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Key Points

Many quantum information and science technologies (QIST) are maturing at a pace that will help solve critical Department of Defense (DOD) capability gaps, including requirements for precision timing and navigation, sensing, and radio frequency reception. With the right investment and focus, DOD could field practical warfighting quantum applications in five years or less.

DOD investment in key enabling technologies such as integrated photonics, miniaturized lasers, classical control devices, and compact atomic cells can accelerate the entire industry.

Many QIST applications that could provide value to national security missions will be specialized for DOD. DOD should identify unique quantum applications it requires and focus its investment on maturing and integrating QIST applications for those use cases.

Classic DOD acquisition program timelines, quantities, and allowed profit margins will be insufficient to meet the venture capital investor expectations of some small startup companies that have made significant progress toward developing quantum technologies. Moreover, DOD's small business programs are ill-suited to help these small startup companies transition to participate in the defense acquisition system. DOD must address the unique needs of these companies to foster and sustain the diversity of the quantum industry.

DOD must cultivate a robust quantum industrial base by establishing an enduring QIST acquisition program of record. DOD leaders must commit to buying a product if they are field pragmatic and rugged quantum QIST capabilities that can yield operational advantages in a peer conflict.

The Quantum Advantage: Why it Matters and Essential Next Steps

Part 3: Operationalizing a Quantum Advantage

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Abstract

Certain quantum-based technologies have matured beyond the theoretical and experimental stages to the point that they can be developed into pragmatic applications that mitigate critical U.S. military operational vulnerabilities. Quantum scientists typically categorize quantum information science and technologies (QIST) into three main categories: sensing, communication, and computing. Of these, sensing applications like quantum clocks, radio frequency receivers, and inertial sensors are the most mature and most relevant to warfighter needs, given the growing threat to resilient position, navigation, and timing in highly contested environments.

To win the quantum technology competition with China, U.S. defense policymakers should allocate resources to further the development of a robust quantum defense industrial base and establish programs of record that will deliver QIST applications to its warfighters. As part of this effort, U.S. defense leaders should also develop a defense-focused QIST strategy that maps quantum technologies to military capability gaps and then identifies and prioritizes near-term QIST capabilities that could be fielded within five years.

At the most basic level, delivering a quantum advantage to warfighters will require DOD to move beyond research efforts and begin buying quantum technologies. Otherwise, potential solutions will fail to transition from the lab to operational reality. DOD must also take a more proactive role in supporting the QIST industrial base facilitization because many defense quantum applications do not share a civilian market. DOD should identify QIST applications that have high potential for near-term fielding and then map them to lead platforms and missions for requirements development. This will provide engineers with the form/fit/function constraints to which they need to design and provide the non-recurring costs necessary to move quantum technologies to full-scale production.

Introduction

Recent advances in the field of quantum mechanics, material sciences, and other technologies have created the potential to use quantum particles in ways that will advantage U.S. warfighters. U.S. adversaries have long studied the U.S. military and its concepts of operation, and many of the foundational technologies that the U.S. way of warfighting depends on are now at risk. Quantum capabilities could create new options to subvert an adversary's warfighting strategy and defeat capabilities designed to counter long-held American asymmetric advantages that have provided the U.S. military and its partners with an overwhelming overmatch. For example, China is fielding weapon systems to counter Link-16 secure datalinks and position, navigation, and timing information from the Space Force's Global Positioning System (GPS) satellite constellation, which is used by all U.S. forces. China's countermeasures threaten the U.S. ability to assure and protect its own assets, as well as those of its partners and allies. This ultimately erodes America's ability to dissuade, deter, and defeat aggression anywhere on the globe.

The ability to close kill chains and execute other fundamental military missions may face severe challenges if the U.S. does not advance its execution of core functions; it is time to evolve to next-generation solutions. Quantum information and science technologies hold the potential to help maintain or restore some key U.S. operational advantages. This report is intended to provide U.S. defense policymakers with an overview of the quantum defense industrial base, the U.S. government's efforts to support the development of quantum capabilities, and the challenges quantum companies face in growing into a viable industry.

The ability to close kill chains and execute other fundamental military missions may face severe challenges if the U.S. does not advance its execution of core functions; it is time to evolve to next generation solutions. Quantum information and science technologies hold the potential to help maintain or restore some key U.S. operational advantages.

Applied quantum technologies have matured to a point where some capabilities, such as timing, inertial sensing, or radio frequency receivers, could be integrated onto major weapon systems in five years or less. The major defense prime contractors, government laboratories, major information technology (IT) companies, and small university-spun startups comprise the primary entities developing QIST applications. Many of the small startup quantum companies are leading the development of these capabilities, but they have unique challenges that the U.S. Department of Defense (DOD) needs to consider if they want to accelerate the development, integration, and large-scale production of QIST capabilities for the warfighter. A main challenge to meaningfully fielding any quantum capability is the immaturity of the quantum industrial base. Without a strong market demand for many bespoke military applications, the quantum industry will continue to be characterized by small-batch, artisanal production—even for defense prime contractors.

This report is the final of a three-part quantum series intended to educate senior U.S. defense leaders about quantum technologies. The first report provides a basic explanation of the quantum science that underpins this rapidly developing field. The second is a primer on quantum computing to provide senior defense leaders with an understanding of the different types of quantum computers and their properties and to establish a knowledge base from which to evaluate these machines. This third report builds on the first two, focusing on how to cultivate the quantum defense industrial base to provide U.S. warfighters a quantum advantage in a peer conflict.

The new quantum advantage

Quantum capabilities are not new: long-established applications of quantum phenomena include atomic clocks, lasers, solid-state semiconductors, solar cells, LEDs, and charge-coupled devices (CCD) used for digital imaging and optical sensors, among others. These devices took advantage of quantum properties but could not directly control them. What is different about today's "second quantum revolution" is that researchers are now able to apply advances in classical control technologies to deliberately isolate, control, manipulate, and measure atoms and subatomic particles.[1] This enables QIST entrepreneurs to capitalize on quantum behavioral principles like superposition or entanglement to engineer radically new technologies. Quantum scientists typically categorize quantum information science and technologies (QIST) into three main categories: computing, communication, and sensing. Technologies in each of these categories have the potential to provide an operational advantage to the nation that develops, fields, and integrates them into its military forces.

Quantum computing has generated the most enthusiasm and commercial financial investment because of its potential to rapidly solve algorithms that traditional binary computers cannot. Problems that quantum computers could solve include breaking encryption algorithms that secure financial data and national security secrets. Quantum computers, however, are not simply super-fast supercomputers. There are many uses where binary computers will remain faster and more accurate. Instead, quantum computers are best understood as extremely powerful, specialized processors that will have the ability to solve "intractable" problems that today's strongest supercomputers cannot. Examples of these complex problems include cracking the most advanced encryption schemes, modeling complex chemical and biological interactions, solving thorny optimization problems, and rapidly advancing machine learning. The fields quantum computers will impact include everything from financial markets to national security, intelligence, and logistics. Yet despite much of the hype and enthusiasm that surrounds quantum computing, these devices are early in their development—a practical, error-tolerant, universal quantum computer is still roughly a decade away, and even that timeline will require aggressive investment and development.[2]

Quantum communication and networking will be essential to scaling quantum computing. Researchers are also exploring how to use quantum networks for distributed sensing, other secured communications, and encryption.[3] Future quantum networks could transport quantum information or even "teleport" information instantaneously across vast distances.[4] These technologies, however, are still immature when compared to the level of sophistication needed to provide a practical capability.[5] Although scientists are diligently working to solve the many technical challenges of fielding quantum networks, their operational utility on major weapon systems may be limited in a highly contested and dynamic battlespace.

Currently, quantum sensing is the most mature and relevant QIST application for warfighters, and U.S. defense leaders should focus their efforts on developing and fielding these quantum-enabled capabilities.[6] Quantum sensors are powerful because of their extreme sensitivity to the external environment.[7] While this sensitivity can make filtering external stimuli a challenge, quantum sensors can detect signals that are too weak for today's most advanced technologies and can improve the precision and accuracy of sensing. Quantum sensing applications include timing, inertial devices, magnetometers and gravimeters, and ultra-wideband radio frequency receivers. These capabilities could provide resilient position, navigation, and timing in highly contested environments; improve electronic protection and electronic attack; detect and map underground tunnels; enhance undersea sensing and navigation; render the oceans transparent; and detect and analyze radio frequency emissions ranging from zero to 20 GHz in a single antenna. As quantum sensing and control technologies advance, other applications that provide a combat edge for warfighters could emerge.

Despite the significant operational potential of fielding these capabilities, the quantum industry is still very nascent, and in addition to identifying and developing military-specific QIST capabilities, the DOD must also invest in building its quantum defense industrial base. When determining where to prioritize its resources, U.S. senior leaders should focus on those near-term, military-specific quantum technologies that do not benefit from substantial commercial investment. Some QIST applications, such as computation, receive enormous amounts of corporate, private, and venture capital for development. Moreover, the ability of private industry to move fast, pivot their development efforts toward more promising technologies, and produce a viable computer can outpace DOD's developmental processes. Defense leadership should encourage commercial and private industry to lead the charge in areas where there is clear commercial activity and investment. Conversely, the DOD should direct its developmental focus and resources to national security-specific applications, which may not have strong commercial support. DOD should also accelerate QIST more broadly by supporting the maturation and production of the classical enabling components of QIST that underpin a broad swath of quantum technologies, such as atomic vapor/ultra-high vacuum cells and integrated photonics.[8]

A race is underway, and the winner will hold an outsized advantage over those who trail. Focusing DOD's development and fielding on quantum sensors will be a key step toward winning the competition to develop a robust quantum industry and field the critical advantages QIST can provide.

U.S. adversaries are also working toward capabilities to exploit the advantages quantum sensing technologies offer, which is another reason why it is critical for DOD to understand and shape the development of these capabilities and their industrial base. A race is underway, and the winner will hold an outsized advantage over those who trail. The Congressional Research Service (CRS) recognizes the two sides of this coin and notes that if quantum technologies are integrated onto military capabilities, "They could hold significant implications for the future of international security writ large."[9] Focusing DOD's development and fielding on quantum sensors will be a key step toward winning the competition to develop a robust quantum industry and field the critical advantages QIST can provide.

The Quantum Scale-up Challenge

DOD has not been stagnant when it comes to pursuing quantum applications for tomorrow's challenges. The *2023 National Defense Science and Technology Strategy* designated QIST as one of DOD's "critical technology areas," meaning that DOD has identified QIST as an essential asymmetric capability needed to successfully compete against China and meet the *2022 National Defense Strategy*'s requirements.[10] Both strategies identify the urgent need for practical, ruggedized QIST technologies that can be integrated onto DOD's weapon systems to address critical capability gaps and vulnerabilities, but neither provides a sufficient compass for how to do so. It is time to develop a strategy.

Beyond the laboratory: delivering pragmatic quantum capabilities for the warfighter

The recent national focus on QIST research and development is important to advance the state of the art, but it will not deliver useful hardware to warfighters in the timelines that matter. It is crucial that senior leaders understand the quantum science behind these capabilities so they can make informed decisions about what QIST applications to pursue and, based on their educated understanding of their technological maturity, when to prioritize their development. Another challenge is that industry is not structured to manufacture new quantum devices and do so in the quantity required by U.S. warfighters.

To address this, the Department of the Air Force (DAF) should cultivate the quantum industry so it will provide its warfighters with the capabilities they need and at the scale they require to succeed in a peer conflict. The first step is for DOD to identify near-term quantum technologies that can solve critical vulnerabilities that U.S. warfighters are likely to face in a peer conflict, such as the need for position, navigation, and timing (PNT) to augment or replace GPS. For example, quantum timing integrated with quantum inertial sensors could provide warfighters with an internal, self-contained PNT capability whose accuracy exceeds current GPS solutions.[11] This analysis of applications can provide insight to prioritize prototypes that can be stressed and evaluated in operational exercises to validate their value and provide additional feedback to refine designs. Finally, creating DOD programs of record to begin acquiring QIST applications is a more viable path for maturing key quantum technologies and integrating them onto major weapon systems that provide operational capabilities to America's warfighters at the speed of need.

Increased U.S. Government support and funding is necessary but insufficient on its own to ensure the long-term health of the U.S. quantum industrial base.

Beyond this, U.S. service leaders should continue to conduct rigorous analysis to identify which advancing QIST applications can fill critical vulnerabilities and capability gaps and then prioritize the development of high-impact, near-term, military-specific capabilities. Smart investment demands a strategy tied to specific outcomes that will empower specific concepts of operation and mission requirements. Capabilities that could be fielded within five years should be prioritized for operational relevance and accelerated to prototypes that can be stressed and tested in operational exercises. Many quantum sensing applications are near or even inside this timeline—they do not need basic research and development but rather the design requirements of form, fit, and function to transition from a "lab-in-a-box" design to one that is ready to integrate onto a lead platform or weapon system.

The U.S. quantum industrial base needs a market if it is to scale

Increased U.S. Government support and funding is necessary but insufficient on its own to ensure the long-term health of the U.S. quantum industrial base. Of the approximately $1.8 billion total the U.S. Government allocated to QIST research and development in FY 2022, most is focused on quantum research and educational initiatives at government-affiliated centers.[12] While economic or technical sectors require a solid research and development base to field innovative products that advance the state of the art, viable companies grow by selling products. Studies, research, policy development, and education are critical to furthering the development of quantum technologies, but growing a robust quantum industrial base also requires market pressure—a demand signal from end users, including DOD, for actual capabilities. This means buying quantum capabilities. The U.S. quantum investment approach must account for this fundamental truth.

A 2019 Defense Science Board (DSB) study on applications for quantum technologies found that quantum technologies "offer critical value to DOD and must be pursued vigorously."[13] Although the study found that not enough analysis had been done to tie quantum capability form, fit, and function requirements to mission specifications, the DSB made very specific recommendations for senior leaders to initiate quantum sensing programs. The DSB was prescient when it implied DOD should assess how quantum technologies could provide operational advantages for specific missions, including quantum sensing technologies that are "currently poised for mission use."

This program would move the DOD quantum enterprise in the right direction, but it is not enough. To really impact and motivate the quantum industrial base, the DOD—including the Department of the Air Force—must buy quantum technologies. Stimulating a dynamic U.S. defense quantum industrial base requires clear signals of DOD's intent to *procure*. Potential profits are directly related to industrial base and venture capital investments. The more potential revenue a company is projected to command, the more funding venture capitalists are motivated to provide.[14]

The Air Force Research Laboratory's (AFRL) May 2023 demonstration of magnetic navigation, or MagNav, provides an excellent example of how to accelerate quantum capabilities to the warfighter.[15] General Mike Minihan, Commander of the Air Force's Air Mobility Command (AMC), identified navigating aircraft with precision without the assistance of external GPS signals as a critical capability gap.[16] He pushed his command to aggressively pursue solutions through a "Magnetic Navigation Open Challenge" that entails removing "the aircraft magnetic field from the total magnetic field… in order to derive a clean signal for magnetic variation."[17] A quantum magnetometer coupled with an artificial intelligence program that cleans the aircraft's magnetic field from the quantum sensor positions the aircraft by matching the magnetic field to the Earth's known magnetic map.[18]

Equipment for AMC's MagNav initiative loaded on a C-17A Globemaster III for it's first real-time demonstration on a DOD aircraft during Golden Phoenix in May 2023.

Credit: U.S. Air Force/MIT.

AMC's MagNav initiative is a template for how DOD should pursue QIST capabilities. Major operational commands should identify mission gaps that can be matched to high-potential, near-term quantum technologies. These use cases can then serve as the basis for prototype competitions that identify the best-fit modalities, most mature technologies, and best-performing companies. Moreover, stressing prototypes in military exercises can both validate the value of QIST capabilities and highlight gaps in design or integration. There are two crucial elements of this approach. First, it connects quantum scientists and engineers to warfighters, their operational challenges, and their specific needs. Second, this kind of prototype experimentation integrates QIST capabilities with other technologies, such as advanced algorithms, control systems, or even aircraft navigation models that are needed to be practical and useful to warfighters.

The U.S. Government Support for QIST Development & Education Across Multiple Departments & Agencies

At a top level, the U.S. Government is implementing a "whole of government" approach to quantum development that focuses funding predominantly on general quantum education and research. These initiatives are important because accelerating QIST applications can pace China and meet other U.S. defense requirements. However, the quantum technologies that can provide U.S. warfighters the advantages they need do not have strong commercial markets and will be extremely difficult to mature, produce, and field without significant DOD support. These research and education efforts are both crucial foundations for a healthy quantum industrial sector, but ultimately, these initiatives are limited in establishing a real quantum advantage on the battlefield—they do not *procure and field* capabilities. In other words, relying solely on a whole of government approach to develop relevant combat capabilities risks leaving quantum companies on the wrong side of the notorious defense acquisition "valley of death." This is why the DOD must assume a bigger developmental role. Many research and development projects, especially generic ones, fail to make the transition from the laboratory to the acquisition, production, and fielding of an operational capability. Ultimately, the "win" goes to the nation that can use its innovative and pragmatic quantum technologies in civil and defense applications in the real world.

The National Quantum Initiative (NQI) Act established quantum technology development as a national imperative

Congress has recognized that securing the lead in quantum science and applied technologies is a national imperative, but these initiatives fall short of what the DOD needs to build a quantum industrial base that can deliver critical defense capabilities. In 2018, Congress passed the National Quantum Initiative (NQI) Act that directed the National Institutes of Standards and Technology (NIST), the National Science Foundation (NSF), and the Department of Energy (DOE) to work together to improve quantum education, research, and workforce training.[19] To avoid creating an unfunded mandate, the NQI authorized an additional $1.25 billion for quantum research in NIST, the NSF, and DOE as lead agencies for QIST development. The NQI established the Quantum Economic Development Consortium (QEDC), a membership organization consisting of government agencies, industry, academic institutions, and other stakeholders whose charter is to "enable and grow a robust commercial quantum-based industry and associated supply chain."[20]

It also directed the National Science and Technology Council (NSTC) Subcommittee on Quantum Information Science (SCQIS), the National Quantum Coordination Office (NQCO), and the National Quantum Initiative Advisory Committee (NQIAC) to guide the actions of the many entities involved in these activities.[21]

DOE has established five separate quantum accelerators, creating formal relationships between national laboratories and universities.[22] These national quantum information science research centers (NQISRC) knit together more than 70 institutions and coordinate their research.[23] Separately, the White House designated and funds the University of Colorado, the University of Illinois, and the University of California as innovation centers in quantum science.[24] Like the NQISRCs, these hubs actively partner with quantum companies. At least a dozen other universities have set up quantum centers, hubs, or accelerators with industry partners.[25] When added to the number of U.S. quantum companies, the quantum ecosystem appears vibrant and flourishing.

In addition to the NQI, Congress has included provisions on quantum technology development in the annual National Defense Authorization Act (NDAA) since 2018. The Fiscal Year (FY) 2022 NDAA amended previous legislation to establish the Subcommittee on Economic and Security Implications of Quantum Science (ESIX), whose charge is to monitor, assess, and provide policy recommendations regarding how federal QIST investments are impacting U.S. economic and national security interests.[26] Whereas it is important to understand these dynamics, there is a distinct difference between studying and reporting on QIST investments and deliberately enacting a strategy to build a quantum industrial base that can deliver critical defense capabilities.

The CHIPS & Science Act amended the NQI Act to expand quantum research & development funding

In 2022, Congress passed the CHIPS and Science Act to restore and strengthen domestic U.S. semiconductor research and development, manufacturing, and workforce and cultivate the long-term health of the quantum industry. The CHIPS and Science Act establishes quantum information science and technology as a key "science" focus area by increasing funding for quantum research and workforce development.[27] Specifically, the Act authorizes $153 million annually over the next five years across three broad areas: 1) developing quantum applications; 2) developing a quantum workforce; and 3) building research infrastructure such as laboratories, networks, and cloud computing.[28] This focus and additional resourcing will advance quantum science broadly and is necessary to bolster the industrial base.

DOE, NIST, and the NSF are the targeted recipients of the Act's funding and associated mandates.[29] Each of these lead agencies is charged with specific research and programmatic objectives. The DOE will use the Advanced Scientific Computing Research Program to support the development of a quantum network infrastructure and establish a Quantum User Expansion for Science and Technology (QUEST) program that will broaden access to quantum computing hardware to selected researchers. Through QUEST, DOE is further charged with encouraging research and cultivating a quantum computing workforce.[30] NIST's efforts will focus on quantum networking and communications standards, and the NSF is responsible for conducting a study on America's quantum workforce, creating initiatives to incorporate quantum information science and engineering into STEM curricula at all levels of education, and establishing a program to train K-12 educators and their students on the core principles of quantum science.[31]

While these national initiatives are clearly important, they do not address DOD-specific quantum needs or provide for DOD equities in relevant competitive timeframes—any time now through 2035. The DOD will eventually and indirectly benefit from these broad efforts to advance quantum science and cultivate a QIST workforce, but more must be done to ensure that warfighters benefit from QIST in critical temporal windows of risk. CHIPS and Science Act funding will not substantially alter the QIST industry for at least a decade, and potential benefits to DOD will lag that timeframe.[32] U.S. warfighters need mature QIST capabilities integrated onto their weapon systems in the next three to five years to close critical operational vulnerabilities and keep pace with China, the U.S. military's pacing threat.

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The trilateral AUKUS security partnership is critical to accelerating the development & integration of QIST defense capabilities

To move the needle on *delivering* game-changing capabilities to U.S. and allied warfighters, DOD and the Administration must also smooth the way for trusted partners and allies to buy U.S. quantum technologies and for the U.S. to procure allied capabilities. Lowering these barriers can accelerate innovation inside quantum companies, expand the quantum supply base, and increase potential production opportunities for U.S. quantum companies.

In September of 2021, Australia, the United Kingdom, and the United States announced an "enhanced trilateral security partnership," colloquially called AUKUS, to "deepen diplomatic, security, and defense cooperation in the Indo-Pacific region" and counter an aggressive China.[33] This partnership will advance quantum technologies and grow the quantum industrial bases of the United States and two of its closest allies. By engaging AUKUS quantum companies, DOD can stimulate rapid capability development, grow a robust ecosystem, and establish a stable supply chain across the trilateral partners.

While defense media and other outlets focused primarily on the AUKUS Pillar One initiative that supports Australian acquisition and development of nuclear submarines, AUKUS Pillar Two will "enhance joint capabilities and interoperability, focusing on cyber capabilities, artificial intelligence, quantum technologies and additional undersea capabilities."[34] This second AUKUS initiative could prove far more transformational than Pillar One. RAND has lauded AUKUS for its potential for "revolutionizing how the U.S. works with a select group of its most capable allies through the extraordinary depth of technological development, access to highly classified materials and expanded sharing of intellectual property."[35] Pillar Two's focus on quantum could leverage the respective strengths of each nation, allowing quantum companies to share not just intellectual property but technologies and supply chains to rapidly advance the state of QIST.[36]

Quantum technological development under the AUKUS Quantum Arrangement (AQuA) aims to help "accelerate investments to deliver generation-after-next quantum capabilities."[37] Initial efforts over the next three years will focus on quantum position, navigation, and timing (PNT) sensors. Prioritizing quantum PNT solutions makes tremendous sense since quantum PNT devices are the most mature of the QIST capabilities, and PNT is foundational to coalition cross-domain operations in the Indo-Pacific theater.

To ensure the success of Pillar Two, DOD must address the policy and regulatory obstacles to sharing research, technology, and the export and import of capabilities and hardware. The International Traffic in Arms Regulations (ITAR), Foreign Military Sales (FMS), and Buy America restrictions could present significant barriers to scaling production of key quantum capabilities.[38] ITAR often restricts the transfer of technical data as well as collaborative research and experimentation, thereby obstructing the ability of even America's most trusted partners to work together to advance state-of-the-art capabilities.[39] Even when this kind of collaboration is permitted, FMS and Buy America restrictions can constrain the export or import of technology among allies.

Congress has recognized how these statutes and limitations could adversely impact the implementation of AUKUS and introduced legislation to carve out exemptions for the AUKUS partners and expand selected privileges to Canada.[40] The Truncating Onerous Regulations for Partners and Enhancing Deterrence Operations (TORPEDO) Act would expedite the process of exporting certain U.S.-controlled technologies and reduce the barriers to sharing information across AUKUS. Sharing information is crucial not only to stimulating technological development but also to reducing unnecessary redundancy within companies. U.S. companies currently must firewall their internal country program teams from key intellectual property due to export laws. This can prevent these teams from benefiting from company expertise and force them to reinvent the wheel. By allowing AUKUS partners to share more technological information, TORPEDO would help accelerate quantum developmental timelines and reduce costs.

The combination of AUKUS, AQuA, and TORPEDO create the opportunity to build a more robust quantum defense industrial base among some of America's most trusted allies and partners.

Importantly, and perhaps most significantly, the TORPEDO Act would designate Australia and the United Kingdom (UK) as domestic sources for the purpose of the Defense Production Act. This would enable DOD to procure articles with significant or even wholly Australian or UK content.[41] While this legislation has not yet been signed into law, Senator Jim Risch, ranking member of the Foreign Relations Committee, urged that the TORPEDO Act is necessary to "speed up the implementation process by reforming the U.S. regulatory system so we can cooperate in a timely and efficient manner on the capabilities we and our partners need."[42]

The combination of AUKUS, AQuA, and TORPEDO creates the opportunity to build a more robust quantum defense industrial base among some of America's most trusted allies and partners. By expanding the potential supply chain and market, these relationships could provide the necessary demand and resourcing to accelerate the development, integration, and fielding of critical quantum technologies for U.S. and coalition warfighters.

DOD Must Approach the QIST Industrial Base Differently

In addition to the complicated landscape of USG QIST programs and the difficult but necessary collaboration with international defense partners, DOD leaders should also understand the complex and diverse nature of the quantum industrial base if they are to manage this valuable resource well. Government laboratories (both civilian and defense), universities, large commercial computing companies, defense primes and subcontractors, and small startups are the basic units of research, invention, design, development, and manufacturing for the nation. These companies and organizations have come together to collaborate on advancing quantum science and technologies through consortiums, collaborations, accelerators, or centers of excellence—and even through cross-investments. Some defense prime contractors have also invested as venture capitalists in small quantum companies.[43] Each of these entities has different scientific and technical perspectives, different value propositions, and different incentives and pressures. DOD cannot treat quantum startups like other small businesses or other defense companies in the industrial base.

The U.S. quantum industrial base is now dominated by small startups

The U.S. quantum industrial base is best categorized into four main groups: large defense prime contractors, large commercial IT companies, government laboratories, and small startups. Each of these plays an important role in advancing QIST, but the leading edge of quantum technologies is dominated by small startups. A 2023 investment landscape analysis by McKinsey classified 106 QIST startups, with most emerging within the last five years. These companies make up nearly half of the organizations focused on quantum computing (QC) in the United States, and roughly 80 percent of those cropped up in the last three years.[44] Many of these QIST startups are founded by leading researchers at universities whose science has reached a point of application and commercialization. These sorts of companies are on the bleeding edge of developing advanced quantum technologies that have a high potential to solve certain critical capability gaps and vulnerabilities for the U.S. Air Force and other services.

If DOD and Air Force leaders are serious about integrating QIST capabilities into its force design at a pace that will maintain the advantage over China and other adversaries, they must create a "requirements pull."

A major barrier to growth for these companies is that they are caught in a no man's land—the space between research and development and actually producing commercial quantum capabilities. Despite the plethora of DOD small business programs, contract options, and venture initiatives, many of these quantum startups are struggling to gain traction. Furthermore, many of the quantum applications that can provide an operational advantage in the battlespace do not have closely aligned commercial markets.

If DOD and Air Force leaders are serious about integrating QIST capabilities into its force design at a pace that will maintain the advantage over China and other adversaries, they must create a "requirements pull." Only by creating the demand can they foster the small business innovation ecosystem for startup companies. As an even more productive measure, DOD should establish high-potential, high-payoff QIST programs of record to transition and acquire capabilities. This would give quantum companies specifications to which they can design, programs for which they can compete, and ultimately revenue from which to grow.

DOD & Air Force small business programs & venture arms are ill-suited for small QIST companies

Small developers and prospective manufacturers of highly specialized QIST capabilities are in a quandary that, left unanswered, threatens broader DOD goals for quantum capabilities. While the commercial demand for quantum technologies is expected to surge in the future, it is forecasted to remain low over the next two to three years while the industry and its supporting network scale up. If the semiconductor industry is a model, the cost of facilitizing and scaling the production of quantum applications will be significant. A semiconductor chip factory costs a minimum of $10 billion dollars and takes roughly five years to build.[45] IonQ recently announced its intention to invest over $1 billion of its internal funds to build a quantum computer manufacturing facility in the Pacific Northwest.[46] Most quantum companies are hesitant to disclose their internal cost estimates for new plant construction, but even modest manufacturing infrastructure investments of $80 million to $100 million could take a decade or more to recover costs.

This time frame does not fit the business model of private venture capital firms, nor does it provide the financial returns that meet their expectations. Venture capital typically targets returns measured in multipliers, not percentages, that mature in three to five years or less. This means many quantum startups that are now dependent on venture capital may struggle for resources as they move beyond their technology demonstration phase. And since quantum applications for specialized military use cases may never have commercial applications, QIST companies will depend on DOD funding to scale. The Air Force's small business programs currently do not meet the capital requirements or timeframes QIST companies will need to scale production at the capacity the service will need.

Many of the quantum capabilities that will meet the Air Force's needs are not dual use, and even those technologies that ostensibly have commercial applications may struggle with a customer base that remains extremely specialized and limited.

Small Business Innovation Research/ Small Business Technology Transfer (SBIR/STTR) funding may not be a QIST pathway. Both SBIR/STTR are small business set-asides that provide government funding to further the research and development of small businesses' innovative technologies. The SBIR program specifically focuses on assisting with small business concerns to further develop their technology into products.[47] STTR facilitates the partnership between small businesses and research organizations such as universities and federally funded research and development centers (FFRDC). The Department of the Air Force is authorized roughly $600 million each year for its SBIR program, which is divided into three phases.[48] Phase I provides participating companies $50,000 over the course of three months to conduct market research, refine their proposal, and plan out phase II with their prospective Air Force customer. Phase II provides up to $1.7 million over 27 months "to make necessary adaptations and developments *on their existing non-defense solution* to be useful to the Air Force customer."[49] Phase III qualifies companies that have completed phases I and II to receive sole-source contracts directly from the purchasing organization with its own funding.[50]

SBIR/STTR are not suitable for many QIST capabilities. The relatively small awards that this important small business-oriented program provides do not match the high levels of investment needed to move QIST toward a production-oriented, pragmatic capability that can be integrated with major weapon systems. Moreover, both the SBIR and STTR have "dual-use" criteria. To be eligible for SBIR/STTR funding, technologies must have a primary, viable commercial market as well as a defense application.[51] These criteria are a barrier for startups that are focused solely on a specialized quantum military application. Many of the quantum capabilities that will meet the Air Force's needs are not dual-use, and even those technologies that ostensibly have commercial applications may struggle with a customer base that remains extremely specialized and limited. In any case, the capital needed to bring these technologies to the field far outstrips what is available to any one applicant in these programs.

AFWERX and SpaceWERX. The Department of the Air Force (DAF) has done excellent work in institutionalizing its support for small business innovation and creativity. AFWERX enables the DAF to better understand and evaluate small business proposals and serves as an entry point to its SBIR/STTR funding.[52] It also provides a pathway for small businesses to understand the DAF's needs and discover potential DAF customers. In addition to periodically holding "AFWERX Challenges" that are like industry days for companies interested in research program competitions, AFWERX has five programs that are tailored to address specific problems in the defense innovation and acquisition space: AFVentures, Spark, Prime, SpaceWERX, and SBIR/STTR.[53] AFVentures is designed to help companies dependent on SBIR/STTR funding to financially bridge the gap between technology prototyping and production.[54] Spark supports the ideas and initiatives that come directly from airmen seeking to solve the problems they face in the daily execution of their missions.[55] Prime seeks to accelerate the delivery of dual-use capability in designated focus areas over a two-to-four-year timeframe.[56] Finally, SpaceWERX executes the Space Force's SBIR/STTR program, which is focused on Guardian needs.

- **AFWERX's Prime** program may have the greatest potential to support the development of QIST applications. It also has its limitations. Prime offers greater funding support than SBIR/STTR because it leverages other transaction authorities (OTAs).[57] OTAs use legal acquisition instruments that are more streamlined than typical contracts and are often used to fund prototypes with the objective of transitioning them to production.[58] But like SBIR/STTR, Prime requires technologies to be dual-use. This may be problematic for some QIST military-only capabilities that are needed for many of the Air Force's near-term, high-potential, high-payoff use cases. To work around dual-use requirements, the Air Force might consider nominating quantum *enabling* technologies, such as lasers or high vacuum cell development, and quantum production scaling as Prime funding candidates. This approach could significantly advance the U.S. quantum industry.
- **AF Ventures** provides technology developers with three alternate pathways to access Air Force SBIR/STTR funding: 1) Open Topic, 2) Specific Topic, and 3) Strategic or Tactical Funding Increase (STRATFI/TACFI). In practice, the AFVentures Open Topic and Specific Topic do not differ markedly from the standard AFWERX SBIRS/STTR process and, therefore, may not provide small QIST companies with the resourcing they need.[59] STRATFI/TACFI recognizes that some emerging technologies need additional bridge funding to progress through the stages of the SBIR/STTR process, and STRATFI/TACFI intend to fill this gap. For the same reason that SBIR/STTR is not well-matched to most QIST company needs, STRATFI/TACFI are unlikely to solve the quantum industry's scaling challenge.

Office of Strategic Capital (OSC). The DOD set up the new Office of Strategic Capital in December of 2022 to provide "patient capital" to bridge small businesses across the valley of death and fund critical supply-chain technologies.[60] OSC will implement highly targeted partner capital programs expressly to attract private investments by lowering the total funding needed and/or the cost of financing, thereby driving increased investment in commercialization, manufacturing, and infrastructure.[61] Secretary of Defense Lloyd Austin explained that "by working with the private capital markets and by partnering with our federal colleagues, OSC will address investment gaps."[62] Other DOD representatives have asserted that the OSC "aims to be different" than other small business efforts and will take advantage of "non-acquisition-based finance tools" like loans and loan guarantees.[63]

OSC may not be the best pathway to help scale the quantum industry. Since 2022, OSC has signed memoranda of agreement with the Small Business Administration to work with their Small Business Investment Company.[64] But exactly how this joint agreement will function is unclear, and OSC does not yet have its own funding. The FY 2024 President's Budget requested $99 million for OSC in FY 2024 and $154 million in FY 2025, but there are no additional requests for the remainder of DOD's Future Years Defense Program (FYDP).[65] And if this funding is diluted across a sizeable number of companies, it is unlikely to have a meaningful impact. Furthermore, loans or loan guarantees are unlikely to be attractive to startups that are already leveraged through their commitments to investors, especially at the relatively large monetary levels that quantum companies need to move the technology forward.

Developing a practical quantum capability is more than just getting the science and engineering right. Companies must be able to manufacture the hardware with the right volume and quality control to meet the needs of the warfighter as well as meet the demands of their business case. It is this facilitization piece that OSC is intended to bridge, but the quantum industry is still immature, and even modest manufacturing infrastructure investments of $100 million to $500 million could have a decade—or longer—pay-back cycle. Indeed, some anticipate that the cost of building quantum production facilities could approach $1 billion or more.[66] This capital investment and investment return timeframe does not fit the aforementioned business model of private venture capital firms that require financial returns in a three-to-five-year period or less. And because of the large costs associated with standing up quantum production facilities, many quantum startups will struggle—even with OSC support—to reach meaningful viability beyond the technology demonstration phase and into volume production.

Now is the time for action

The nascent quantum industry is at a unique inflection point. Quantum startups are small businesses with unique needs and financing requirements. These startups have demonstrated numerous quantum-enabled capabilities but need additional resources and requirements focus to mature the technology and grow their production capacity. Doing so is extremely capital intensive—well beyond what U.S. Government small business programs now offer.[67] Thus far, U.S. venture capitalists have enthusiastically supported quantum startups, but their investments come with the expectation of reasonable returns in timeframes that are shorter than what may be required for production programs to mature.

Quantum companies are under serious pressure to deliver large returns to their investors on demanding timelines. Now is the time for the U.S. government to make strategic investments to protect and accelerate its growing quantum industry to meet national security needs and keep pace with China and other competitors. If the DOD and Air Force are serious about leveraging private capital, they will need to do more than partner and invest—they need to begin buying actual quantum capabilities.

Conclusion and Recommendations

There is no benefit to pursuing quantum science for science's sake: what really matters is how these technologies can solve DOD's critical capability gaps and provide warfighters with operational advantages that facilitate successful and safe mission accomplishment. This means matching DOD's requirements with research and development efforts, scaling manufacturing facilities for new quantum capabilities, establishing programs of record for their acquisition, and integrating them with key weapon systems.

Current U.S. government support of the quantum industry is generic and not structured to accelerate the delivery of specific QIST capabilities to warfighters. Research and development programs continue to advance U.S. thought leadership but fall short of helping small quantum startup companies transition to viable, independent producers. As a case in point, efforts led by DOE, NIST, and NSF will go far to cultivate the long-term health and sustainability of the quantum industry, but they do little to bridge small startups until there is enough market demand to wean them from their dependence on venture capital. And because the DOD outweighs commercial market interests in near-term quantum applications, it should do more to support the quantum industrial base to bring these technologies to fieldable readiness levels.[68] This includes investing in the quantum supply chain, quantum components and control hardware, and the construction and tooling of production plants—all are needed if DOD is to procure quantum technologies at volumes that are meaningful to its forces.

Senior U.S. defense leaders should prioritize and aggressively pursue near-term applications including quantum timing, navigation, and certain sensing technologies that can deliver bespoke national security benefits.

Senior U.S. defense leaders should prioritize and aggressively pursue near-term applications, including quantum timing, navigation, and certain sensing technologies that can deliver bespoke national security benefits. These capabilities can mitigate real-world vulnerabilities like the denial of GPS information that U.S. warfighters could face in almost any current operation. Moreover, accelerating QIST solutions for these use cases makes sense in the near term because of the overlap they share with other current hardware and software.

The following recommendations are intended to help senior U.S. defense leaders make informed decisions that will help transition the quantum defense industrial base to produce high-payoff QIST applications that provide American warfighters with an unmatched combat edge.

Recommendations

1. **DOD should match critical capability gaps and vulnerabilities to near-term and emerging QIST applications.** DOD must identify potential QIST applications that will meet warfighter needs, develop an understanding of their viability, and determine if industry can produce them at scale within the required timelines. This quantum strategy should also prioritize potential QIST capabilities for operational experimentation, prototyping, development, and—ideally—identify a lead platform for their integration. When matching a QIST application to a candidate platform, the DOD should consider the host platform's mission demands; the physical constraints of size, weight, power, and cooling; and its existing modernization plans and programs.
2. **Establish quantum-based programs of record.** The Department of the Air Force should establish quantum acquisition

programs of record to stimulate the advancement of QIST applications and create a strong quantum industrial base. Funding competitive prototyping initiatives will help enable small startups to design to requirements, integrate QIST capabilities onto major weapon systems, and scale their manufacturing. Establishing programs of record will be the real key to ensuring Air Force warfighters have the operational advantages they need.

3. **Air Force Major Commands should champion QIST capability development, experimentation, and integration.** Air Force major commands should identify what QIST capabilities may solve critical operational vulnerabilities and then promote their development through the many routes available to them. This is crucial because QIST cannot remain a lab-in-a-box. Much like how Air Mobility Command sponsored the development of a MagNav prototype for its aircraft, these capabilities must be ruggedized, integrated with platforms, and stressed in realistic combat conditions like major operational exercises to demonstrate their value to warfighters.
4. **Enact policies that enable the sharing of quantum technology, data, and intellectual property among the AUKUS and TORPEDO partners.** To accelerate the development of QIST applications, the United States will be best served by leveraging the talent and innovation of the scientists and technologists of its closest allies. Enabling this information sharing can help reduce internal friction for quantum companies that have sectors and personnel based in Australia, