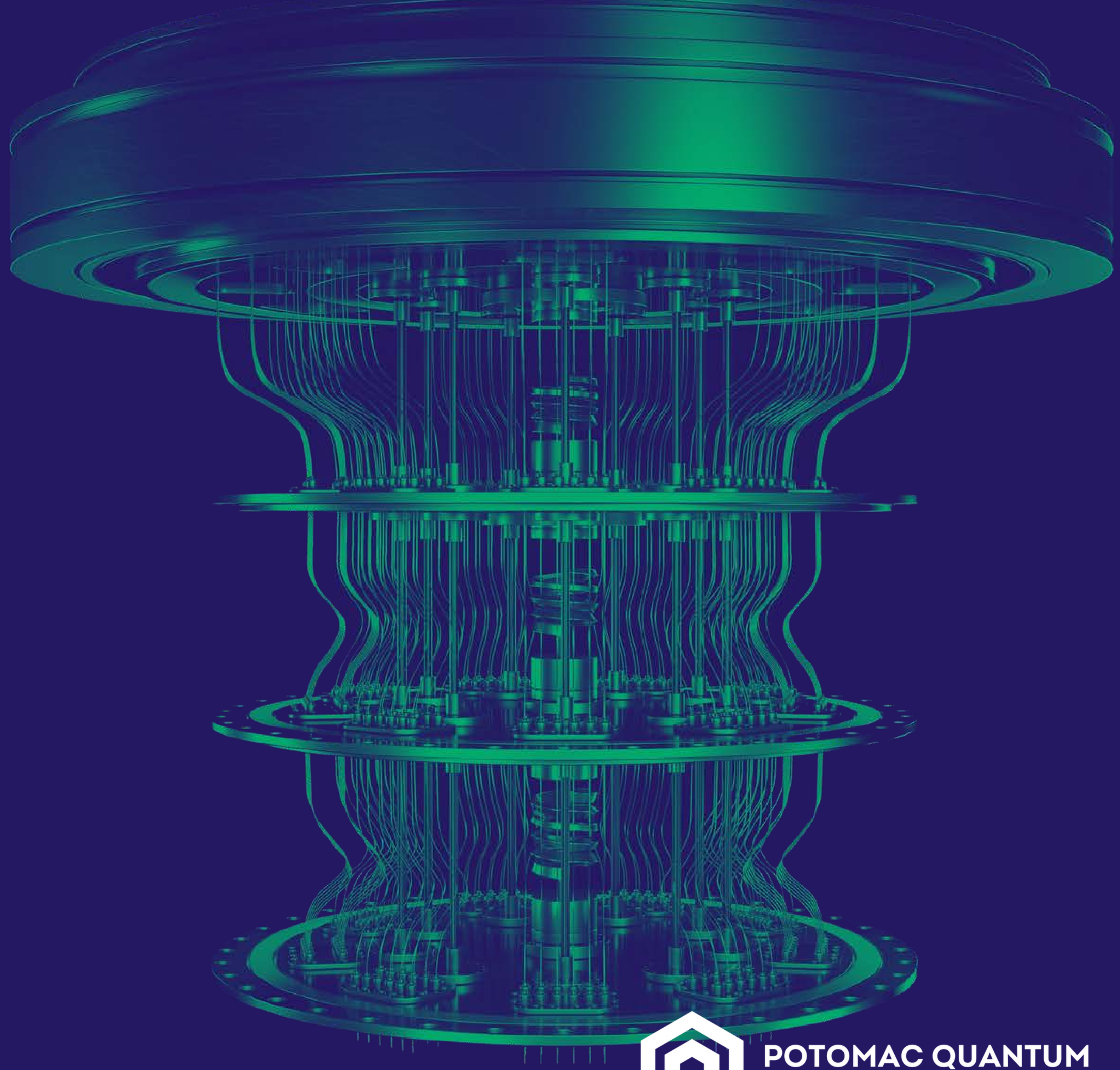
Our Quantum Future: Some Assembly Required

A COLLABORATIVE APPROACH FOR ETHICS, POLICY, AND STANDARDS



POTOMAC QUANTUM INNOVATION CENTER

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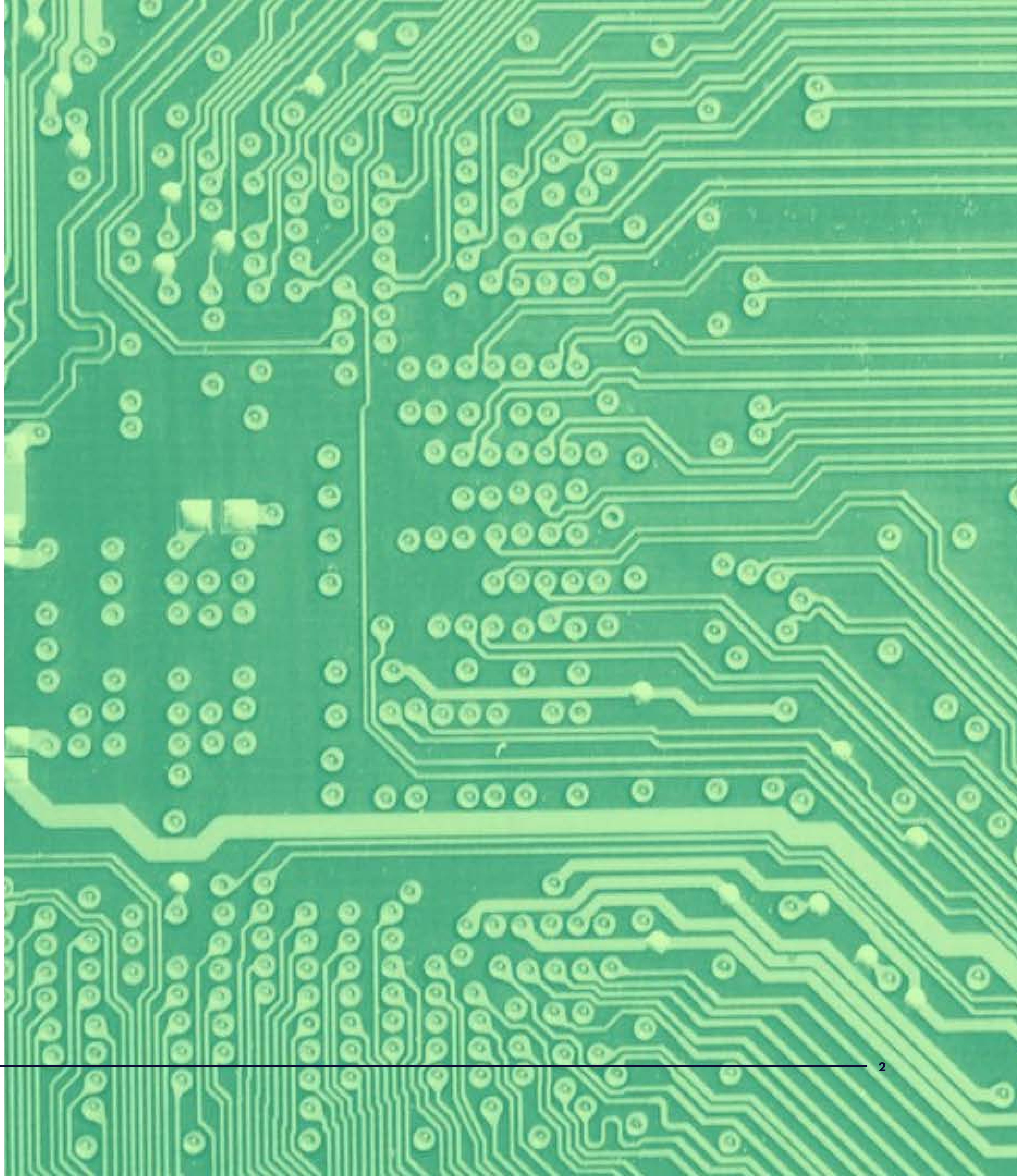
This whitepaper articulates the value proposition for a Quantum Policy and Ethics Center to assemble cross-sector experts, both domestic and international, in an open, collaborative forum to investigate and develop solutions for the governance of quantum technologies.



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Call to Action

The possibilities raised by how the world works at the atomic and sub-atomic level now encompass a rapidly emerging set of technologies with the potential to change the way people live, work, and learn. As more companies and governments invest time, energy, and resources into the development of quantum and quantum-adjacent technologies, they must also proactively address key issues to offset the associated risks and maximize market and technology gains. The global quantum ecosystem is rapidly evolving and needs mechanisms to align a wide variety of independent initiatives to accelerate quantum innovation. The Potomac Quantum Innovation Center (PQIC) launched in November 2019 with a mission to prepare for the future by bringing together Greater Washington's quantum stakeholders — across borders and sectors — to drive innovation, talent development, economic growth, and positive social impact. PQIC consists of four initiatives: a Quantum Academy that will prepare a talent pipeline for future quantum jobs; Quantum Innovation Hubs that will accelerate quantum investment and solution adoption across key industry clusters; the Quantum World Congress as an annual event convening global quantum leaders; and the Quantum Policy and Ethics Center to strengthen global collaboration and help align stakeholders on ethics, policy, standards, and regulations.

The parties to drive this initiative forward include ethics, policy, regulations, and standards experts collaborating globally across academia, industry, government, and community on a strategy and plan for the formation of the Quantum Policy and Ethics Center (Center). This cross-sector effort reflects the strong marketplace need to co-create and establish a global open public forum for quantum technology research, governance, norms, and practices.

This whitepaper is the product of discussions and deliberations over the last year, and provides an early collection of background information, key concepts, and strategic parameters intended to increase awareness of the need for a Center. The Center would facilitate proactive dialogue between a community of multi-disciplinary experts and establish U.S leadership in socially responsible quantum industry development. It would serve as an open public forum for collaboration among governments, academia, industry, community, and investors to validate and accelerate the value of quantum to society.

The first draft of the whitepaper was presented to a group of global subject matter experts across multiple industries and sectors for discussion during a workshop in October 2022; and formally released publicly on November 30, 2022, at the Quantum World Congress, where several co-authors addressed the effort in a panel discussion. The whitepaper is available via web and PDF and is open for public comment until December 9, 2022. This whitepaper provides a call to action for philanthropists, governments, communities, industry, and academia.

We invite you to join with this global community of champions as we build a thriving and responsible quantum industry together.

