives and hold private partners accountable via milestones to ensure their continued investment and dedication ▪ Involve most relevant and capable government agencies to maximize support and funding
National Spectrum Consortium (NSC)	Incubate new technologies to expand how the electromagnetic spectrum, and the information that rides on it, is utilized, especially for the sake of U.S. economic and security interests	National security	▪ Funder ▪ Program manager	▪ Consider using an OTA to bring a variety of organizations within the QC industry under contract with the government in order to keep government apprised of cutting-edge technical developments, allow government to move quickly if QC technologies are needed for mission critical purposes, and improve the scope of requests for proposals
Manufacturing USA	Build future manufacturing capabilities by developing and testing new technology and providing training opportunities to build the workforce necessary for a strong domestic manufacturing industry	Manufacturing	▪ Funder ▪ Program manager	▪ Involve stakeholders from all sectors in the development of a focused vision and a roadmap for the PPP ▪ Require cost-sharing for private grant recipients

PPP	Primary goal	Government mission	Government role	Lessons learned for potential QC PPP
National Cybersecurity Center of Excellence	Bring together government agencies, industry organizations, and academic institutions to protect U.S. critical infrastructure through modular, easily adaptable cybersecurity solutions that demonstrate how to address pressing private-sector cybersecurity problems using commercially available technology	Cybersecurity	▪ Funder ▪ Performer ▪ Program manager	▪ Keep open lines of communication among government, industry, academia, and the public, and refine project(s) via these channels ▪ Invite outside organizations and individuals to provide feedback at multiple points throughout a project's lifecycle to ensure the most pressing QC challenges are addressed with solutions that can be widely adopted by the industry
Innovation Network for Fusion Energy	Provide private-sector fusion energy companies access to technical and financial support to overcome specific critical scientific and technical challenges to accelerate the development of cost-effective fusion energy systems	Fusion energy	▪ Funder ▪ Performer	▪ Direct government funding toward private sector access to unique capabilities of national labs to advance basic research and to broaden the research base across the industry
Accelerating Medicines Partnership (AMP)	Compress timelines, reduce costs, and increase success rates of new targeted therapies for significant diseases	Public health	▪ Funder ▪ Program manager	▪ Externalize PPP data, test results, and findings to broader relevant community to potentially expedite and improve development via crowdsourcing (employ security measures as needed)

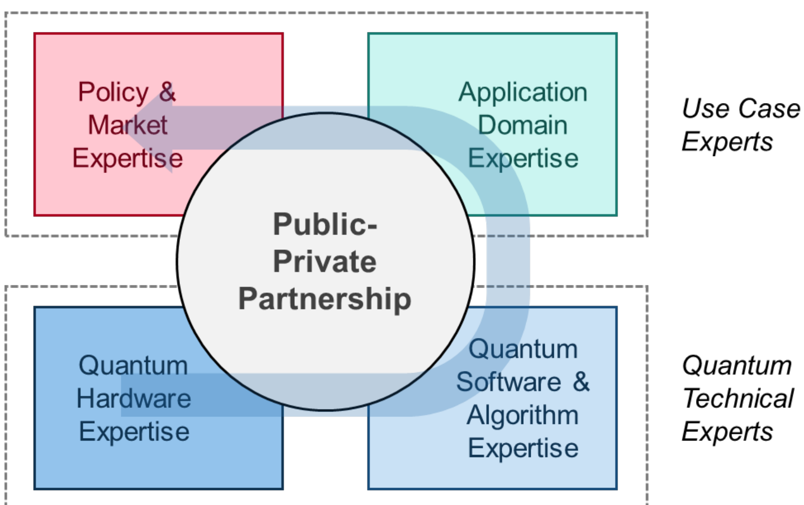
PPP	Primary goal	Government mission	Government role	Lessons learned for potential QC PPP
Partnership for Accelerating Cancer Therapies (PACT)	Identify, develop and validate biomarkers to advance new therapies and treatments that harness the immune system to attack cancer	Public health	▪ Funder	▪ Establish S.M.A.R.T. (specific, measurable, achievable, relevant, and time-bound) goals for PPP; without knowing how goals will be measured and by when, it is difficult to gauge partnership success ▪ Implement a public-facing progress tracker to both keep the public proactively informed of progress and motivate the PPP to continue achieving its goals
DARPA Grand Challenge	Accelerate development of technological foundations for autonomous vehicles, with long-term goal of being able to use autonomous vehicles for hazardous miliary operations, such as supply convoys	National security	▪ Funder ▪ Program manager	▪ Consider a challenge prize model to accelerate development of quantum computing among private companies, with well-defined milestones and monetary rewards commensurate with expensive technology investment
National Science Foundation (NSF) Convergence Accelerator (CA)	Convene representatives from all sectors to collaborate, receive mentoring, and build partnerships so they can turn R&D into a user-inspired prototype that can achieve real societal impact at scale	Various	▪ Funder ▪ Program Manager	▪ Focus investment on translational research projects that will surmount the research to commercialization valley of death ▪ Engage stakeholders from industry and academia when developing topics for research.
Covid-19 High Performance Computing Consortium	Provide COVID-19 researchers with access to computing resources, including super computers, to expedite the pace of scientific advances to combat the virus	Public health	▪ Funder ▪ Performer	▪ Open more computational resources, and super computers, to researchers to help spur more quantum technology breakthroughs ▪ Set up the PPP to be nimble, minimizing bureaucracy and formalities where possible to progress quickly

Partnership recommendations

Applications of quantum computing, if they are to emerge, will depend on matching the unique capabilities of quantum computers to important problems faced by end-user communities. The history of innovation makes clear the principle that the invention of revolutionary technology alone does not lead to its use. New technology must be significantly better at solving real-world problems if users are to adopt it at meaningful scale. *Significantly better* implies of level of superiority sufficient to overcome the costs—financial, operations, organizational, educational—of switching from one approach to another. Sustainable use of new technology in the real world is what distinguishes innovation from mere invention. As of the date of this report, it is fair to characterize quantum computing as a spectacular invention aspiring toward the status of true innovation. To reach this goal, QC capabilities need to be exposed to as many real-world use cases as possible. Partnerships, including PPPs, represent an ideal mechanism for facilitating this exposure.

Making progress in applying quantum computing requires multiple domains of expertise, shown in Figure 3. Quantum hardware developers understand the physics upon which quantum computing depends and how qubits behave; quantum software and algorithm developers apply the principles of quantum information theory to create software solutions to physical problems; application domain experts understand the science of the fields of application, for example, molecular chemistry; and policy makers and business managers understand how new technical solutions will be used and will compete in the marketplace. The recommendations made in this section take into account the fact that QC application development will benefit from input by all four types of expertise and emphasizes partnership design that facilitates the interaction of these diverse areas of expertise. Two of the recommendations, thematic application discovery and quantum challenge, are intended to accelerate exposure by quantum technical experts to experts on potential use cases.

Figure 3: QC application expertise



Although real-world QC applications are not likely within three years, there is still significant rationale for government-led PPPs focused on advancing the state of the art of quantum computing and moving up the date of eventual real-world application. Three recommendations are made below for quantum PPPs. The first, thematic application discovery, highlights the value of a concerted, multi-participant effort to find applications for which QC technology is more mature and government needs are clearly apparent. Second, the quantum challenge is inspired by past effective use of competitions to push technology capabilities forward and draws upon significant industry activity in the area of financial modeling. The final recommendation, enabling technology acceleration, focuses on advancing the underlying technology of quantum computing in a way that addresses cross-industry technology challenges. QED-C, as an existing quantum-focused PPP with participation by most of the QC community including industry and government, is well positioned to further develop the details of the following recommendations and to potentially play a coordinating role in any eventual PPPs.

Recommendation 1: Thematic application discovery

Finding a set of potential near-term QC applications of value to government is best done through a concerted discovery process that involves cooperation among each of the expert communities of Figure 1. The federal government should consider establishing a PPP whose mission is to find possible near-term QC applications by facilitating cooperation between QC hardware and software experts, application domain experts, and policy and market experts. Such a partnership should be organized around a significant public interest thematic application area, such as climate and sustainability or public health, in which there is an emerging critical mass of quantum R&D already underway.

The near-term goal is not defined in terms of achieving real-world application in three years. Rather, the proposed partnership's objective would be to evaluate use cases for the purpose of pulling forward the date at which real-world progress can be made. Government participants would bear primary responsibility for identifying important use cases and the criteria for making meaningful progress in addressing these use cases. This would be done within the thematic area chosen. The government and industry partners would evaluate the feasibility in greater depth than can be done via a literature survey. In the context of a climate-focused partnership, for example, this might mean identifying and describing particular targets associated with carbon emission reductions and working with environmental scientists to translate these goals into technical challenges and identify where classical computational methods are not sufficient to solve these challenges.

Quantum scientists could then evaluate candidate use cases for application of quantum computing and outline an agenda of QC application development that addresses the identified computational gaps. The near-term use section identified a number of application areas being explored relevant to sustainability. Individual computational problems are most effectively tackled with a specific set of QC algorithms and each algorithm has different requirements of the QC hardware on which it runs. Understanding the entire problem space of Figure 1 is thus essential. It is possible, for example, that bespoke quantum hardware might be developed within the proposed partnership. Given the current importance of hybrid computing, the proposed partnership would likely evaluate combined quantum-classical approaches for each goal. Focusing on quantum-only solutions would likely restrict the ability of the consortium to find meaningful areas for QC application.

As candidate applications are identified at the intersection of (a) high importance and (b) encouraging prospects for QC-based solutions, the partnership would plan, fund, and execute an ambitious R&D plan to push forward applications. Given the highly non-linear nature of this type of work, the distinction between identifying promising candidates and R&D work on these candidates will be blurry. R&D will likely yield new insights into the application areas and may lead to reassessment of where quantum computing can best be applied. It is possible that work on developing quantum algorithms for specific problems will lead to ideas on how to improve classical algorithms and lead to reevaluation of the quantum-classical division of labor.

The spirit of this proposal aligns with the May 2021 recommendation of the President's National Security Telecommunications Advisory Committee (NSTAC) regarding quantum sandboxes.[82] NSTAC recommended the use of a sandbox to serve as a testbed for the near-term government quantum application development and testing in the context of network security. It is also consistent with the view of many experts, reported by McKinsey, that insufficient time and resources have been invested to assess the viability of use cases.[83] It represents a top-down approach to accelerating the use of quantum computing that complements the traditional bottom-up funding of principal investigator R&D by NSF and other government agencies.

The proposed partnership will need a public entity to steward the government's participation. If significant progress were to be made in a given application area, the government partnership may decide to transition further R&D out of the partnership and into an existing government agency or department to champion. Potential recipient entities should be involved in the partnership and the original use case evaluation.

Recommendation 2: Quantum challenge

Government-sponsored challenges have demonstrated their effectiveness in accelerating the development of technology intended for use in government mission areas. They also follow an iterative approach to competition that allows the government to revise timelines and objectives in response to participant progress and improved understanding of what is technologically possible. The U.S. federal government should consider organizing a QC challenge. A narrowly focused quantum challenge would complement the broader focus of Recommendation 1. The challenge should focus on an area with (a) clear government mission relevance, (b) active interest by the private sector, and (c) a critical mass of current QC research. Several areas described in the preceding near-term applications section meet these criteria. Financial fraud detection stands out given the level of interest on the part of private sector financial services firms in quantum computing for fraud detection and the enormous amount of real-world data available with which to experiment and develop QC anomaly and fraud detection tools.

The DARPA 2007 urban challenge included cooperation between academic and corporate teams and similar teaming would benefit a quantum challenge focused on financial fraud detection. The sponsoring government agency would provide the policy domain expertise and be responsible for identifying government financial fraud detection needs (regulatory or law enforcement), translating these needs into QC challenge goals, and leading the creation of challenge evaluation criteria.

DARPA's vehicle challenge was successful in accelerating autonomy-related technology development and hastening the advent of driverless cars in the consumer market. It has been argued, however, that its impact on vehicle use by the military has been more modest.[84] This may be due to the fact that the DARPA challenges were technology-focused and not designed to address a specific military use case. The anticipated use case was inspired by a clear and important challenge—limiting warfighter exposure to

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[82] President's National Security Telecommunications Advisory Committee, "NSTAC Report to the President on Communications Resiliency" (6 May 2021). Regulatory sandboxes represent a regulatory approach that allows live, time-bound testing of innovations under regulator oversight. They are used to encourage innovation by product and service developers, often via limited, temporary exemptions from existing regulation.
[83] McKinsey & Company (2021).
[84] https://defence.nridigital.com/global_defence_technology_jul19/darpa_s_grand_challenge_at_15_how_far_have_autonomous_military_vehicles_come

life threatening environments—but this use case is broad. As the government defines the quantum challenge, it should emphasize a narrowly defined goal that addresses a specific regulatory or law enforcement challenge.

Recommendation 3: Quantum enabling technology acceleration

In addition to the two application-focused partnerships described above, the federal government should consider supporting a PPP focused on addressing the underlying technology development challenges of quantum computing. DOE's INFUSE program funds projects directed at addressing technology roadblocks to developing practical fusion energy. It is a model worth considering for adaptation to QC R&D.

The INFUSE program gives private-sector fusion energy companies access to the technical and financial support necessary to move fusion energy technologies forward by leveraging the unique capabilities of the DOE National Laboratories. INFUSE awards are not intended to help companies commercialize technology nor provide access to research services, expertise, or equipment that is readily available elsewhere. Rather, companies make requests for assistance to solve specific challenges related to fusion enabling technology development. Requests are evaluated based on the impact of the proposed project on the overall progress on fusion energy R&D. The INFUSE model requires little from applicant companies other than a 20 percent cost share.

An INFUSE model for quantum would start with participation of the DOE's QIS Research Centers. The QIS centers, coupled with DOE's core research portfolio, are intended to steward the national ecosystem needed to advance QIS in the United States. From this staring point, the INFUSE model could be adapted for quantum computing in a number of ways. It would benefit from active R&D participation on the part of participating firms rather than a mere cost share. It should also include an expanded set of additional participants including universities and other entities with relevant capabilities. The proposed PPP should also focus on projects with prospects for general use within the quantum industry, giving it a pre-competitive focus. Developing appropriate eligibility criteria for projects and evaluation criteria for applicant requests represent key governance parameters for such a partnership. In effect, the partnership would create focused PPPs for each request made by the private sector, each with a defined budget, timeline, set of goals, and statement of work created as an outcome of the application process.

A partnership focused on enabling technology would not address specific QC applications. Instead, it would address the numerous technical challenges facing QC development, such as qubit quality, qubit control, error correction, cryogenics, and system scaling. An enabling technology-focused partnership would complement partnerships focused on finding and developing applications and could hasten the timeline for seeing those applications develop.

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