GEORGE THOMAS
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Director, Potomac Quantum Innovation Center

Executive Summary

There is a new revolution of technology emerging based on the understanding of sub-atomic physics: quantum. This revolution leverages advanced scientific understanding and engineering capabilities at the sub-atomic level to create new solutions across critical domains such as computing, sensing, cryptography, materials, and communications. Through particle-level precision controls, technologies may provide uniquely powerful, fast, and precise capabilities that will benefit society. Quantum computers, which will solve certain types of problems better and faster than classical computers, have the potential to yield step-change improvements across life sciences, healthcare, energy, finance, manufacturing, transportation, logistics, and other industries by optimizing existing processes and unearthing entirely new capabilities. Quantum sensing, which allows for more precise measurements of physical properties, will vastly improve positioning, navigation, and timing technologies and our earth sciences and astronomy solutions. Quantum communications and cryptography could allow for more secure transactions and higher networking potential. Advances in quantum materials could portend the advent of entirely unforeseen types of materials for a variety of uses.

Previous technology revolutions have resulted in profound societal impacts. Establishing technology governance and benchmarking for good behavior early on is essential and enhances market trust and adoption. Quantum's impact on society is yet uncertain, and governments are interested in creating standards and policies, while industries are interested in responsible commercial deployment. Questions such as, "How do we mitigate unintended consequences?" "How will quantum be applied?" and "Who will have access to it?" are important. Democratization of access to benefits must be adopted as a core value so that inequities do not become more extreme and societal trust in quantum can be earned and maintained. The quantum ecosystem needs to begin addressing these issues now in order to de-risk or limit potential adverse impacts and accelerate the timeline to widespread adoption of the transformational quantum capabilities needed to tackle a range of pressing global challenges. These efforts must focus on quantum's potential societal impact along the dimensions of speed, scope, scale, and social equity.

Such self-imposed guide rails are not just to protect against adverse possibilities. They have been shown to help accelerate industry advancements and clear roadblocks and uncertainties in the development of other nascent technologies.

To achieve these goals, the co-collaborators recommend the formal establishment of an open public forum and global hub located in the Washington, D.C. region (Greater Washington) to advance the understanding and development of sound policy, regulations, and standards that accelerate commercially driven and ethical quantum industry development. The quantum industry needs a focused mechanism for cross-sector, open, policy-shaping dialogue and a center that better enables solutions through research, analysis, advisory services, training programs, awareness campaigns, tools, and memberships.

It is important that guardrails be established to better facilitate safe, responsible, and ethical development and deployment of technologies. An illustrative acronym for ethical considerations is FATES: Fairness, Access, Trust, Equity, and Security. Ensuring fairness in developing algorithms and evaluation metrics is important. Additionally, the access and equity impact of quantum technologies must be considered. Transparency of development goals and strategies will be imperative to foster trust across a diverse array of stakeholders. And finally, policymakers must remain vigilant for potential security and privacy risks that may arise and preempt potential vulnerabilities from being realized.

Quantum ethics sits at the intersection of quantum information science, technology ethics, and moral philosophy. The unique features of quantum computation have consequences for the imposition of fairness and ethical constraints. Despite its significance, there is little structured research into the ethical implications of such quantum technologies nor a highly advanced Center focused solely on building a firm foundation for ethical quantum innovation. This Whitepaper examines the need for a Quantum Policy & Ethics Center as a hub for national and international dialogue, solutions, and training.

The Global Race

The geopolitical stakes of quantum technology are high. For example, the first country to achieve quantum computing breakthroughs or full-fledged quantum networks that could provide un-hackable communication channels will significantly strengthen its strategic positioning vis-à-vis rivals. After China’s demonstration of the Micius satellite in 2016, U.S. politicians responded by investing hundreds of millions of dollars into quantum information science via the National Quantum Initiative. Europe also joined the race. In September 2022, the European Space Agency announced a plan for a consortium of 20 companies to launch a quantum satellite in 2024. The satellite will use quantum key distribution (QKD) technology for European quantum-secure communications networks. The race over the development of quantum technology has major implications for both the future of science and geopolitics.

The U.S. National Imperative

The U.S. and its allies are currently engaged in an international science and technology (S&T) competition, predominantly with China. The People's Republic of China is targeting sources of U.S. and allied strength through means that include "stealing technology, coercing companies to disclose intellectual property, undercutting free and fair markets, failing to provide reciprocal access to research and development (R&D) projects, and promoting authoritarian practices that run counter to democratic values." China's ascension in both activity and influence within the international S&T community has been rapid and extensive.

In three technologies (microelectronics, wireless technology, and artificial intelligence), we have come "perilously and unwittingly close to ceding the strategic technology landscape and along with it the capacity to shape the future." Quantum joins these technologies, and a few others, such as semiconductors, on a small White House list of technologies that are most critical to the future of U.S. technological leadership.

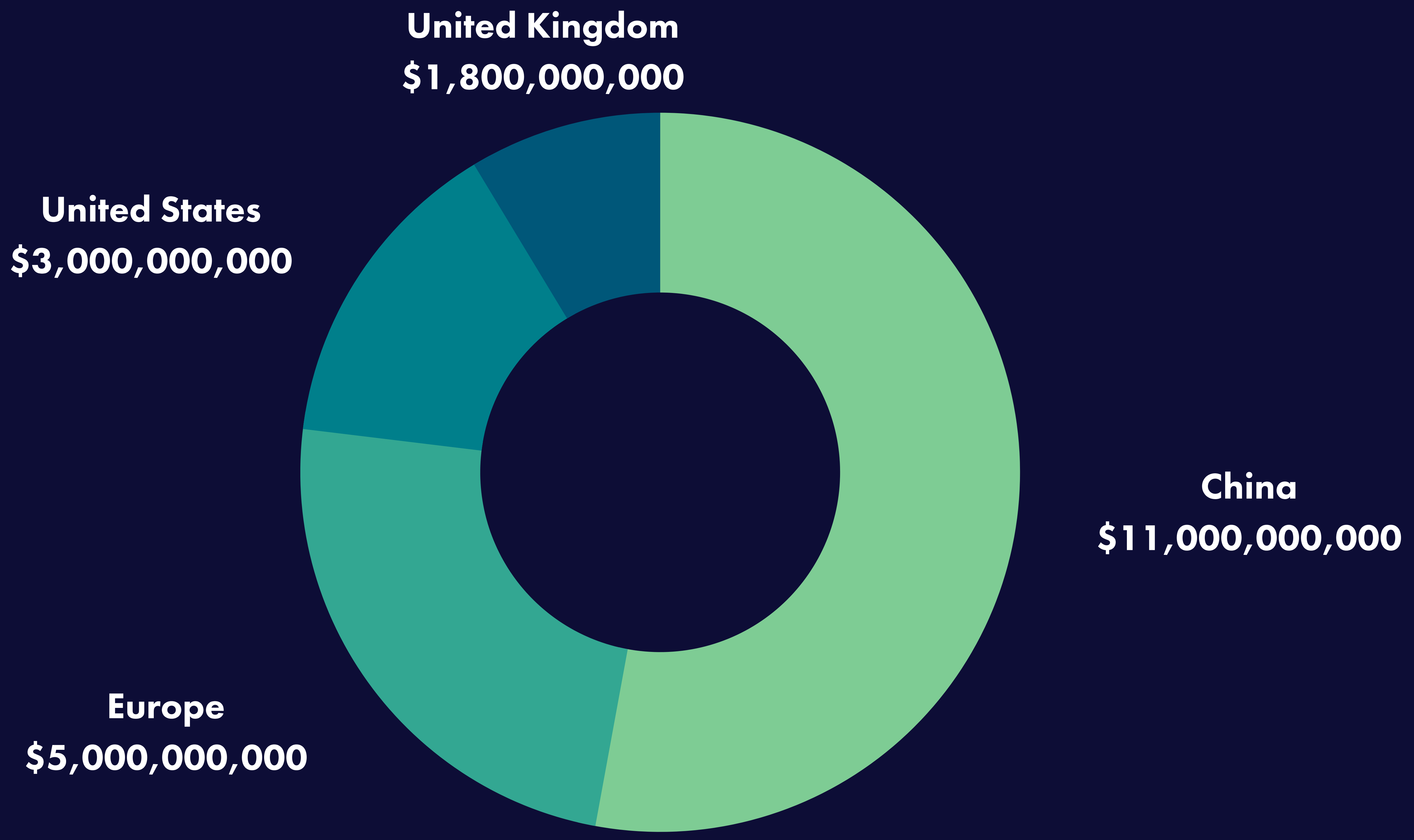
The nation's current approach to advancing S&T, while successful for several decades, needs to be enhanced to succeed in this new era of international competition. The current advancement paradigm is based on large federal sums of money for research and development in basic science, the results of which are then individually leveraged by private sector entities to create products and sustain their use. Ethical considerations, community standards, best practices, and regulations develop organically as the S&T community evolves. This unstructured and often disconnected approach may now leave the U.S. vulnerable to China's authoritarian, yet often quite holistic and organized, approach. This vulnerability has existed for decades and has been exploited by China.

A safe and reliable quantum-enabled future requires "innovation-fostering partnerships: a voluntary coordination of government, industry, and academic activities to holistically address our nation's most-critical S&T priorities. These partnerships should integrate diverse players into a collaborative network to share information about opportunities and solutions and to coordinate shared, complementary efforts across sectors, institutions, and disciplines in order to help catalyze solutions to the biggest technology-related challenges our society faces. It must do this, furthermore, while safeguarding the intellectual property, privacy rights, and autonomy of all participants and stakeholders."

Within the context of quantum, scientific advancement, application and usage best practices, workforce development, and a range of ethical investigations and policy development activities must be addressed in a coordinated multi-year framework due to their inherent interconnectedness and the timelines of technical maturation. The Quantum Policy and Ethics Center will bring together experts to investigate and collaborate on the ethical and policy considerations of quantum technologies, applications, and issues and serve as a collaboration partner and resource for others performing similar research or advancing complementary efforts.

Global Investment in Quantum 2019-2021

SOURCE: FORTUNE MAGAZINE (2022)



The International Objective

There are several international efforts to lead the quantum race and shape its trajectory. The UK National Quantum Technologies Programme has invested in several national research hubs aimed at "weaving the science of quantum technologies with ideas for their commercialization and delivering a route to market." The EU has launched its Quantum Flagship program as a "long-term research and innovation initiative that aims to put Europe at the forefront of the second quantum revolution." Recently, the EU also announced selected projects for its quantum research partnership call with Canada's National Sciences and Engineering Research Council. The EU's Quantum Flagship program co-exists with national research hubs of member-states, such as the Quantum Delta partnership in the Netherlands and the Quantum Alliance in Germany. National quantum efforts are also underway in Australia, Canada, China, Japan, and South Korea, among other countries.

Given the enormous potential of quantum technology to bring about significant change in various domains, there is a recognized need to start discussing possible societal, legal, and ethical impacts and associated risks of quantum computing at a global level. This awareness might drive global efforts in setting governing principles for the technology. In June 2022, the Quantum Economic Development Consortium (QED-C) announced that its membership is now open to an additional 27 countries, which puts its global member reach at more than 36 countries. The Institute of Electrical and Electronic Engineers (IEEE) has a quantum section with international members. Currently, IEEE Quantum has active standardization efforts in domains such as "software-defined quantum communications" and "quantum algorithm development and design." Currently, discussions are occurring on principles and guidelines for quantum that might garner support from a multitude of stakeholders across countries. One example can be found in the "Quantum Computing Governance Principles" developed under the auspices of the World Economic Forum (WEF). These principles were co-designed by various stakeholders with diverse backgrounds, including quantum computing experts, experts on the ethics of emerging technology, legal experts, and policymakers, among others. The WEF report suggests a set of principles intended to guide the responsible design and adoption of quantum computing to generate positive societal outcomes.

In order to facilitate the deployment of this critical technology, it is also necessary to have communication channels between researchers and policymakers. According to a survey published in November 2022, 61% of industry respondents reported that they are planning to invest $1 million or more in quantum over the next three years. The Quantum Policy & Ethics Center would be well positioned to facilitate policy-shaping dialogue with its reach to diverse U.S. and global stakeholders, investors, researchers, and policymakers to foster the development of this technology, boost deployment benefits, and contribute to mitigating potential risks.

To balance the competing opportunities and risks of quantum computers, U.S. leadership must increase its domestic investment and partnerships with allies as well as provide a balanced approach to technology promotion and protection. There is an increasing need to work in concert with like-minded countries to craft a unified approach to technology policy. A repeatable but adaptable structure is required to align efforts for establishing common ground and agreeing to a shared playbook, such as approaches to alleviate supply chain risks, responsible and ethical development of quantum technologies, standard setting, and secure digital infrastructure.

Governance: Policies, Regulations, & Standards

While leaders have begun to recognize the impact of quantum technologies on industry, government, and society, a clearer, structured policy pathway to achieving this objective is needed. U.S. quantum policy announcements have demonstrated a commitment to establishing national directives on quantum technology development. However, given the scope of stakeholders involved in the domestic quantum enterprise, the government has not been able to provide timely and actionable directives and recommendations. As will be discussed in this section, developing a roadmap for policy and ethics requires a mix of timely technology standards, robust engagement with industry, and strategic objectives to promote technological power and potential responsibly. To achieve this, government must draw on and partner with external bodies that convene stakeholders to understand the quantum and broader S&T ecosystems.

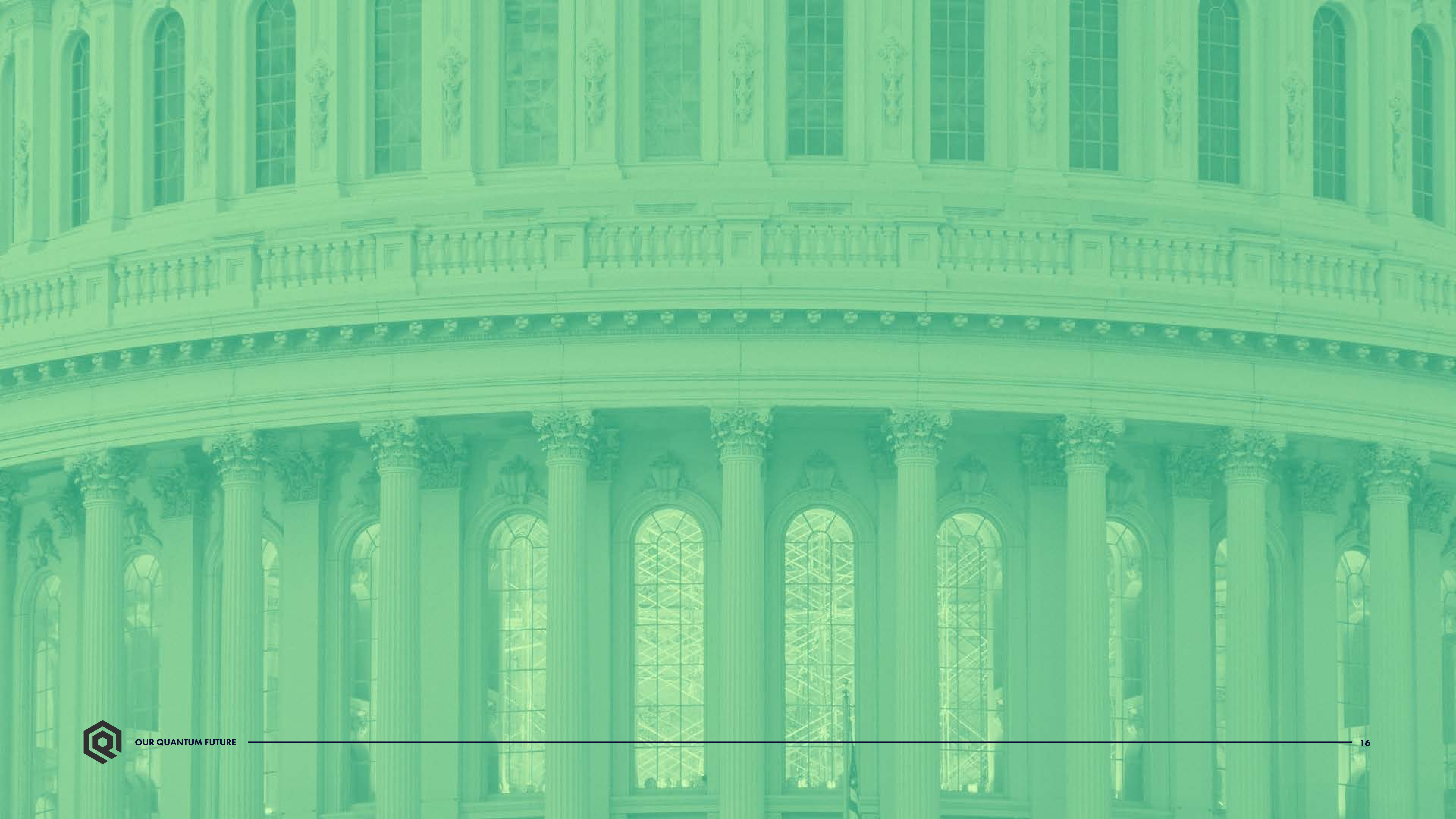
Current Policies & Policy Precedents

U.S. policymakers' efforts within the last five years indicate heightened interest in establishing strategic objectives, standards, and regulations for quantum technologies. In 2018, the U.S. Congress passed the National Quantum Initiative Act (NQIA) to promote national quantum development. The NQIA authorized the creation of an advisory committee to assist in identifying national goals for quantum development and strategies for meeting these goals. In 2022, the Biden Administration strengthened these policy initiatives. On May 4, the White House announced two new policies on quantum technology development in the United States. The first, an executive order, enhanced the role of the NQIA advisory committee, placing it under the direct authority of the White House to allow for more direct communication and expedient policymaking. The second, a national security memorandum, highlighted the government's concern over cybersecurity risks introduced by quantum computers and provided a plan for addressing those risks while still advancing quantum technology development.

Key U.S. Government Stakeholders

One recurring goal across the various U.S. quantum policies is to establish government-wide strategies that increase employee proficiency. This means that each agency and department has been tasked with developing some degree of in-house quantum competency, raising awareness of key implications quantum might raise related to organizational missions, and identifying potential use cases to utilize quantum technologies. Moving forward, increased efforts are likely across U.S. government agencies to strengthen in-house quantum capabilities and engagement within the global quantum ecosystem.

While the White House supports a whole-of-government approach, Congress has directed several federal entities to provide organizing direction to the broader government enterprise in developing standards, allocating funding, and providing laboratory resources. The National Institute of Standards and Technology has led in developing standards and establishing quantum-safe encryption methods and has led a subcommittee on quantum research for the last decade. These bodies have developed whole-of-government research strategies that the agencies have implemented. The National Science Foundation and the Department of Defense have provided necessary funding streams to support quantum technology development in the academic and private sectors. Finally, to distribute laboratory and resource access, as well as to boost regional collaboration, the Department of Energy has established five regional hubs based at the Argonne, Brookhaven, Fermi, Lawrence Berkley, and Oak Ridge National Laboratories.

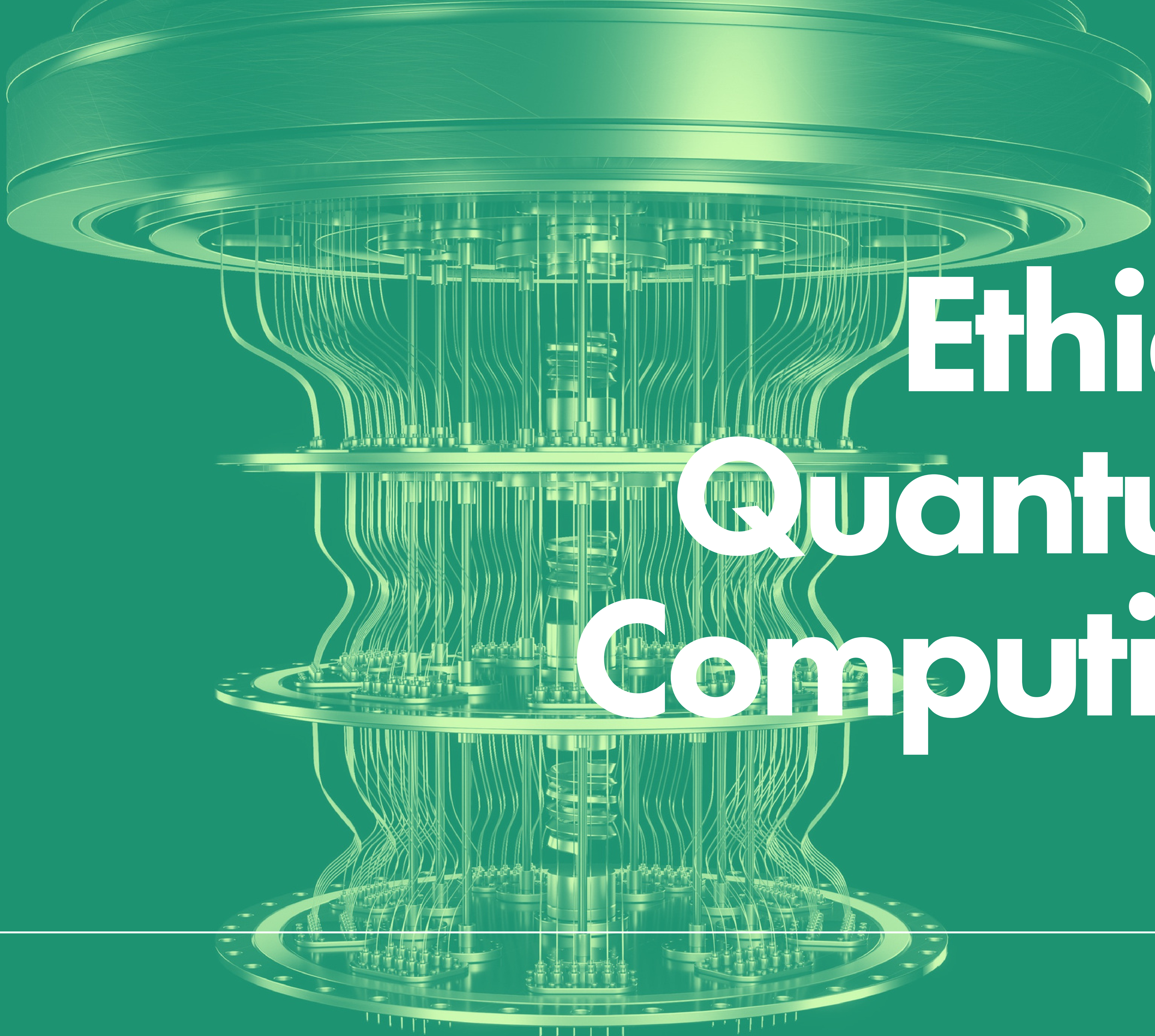


Policy Requirements

While the U.S. government has laid the groundwork for sustaining and enhancing quantum momentum in the U.S., more specific policies will be needed in the next few years. Government should strengthen its efforts with industry and academia to evaluate the risks and benefits of quantum technology development (related to agency missions and industries), identify clear benchmarks, and establish standards for development. Stakeholders should also consider the ethical implications of quantum technology development and assess whether quantum resources and benefits are accessible to diverse communities.

Multiple dimensions must be considered in a new policy roadmap, including risk assessment, accountability through third-party verification, and metrics for accessibility. Finally, in executing the policy roadmap, the government should engage a wide array of stakeholders in the quantum ecosystem. Because research and innovation are happening both within and beyond government labs, policies will have wide-reaching impacts. For the U.S. to respond cohesively, consent on key strategies and approaches should be sought from relevant participants. This will also help to improve the efficacy of the policies, as stakeholders will be more willing to engage with policies and directives if they perceive a benefit to themselves and to the ecosystem. This can be facilitated more easily through collaborative quantum efforts such as the Quantum Economic Development Consortium (QED-C) and would benefit from an organizing group that is inclusive of a broader interdisciplinary and cross-sector ecosystem.

Ethical Quantum Computing



Scientific and technological innovation is at the core of our humanity, allowing us to chart, navigate, and harness the power of what Isaac Newton called "the great ocean of truth." Ethics is an integral part of this process and has significant historical and contemporary precedent across disciplines such as life sciences, physics, computing, and engineering. There is a need to place policy and ethics at the center of quantum research and development. Doing so will better enable the full potential and opportunity of quantum.

Quantum raises ethical considerations that can be categorized in different ways. First, there are those that are cross-cutting and which apply to all five principal quantum technology domains: computing, cryptography, communication, sensing, and materials. This includes considerations about fairness, access and equity, security, transparency, privacy, and trust. Second, there are use cases of quantum that fall into one or more of the principal quantum domains. For example, quantum computing and sensing are poised to provide significant improvements in agricultural fertilizer, a use case area that will bring different ethical considerations than, for example, communications and cryptography use cases.

What follows is a brief overview of several areas of ethical consideration as they relate to quantum technologies. We make no claim that these are the only areas of ethical consideration nor that they are the most important. Instead, each contains illustrative examples of ethical issues. These issues are specific to categories of quantum technologies and to uses of quantum.

Fairness

For quantum computing to be ethical, it must be fair. The term fairness can mean substantially different things to different people. Some regard fairness as similar treatment of people who are similar and the presence of processes to ensure as much. Others focus not on processes and procedures but on outcomes. Some consider individual people as the appropriate level of analysis for fairness, while others place emphasis on groups.

A recent area of research on fairness focuses on quantum fair machine learning (QFML). The point of departure for QFML is typically fairness in AI, particularly fairness in classical computing machine learning (ML). In both cases, algorithmic fairness is often viewed through the lens of harmful bias. An algorithm, model, process, or its impacts are unfair if they contain harmful bias and thereby treat or impact individuals or groups differently when such individuals or groups are sufficiently similar that they should be treated as such. Harmful bias has resulted in denying people jobs and housing and even has led to innocent people being arrested.

Significant technical steps, including fairness and bias metrics, measures, and remediation strategies, have been developed and deployed to locate and mitigate bias in classical ML. While these efforts have met with mixed success, the applicability of these methods to quantum machine learning must be evaluated, and new methods may need to be developed.

A leading mitigation and remediation strategy that has been employed in classical ML is audits of data that focus on rooting out bias in datasets, algorithms, and applications. AI industry leaders have created tools to identify and mitigate harmful bias, and non-profits have created “bias bounties” to incentivize people through monetary rewards to find bias in datasets, algorithms, and applications. At the governmental level, NIST has identified bias bounties as a key component of ensuring ethical algorithms. To the extent that quantum machine learning is sufficiently transparent and accessible, bias bounties may be an effective tool to develop QFML. One obvious constraint will be the initial lack of widespread access to quantum computing resources, which will certainly not be on the scale of the access and possession of classical computing hardware and software that has made bias bounties effective.

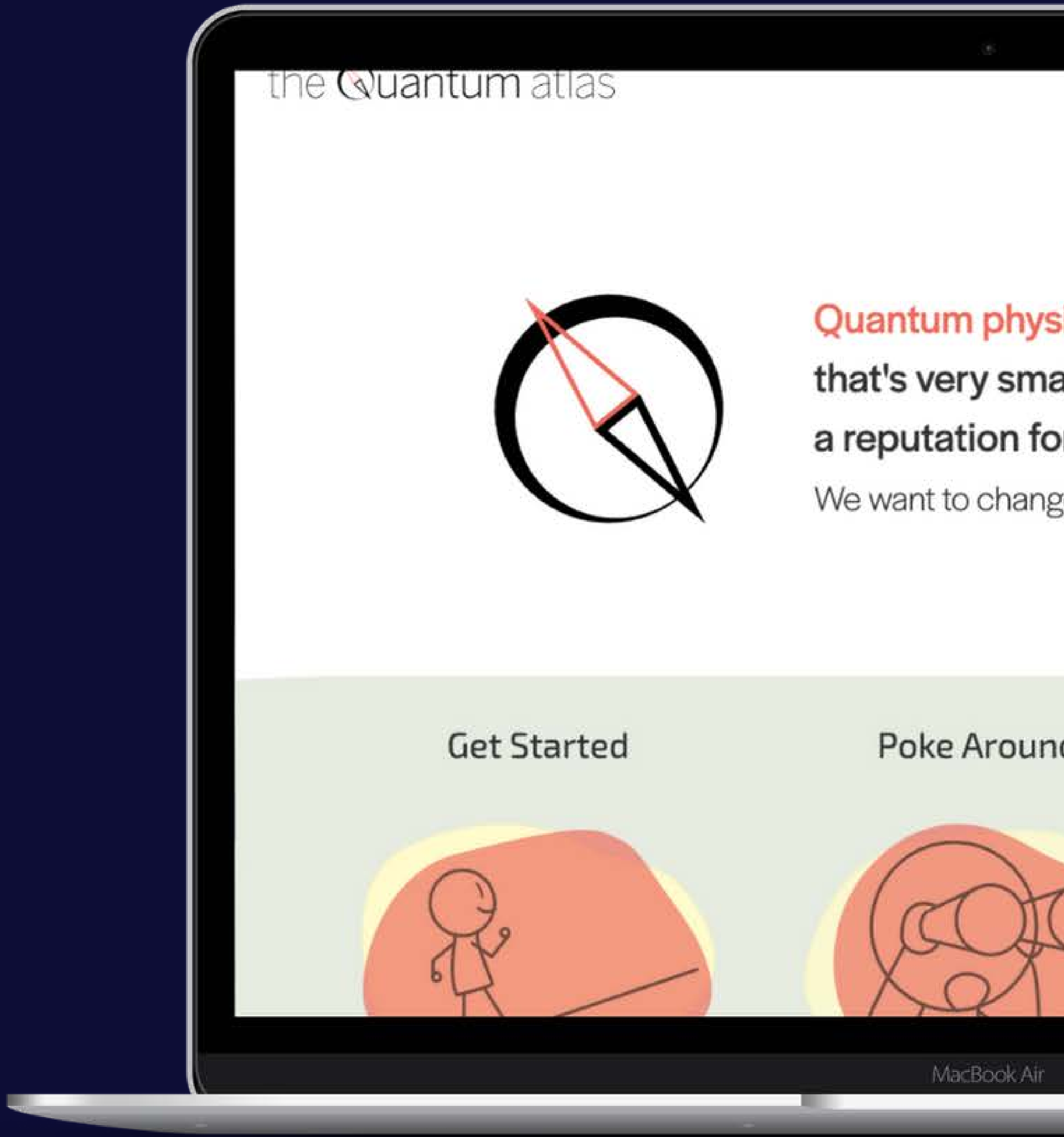
Access and Equity

To maximize the positive impact of quantum technologies, relevant stakeholders must have a seat at the table. Our society's diversity is our strength, and it is crucial that members of the general population, civil society, academia, business, industry, and government are involved in developing, deploying, and using these technologies. We take "access" here to entail meaningful opportunities to contribute to developing and deploying quantum and an ability to use the technology and receive its benefits. While access to such quantum technology as sensors, cryptography, and computing models and simulations will be crucial, access to knowledge and research will be a critical aspect of ensuring equity and building public trust.

To the layperson, quantum technology may be viewed as mysterious and opaque. There is a reason that we think of quantum as strange. Our beliefs and intuitions about the world and the objects that comprise it are built on classical physics. That is, the physical laws that govern ordinary objects and their behavior. The quantum world is different. Take, for example, that in the world of quantum, objects don't have predictable motions. One way of building access to knowledge of quantum is through popular, publicly accessible, and free resources.

An excellent example is the recent development of a free, online version of chess that "incorporates quantum phenomena as a core gameplay mechanic" while providing accessible explanations of quantum. Another example is The Quantum Atlas, a web-based resource replete with images, podcasts, and animations, all designed to be an accessible guide to the world of quantum.

In addition to providing accessible, publicly available educational information that enables laypeople to understand quantum phenomena and technology better, so too will there be a need for open and accessible outputs of research and development, particularly those supported with public funds. Embargoing research and development findings for a period of time ensures the protection of intellectual property (IP). This is a reasonable practice and one that can be balanced with the need for open scientific research. One existing model is the recent OSTP policy guidance, "Ensuring Free, Immediate, and Equitable Access to Federally Funded Research." The guidance focuses on access to scholarly publications and digital data resulting from federally funded research. Access to publicly funded research will need to be balanced against the likelihood of bad actors using such research for nefarious purposes, such as developments in quantum cryptography for illegal purposes or the decades-long practice of global competitors accessing publications and data in an effort to gain national competitive advantage.



Trust and Security

A cornerstone of the social acceptance of quantum technologies will be their trustworthiness; nowhere is this more crucial than in communications. While quantum communications can be used to transmit secret data with provable privacy and security, it also poses a potential threat to existing cryptographic algorithms. Consequently, it is possible that advances in quantum technologies could be used by bad actors to break existing encryption protocols that are currently used across all sectors of society, from healthcare providers to financial credit agencies, and underpin personal and private electronic communications. Breaches of this sort threaten personal data and privacy while undermining trust in the security of our online transactions and the ability to verify sources of data and communications.

Fundamental areas of our national security rely on existing encryption, including classified information, financial and health information, and critical infrastructure. Although quantum computers capable of cracking current encryption are not yet here, there is an indication that near-peer competitors may be employing a "harvest now, decrypt later" strategy of stockpiling encrypted data and waiting for the quantum future.

The National Institute of Standards and Technology (NIST) is already planning for a post-quantum future by, in part, developing public-key cryptography algorithms for security against quantum and traditional computers, and the World Economic Forum has called for a Quantum Security Coalition. Some current estimates indicate that "20 billion digital devices will need to be upgraded or replaced with post-quantum cryptography in the next 20 years," ranging from ATMs to smartphones.

Domains & Use Cases

Domains

Quantum computing is a new technology that uses quantum physics to address issues that are too difficult for traditional computers to solve.

Quantum cryptography is the practice of techniques for secure communication in the presence of adversarial behavior. Cryptography is constructing and analyzing protocols that prevent third parties from reading private messages.

Quantum communication is the transmission of data along optical lines and takes advantage of the laws of quantum physics to protect data.

Quantum sensing looks at the quirks of quantum systems to design new and better sensors. From detecting small impulses in the body to identifying an earthquake, quantum sensors offer a significant edge over conventional classical mechanics in terms of precision and accuracy.

Quantum materials have properties including quantum fluctuations, quantum entanglement, quantum coherence, and topological behavior that are unique to them.

Quantum technologies will enable shifts towards novel computing, information regimes, and sensors with exquisite accuracies and sensitivities with impacts across many sectors of industry and society. Those shifts will occur across five principal domains of quantum technologies: quantum computing, quantum cryptography, quantum communication, quantum sensing, and quantum materials.

Quantum computing will allow for the computation of difficult-to-solve algorithms related to optimization, machine learning, and the breaking of asymmetric cryptography. It is also ideal for performing computational simulations of fundamentally quantum systems for chemical and materials discovery, for which classical digital computing is poorly suited. Quantum cryptography is being researched as an alternative approach to current methods of asymmetric cryptography for robustly securing data against attacks by a quantum computer. Quantum communication across networks of nodes capable of sharing entanglement will allow for highly secure (and possibly even provably secure) data transfer. Quantum communication is also being explored as a way to enhance sensor synchronization across a network of sensors. Quantum sensors are being researched to realize numerous sensing modalities that perform as well as or better than other classes of sensors for certain sensing applications with some combination of smaller size and weight, lower power, and lower cost. Finally, quantum materials are materials that host electronic, magnetic, and photonic behaviors that emerge from quantum phenomena inherent to the material, enabling these materials to serve as platforms for technologies with applications that include energy storage and power infrastructure, quantum information processing and memory, and advanced computing. These quantum technologies promise to advance capabilities in five major industrial sectors, listed in the sidebar.

The next section provides a summary of proposals for and research on how quantum innovation may impact society in each industry. Besides these five industries, it is likely quantum will impact society in other industries as well, including media and entertainment, consumer goods, and insurance.

- Life Sciences and Healthcare
- Financial Services
- Energy, Earth Sciences, and Climate Change
- Logistics, Transportation, and Space Technology
- Defense and National Security

Life Sciences and Healthcare

Quantum technologies are expected to benefit healthcare by means of advancements promised by quantum computing and quantum sensing. Quantum machine learning algorithms for classification and anomaly detection problems can be solved on quantum computers, enabling medical care providers to perform earlier and more accurate diagnoses and match personalized medicine solutions to individual patients. Further benefits for life sciences and healthcare include increased speed in developing vaccines and pharmaceuticals. Drug discovery has historically been a slow process, demanding explorations of a vast parameter space of chemical compositions, molecular structures, and methods of synthesis, followed by a lengthy process of evaluating how the drug performs under the complex conditions of real-world use as a treatment. As witnessed with the rapid discovery of the novel coronavirus vaccine, the timeline from drug discovery to patient availability is fundamentally limited by the need to evaluate carefully and completely what the drug will do in a real person's body, including how it will interact with other molecules.

With quantum computers, scientists will be able to simulate molecules for testing, providing a pathway to more rapid evaluations of drug safety and efficacy. In a similar fashion, life sciences researchers can use quantum computers to study molecular interactions to advance their understanding of how chemicals in the environment might impact biosystems and agricultural systems. Quantum sensing is another type of quantum technology expected to impact life sciences and healthcare by advancing point-of-care diagnostic capabilities with accurate, sensitive sensors with small sensor units. For example, optically pumped magnetometers (OPM) can leverage quantum phenomena in alkali atoms to perform magnetoencephalography measurements with greater signal sensitivity, improved spatial resolution and uniformity, and lower system size and complexity, extending the application space for this neuroimaging technique. On the business administration side, quantum computers can be used to solve optimization problems pertaining to the optimized pricing of treatments and services.

Financial Services

The financial services sector, which contributes $1.5 trillion to U.S. GDP and employs about 6.6 million Americans, stands to benefit greatly from quantum computing, quantum cryptography, and the use of quantum communications networks. In particular, the needs of finance, more so than many other industries, are well-suited to capabilities that will be enabled by quantum computers in the near term. Thanks to the highly parallelized nature of quantum computation, the ability of quantum computers to solve large multidimensional optimization problems will allow financial managers to rapidly optimize portfolio allocations for assets with price movements that have been too volatile for rapid optimization on classical computers.

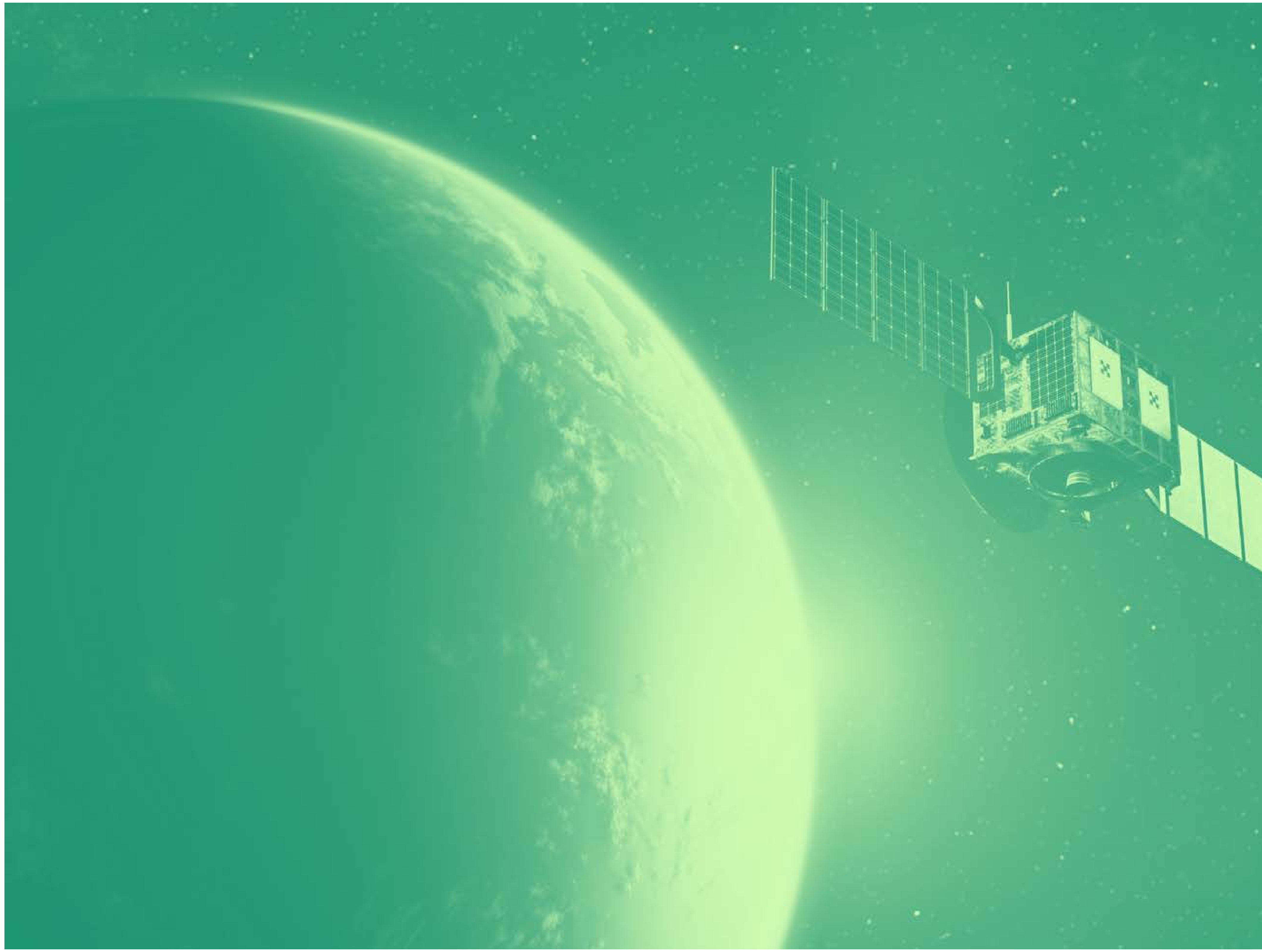
For investors who demand more accurate risk assessments under various potential scenarios, more rapid optimization solutions calculated by quantum computers can help this industry manage risk and improve the efficiency of capital allocation. Lenders can similarly use quantum computers to make more precise calculations about credit risk, leading to better lending rates and less risk from defaults. Financial services can employ quantum networks to perform exquisitely time-synchronized market actions. Quantum networks and quantum cryptography can be used to securely and privately transfer data and secure data against future encryption hacks by quantum computers.

Energy, Earth Sciences, and Climate Change

Quantum computation and simulation are expected to accelerate progress towards greater energy efficiency and sustainability, climate resilience, and the ability of earth scientists to study and understand complex geological and climate systems. With sufficient progress in quantum computation and simulation, researchers expect to be able to predict the composition and structure of materials for catalysis, oxygen transport, CO2 capture, and energy storage. Solutions to optimization problems, such as those pertaining to directing traffic flows and energy supply chains, designing efficient pipeline networks, and managing power grid demand response, can be accelerated by sufficiently powerful quantum computers. Similarly, the speedup of tasks such as seismic imaging and inversion, reservoir simulation, and computational fluid dynamics, thanks to the increased rapidity with which quantum algorithms can solve nonlinear differential equations relative to their classical counterparts, could lead to both improved climate and weather forecasting. Consequently, industries dependent on weather, including shipping, transportation, and food production, and governments and individuals attempting to predict and prepare for climate and weather disasters can make better plans based on better predictions. In addition to the benefits conferred by speedups to certain computations and simulations by quantum computers, this sector is expected to see advances from technologies related to energy storage and power infrastructure based on emerging quantum materials.

Logistics, Transportation, and Space Tech

The logistics and transportation sectors are expected to benefit in the near term from the acceleration of optimization and machine learning algorithms by quantum computers. Quantum optimization algorithms will be able to calculate shipping, trucking, and delivery routes and air traffic control solutions more quickly than classical solutions. As a result, one can expect a reduction in congestion across transportation domains and expedited cargo delivery, increasing efficiency, and profit in any industry that depends on the movement of goods for supply chain management and distribution. Additionally, with speedups to control system optimization and machine learning by quantum algorithms, quantum computers can train algorithms for autonomous vehicles and robots used for warehouse and seaport automation much faster than classical computers running classical algorithms. In the space domain, ground-satellite quantum communications and satellite-based quantum entanglement distribution will enable quantum space communications, eventually leading to a worldwide—or even solar system-wide—quantum communications network.



Defense and National Security

In addition to the advantages quantum technologies are expected to lend to the logistics, transportation, and space technology sectors that will carry over to the defense and national security sector for tasks associated with optimizing supply lines and routing of transported personnel and materiel, there is great potential for quantum sensors to enable capabilities across battle domains. For example, there exist many opportunities for improvements to assured positioning, navigation, and timing (PNT) in a GPS-denied environment enabled by quantum sensing technologies. Stable holdover timekeeping and accurate synchronization can be achieved by using atomic clocks. Navigation and strategic grade inertial navigation systems (INS) that use intrinsically accurate inertial sensors and gyroscopes based on quantum phenomena, such as atomic interferometry and nuclear magnetic resonance, can provide better performance at a given cost and size, weight and power (SWaP) than other, non-quantum INSs. The exquisite absolute accuracy of optically pumped magnetometers (OPM) makes them ideal magnetic field sensors for magnetic navigation capabilities based on matching the measured magnetic fields along the trajectory of the platform to positions on a magnetic field map. Rydberg atom electric field sensors can enable geolocation and radio navigation, as well as advanced, resilient communications, with sensors whose physical size does not scale with the sensing band and can be formed into conformal, embedded receivers. Quantum communications can be used to transmit secret data with provable privacy and security. Further opportunities exist in the space domain, where entanglement across a quantum network can enable exquisite timing synchronization for imaging beyond classical optical limits. Finally, technologies based on emerging quantum materials are expected to advance many capabilities relevant to the defense and national security sector, including the decrypting of adversary's secret information.

Lessons from Emerging Technologies

As new technologies emerge and gain autonomy, ethical concerns are raised, and challenges are not always easy to predict, creating uncertainty. Limiting risk and planning for unintended consequences and ethical difficulties then becomes paramount. One way to reduce the risk of uncertainty is by reviewing and using lessons learned from prior emerging technologies such as cybersecurity and artificial intelligence. The following illustrative examples of ethical challenges have surfaced with existing technologies and could inform and help shape the policy and ethics conversation.

Lesson Learned: Cambridge Analytics

One of the most infamous examples of data misuse and lessons learned occurred in 2018. News outlets revealed that a UK political consulting firm acquired and used personal data from Facebook users that was initially collected from a third party for academic research. In total, Cambridge Analytica misused the data of nearly 87 million Facebook users, most of whom had not given any explicit permission for the company to use or even access their information. The consequences resulted in Cambridge Analytica going bankrupt within two months of the scandal, while Facebook was left with a $5 billion fine by the Federal Trade Commission.

Workforce Gaps

Workforce shortage and talent development gaps have plagued the technology industry for years. As the pace of innovation increases, companies of all sizes are racing to adopt the latest emerging technology, creating the need for information technology teams that have the ability to enable new technologies within their companies. However, there is a severe talent shortage in emerging technical fields, with only 52 unemployed workers available to fill every 100 job openings in the U.S. This is exacerbated by the lack of a prepared diverse talent pool to fuel more effective and ethical innovation within technology teams.

Early awareness for K-12 and continual training of employees in cybersecurity have fallen behind the need for workforce talent. The demand for cybersecurity professionals has surged over the past decade. According to (ISC)'s 2020 Cybersecurity Workforce Study, the global cybersecurity workforce needs 3.1 million people, with nearly 400,000 open cybersecurity positions in the U.S. In addition, more than half of survey respondents (56%) say that cybersecurity staff shortages are putting their organizations at risk.

"This remains an emerging industry with threats shifting almost on a daily basis, including new threat actors, new technologies, and the evolution of 5G," says Erin Weiss Kaya, a Booz Allen Hamilton talent strategy expert for cyber organizations. "Yet we're still dealing with an 0% unemployment rate, with far more demand than we have current supply." The cybersecurity industry will only grow as risks increase, making it imperative to start to implement strategies and attract talent now to begin to close the skills gap.

Without early intervention and planning, quantum workforce gaps will mirror those of cybersecurity as more companies adopt quantum technologies. This shortage of human capital can influence technological development, hindering the adoption of emerging technologies and limiting the ability of organizations to extract value from new offerings. The workforce shortage issue is best witnessed in cybersecurity, a good proxy to estimate the future need for quantum workforce talent needs.

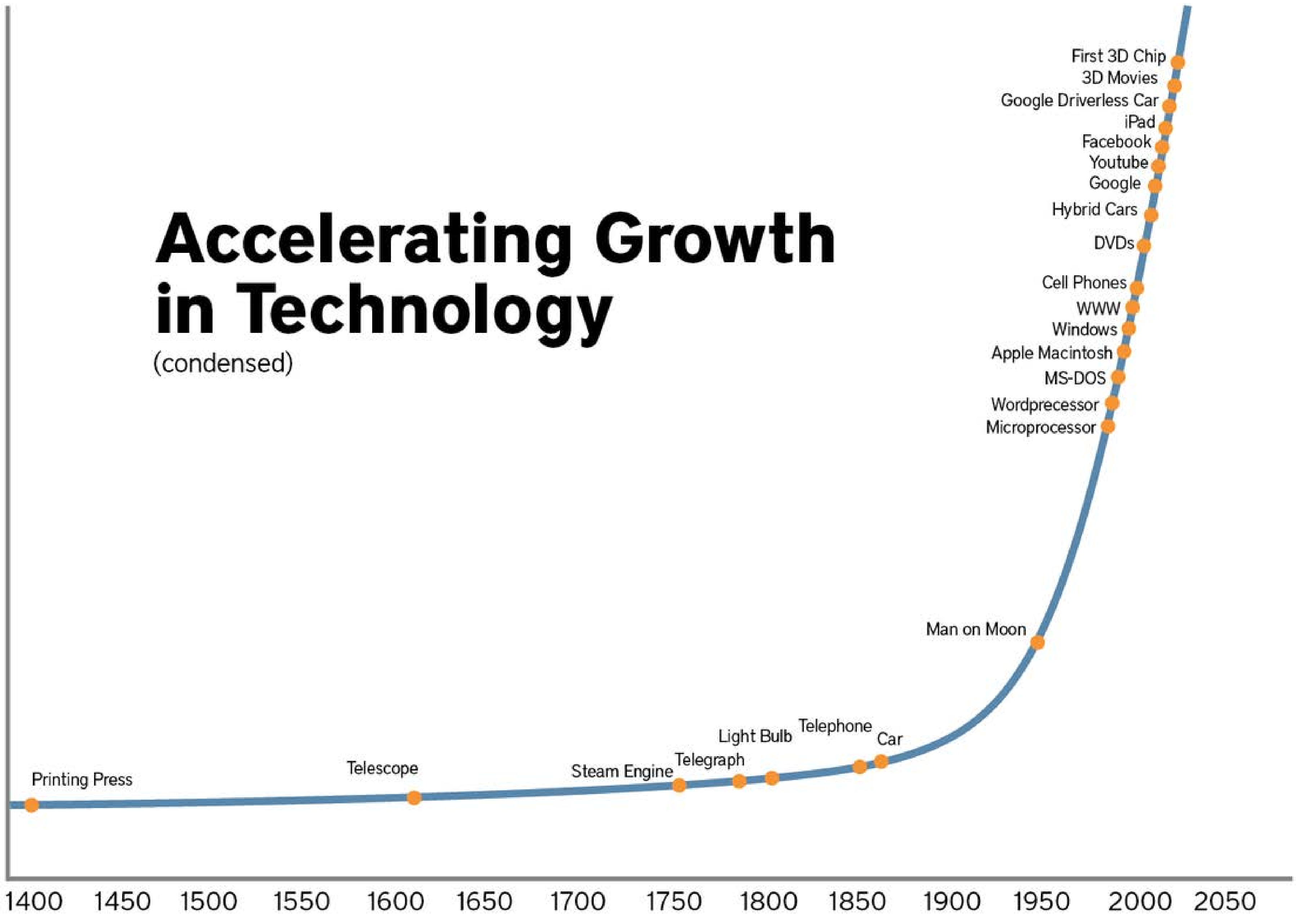
The Pacing Problem

Historically, existing regulatory structures have been slow to adapt to technological advances, and regulatory agencies generally are risk averse.

Technology has changed exponentially over the last two decades, ushering in new innovations that span industries and sectors, changing the structure of cities and humanity functions. Today, technology growth is on an exponential curve and touches almost everyone. Changes that once took centuries now happen in decades, if not years and months. Ubiquitous hardware, artificial intelligence, digitization of data, advanced robotics, deep learning, and the internet of things are fundamentally transforming how people live. Transformational new technologies are appearing at an increasing pace, outdating existing technologies as quickly as three to five years.

Yet, policies, regulations, and standards have not kept pace. Rapid adaptation to emerging technology without policy regulations and ethical standards to guide innovation poses significant hurdles to the technology industries where change occurs rapidly. "If the volume and pace of digital transformation continues, the existing regulatory approach won't work," says Bakul Patel, a former official at the US Food and Drug Administration.

The gap between technological advancements and the mechanisms intended to regulate them, often called the "pacing problem," is only growing wider. "There's a disconnect between the speed, iterative development, and ubiquitous connected nature of digital health technologies and the existing regulatory structures and processes," says Patel. "The current regulatory approach is not well-suited to support that fast pace of development." The pacing problem has acquired new urgency due to the speed with which modern innovations are scaling. When emerging technology systems scale, or act so fast that humans cannot respond in time, then humans must rely on the guardrails and risk mitigation practices incorporated into the system. If these protections and practices are limited because developers focus on deploying the technology as rapidly as possible, the chances for unwanted and unintended outcomes increase. Therefore, it is important to incorporate risk assessment and mitigation protections early in the development of the technology and throughout the system's life cycle.



Siloed Approaches

The challenge with developing many emerging technologies is that an often-insular set of developers and programmers with short-term incentives and siloed perspectives drive development and deployment, sometimes without broader input or constraints. For technology to be successful in a connected world, it's important for stakeholders to share ideas drawn from multiple disciplines and sectors. Technology siloes create structures that limit the development of new ideas and innovation to people with similar roles and views. This can lead to resistance to change and unintended consequences for broader society.

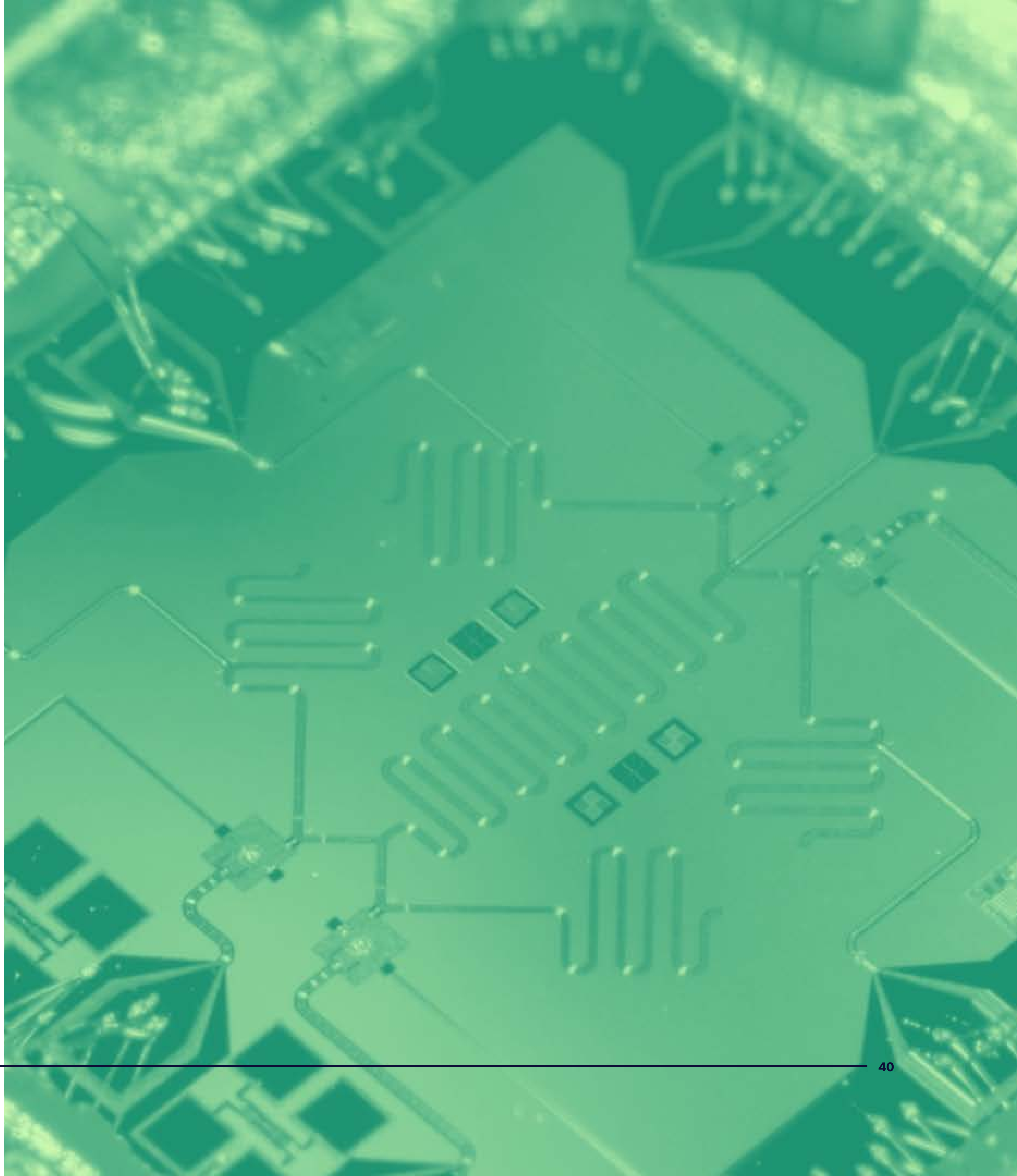
Ultimately, society must judge where it lies on the technology innovation curve. Given that quantum is in the early stages of development, speed and collaborative frameworks, standards, and disciplines are paramount to help ward off unintended consequences. Given that society and the world's economies have been functioning with a classical understanding, and that quantum advances are just beginning to take hold, industry and government need to pursue ethics and standards for emerging technologies with an even more heightened and collaborative sense of urgency.

The Quantum Policy & Ethics Center

Defining the Problem

The quantum industry currently lacks a focused forum for cross-sector dialogue, research, and programming dedicated to advancing policy, regulations, standards, and ethics. An open forum for multi-stakeholder international collaboration and the governance of this critical suite of game-changing technologies is needed to accelerate responsible quantum development, adoption, and impact in an era of rising global competition and related supply chain and industrial security concerns. Such an open forum would advance the understanding and development of sound quantum policy, regulations, and standards required to accelerate the organizational ability and confidence to succeed and maximize social good in a quantum-enabled world. Dialogue across government, industry, investors, academia, and community is required to address quantum policy dynamics and ethics implications holistically.

What is needed is a sustained, independent, cross-sector capability to help public and private sector organizations understand the emerging and dynamic quantum policy landscape and build the capacity to shape a thriving, commercially-driven quantum industry focused on positive social impact.



Purpose and Overview

The Center will serve as a global resource and convenor for government, industry, investors, academia, and community to come together to dialogue, research, formulate, and apply solutions to quantum policy and ethics issues. A forward-looking and focused collaborative platform among like-minded countries and industry organizations can help the U.S. and its partners align ecosystems and maintain competitive advantages vis-à-vis rivals. As the U.S. government focuses on delivering national security and economic prosperity, the entire quantum ecosystem will benefit from an open, collaborative mechanism for developing cross-border, industry-wide policy and ethics initiatives, roadmaps, and solutions aligned with quantum's fast-moving technology development and maturation timeline. Ultimately, the Center will aid in the time-sensitive formation of a thriving, principled, and inclusive global quantum industry that will bring needed novel capabilities to bear at scale on heretofore intractable global challenges.

The Quantum Policy and Ethics Center will help to advance U.S. leadership in socially responsible quantum industry development by facilitating dialogue between a community of multidisciplinary experts and serving the quantum ecosystem through offer research, analysis, thought leadership, advisory services, tools and resources, memberships, training programs, and awareness campaigns on key quantum policy and ethics issues.

Greater Washington as a Hub

Given the need for a function of global scope and for a dialogue forum spanning sectors, industries, and areas of expertise, Greater Washington (the District of Columbia, suburban Maryland, and Northern Virginia) is a natural home for the Center. The region has all the hallmarks of a world-class technology hub. The region boasts the third highest density of tech talent in the U.S. after San Jose and San Francisco and hosts the world's most active data center market handling more than 70% of the world's internet traffic. Greater Washington is the headquarters of the U.S. national security apparatus and home to the biggest purchaser of goods and services — including technology — in the world: the U.S. Federal Government. Furthermore, Greater Washington is striving to become the "Capital of Quantum" and is building a strong quantum industry cluster foundation across the value chain, from education and research to engineering, manufacturing, and applications. The region is home to leading academic research institutions in quantum science and engineering, multiple federal agencies guiding the National Quantum Initiative, and industry leaders with large investments and interests in quantum technologies.

Quantum experts and practitioners across the world will benefit from such a focused center of excellence with proximity to the U.S. Federal Government and other key stakeholders located in Greater Washington. These include well-established and startup quantum technology firms, industry, and professional associations, global embassies and trade missions, think tanks and nonprofits, federally funded research and development centers (FFRDCs), world-class quantum academic institutions, and international organizations such as The World Bank. Importantly, the Center will coordinate closely with the U.S. quantum industry networks driving innovation and manufacturing, such as the Quantum Economic Development Consortium (QED-C) and Quantum Industry Coalition; other regional ecosystem efforts, such as the Chicago Quantum Exchange; as well as relevant global counterparts (e.g., Sydney Quantum Alliance, Netherlands Quantum Delta) and related international quantum governance efforts underway at organizations such as IEEE and the World Economic Forum. High-profile events in the region, such as the Quantum World Congress, provide ready opportunities to spotlight the Center's work and convene global leaders around quantum policy and ethics.

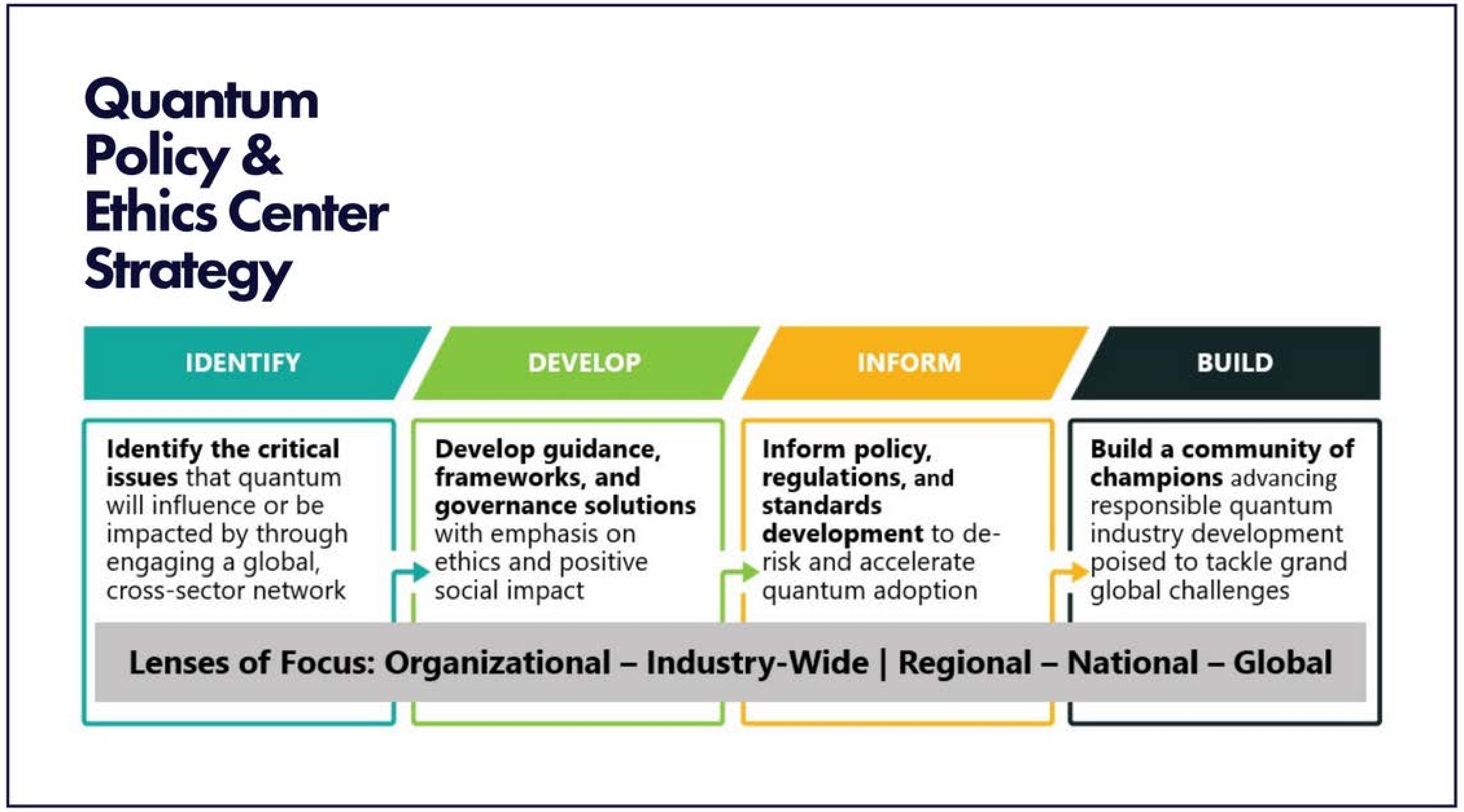
Center Strategy, Focus Areas, and Delivery Model

The Center will provide a means for subject matter experts on ethics and policy to develop models for governance and practice that meet the demands of quantum technology advancement, align ecosystems, and speed global commercial adoption. The strategy is laid out in the graphic included on this page.

Practitioners and specialists will collaborate on a range of activities related to policy and ethics, aligning with quantum maturation and adoption timelines across the key domains of computing, cryptography, communications, sensing, and materials. The Center will deliver programming within the following pillars:

- Establishing an open global, cross-sector forum of experts and practitioners
- Facilitating collaborative research, analysis, and consensus building
- Publishing action-oriented thought leadership and amplifying it through marquee events
- Driving strategic initiatives for industry adoption and conducting advisory services
- Building capacity through a training, credentialing, and resources platform

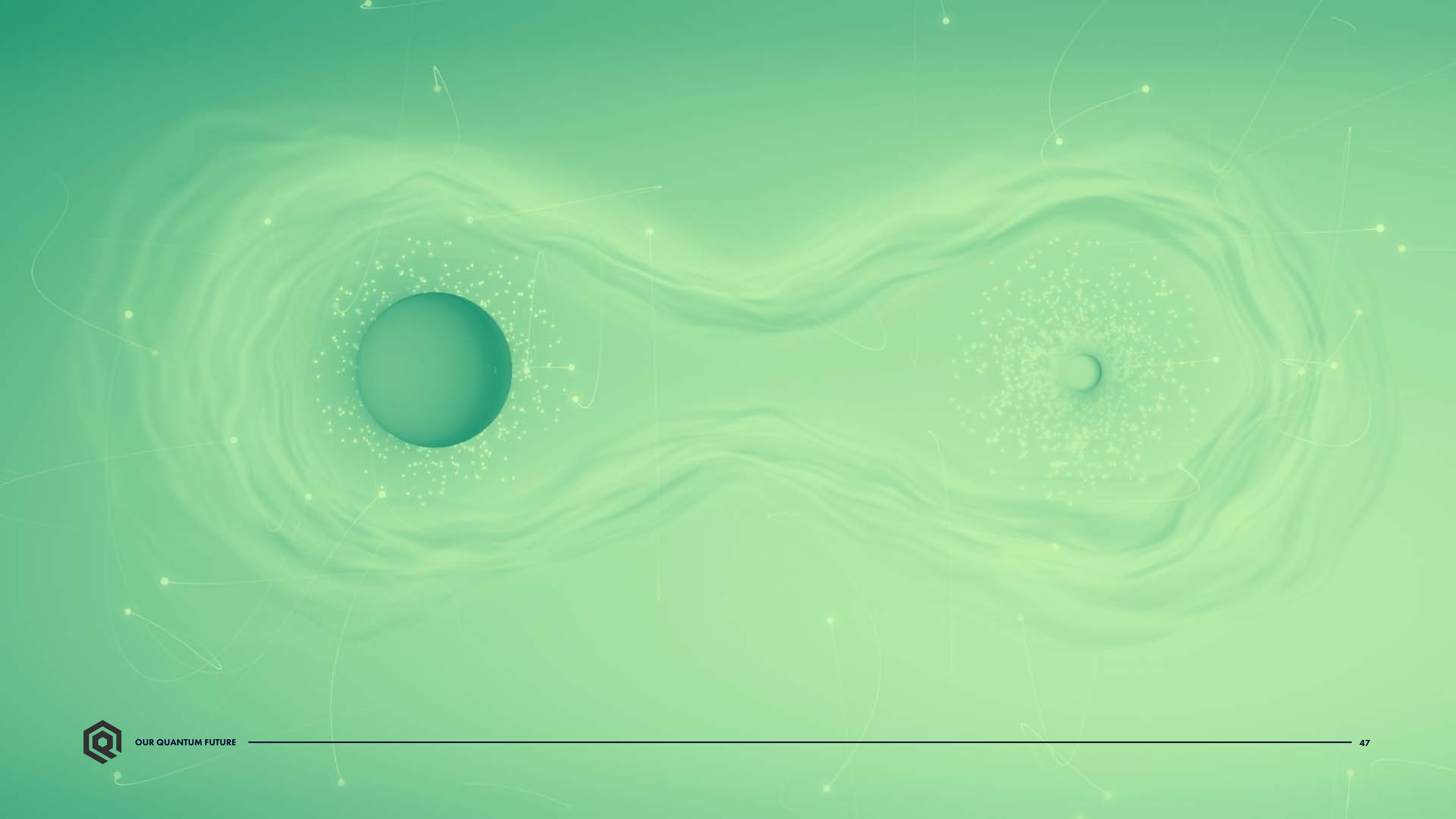
As an open forum, the Center will conduct workshops, public events, podcasts, and awareness campaigns and will organize an annual policy and ethics track at the Quantum World Congress — an annual global quantum industry event held in Greater Washington. Emphasis will be placed on lessons learned from previous emerging technologies and intentional input from diverse perspectives across all programming. Visiting scholars, interns, apprentices, graduate students, and postdocs will support Center programming and utilize the Center as a resource for learning. The Center will be embedded among major FFRDC, academia, and think tank institutions in Greater Washington and will collaborate with national quantum industry organizations aligning on key best practices, standards, regulations, and policies to propel quantum forward. It is envisioned that a cross-sector advisory committee would guide the Center's programs, deliverables, and impact.




Government
Academia
Research & Development
Investors & Funders
Industry Buyers & Users
Quantum Builders
Community
Quantum Policy & Ethics Center

Conclusion

Quantum offers the possibility of major breakthroughs across multiple sectors providing opportunities to improve lives, improve business processes and outcomes, and develop new solutions for humanity's most challenging problems. Quantum innovation, however, if left unchecked, also has the potential for nefarious or unintentionally harmful activities with significant negative impacts on society and international relations. There is increasing "concern about the fragmentation of the global technology sector," including the rise of divergent standards, regulations, and values, as the Chinese have outpaced U.S. investment in quantum technologies three-to-one. Lastly, despite the increase in activities from industry and government, there is a gap in the marketplace for open, public dialogue to advance ethical behavior and provide broad, well-rounded insights and views on important quantum issues. These concerns merit evaluation to identify policy remedies, maintain U.S. economic global competitiveness, and advance good governance. Government and philanthropic investment in a Quantum Policy and Ethics Center located in Greater Washington provides an avenue for consistent open communication, quality training, rigorous research, and accelerated development of standards, regulations, and norms that advance our interests and prosperity.



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POTOMAC QUANTUM INNOVATION CENTER

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The Potomac Quantum Innovation Center is an initiative of Connected DMV, an initiatives-based, charitable 501(c)(3) organization that works with regional organizations across Greater Washington to help drive ongoing improvements to social, digital, and physical infrastructure. Connected DMV focuses on initiatives that span local jurisdictions and require public-private-academia-community collaboration to best achieve the dual objectives of enduring economic health and social equity.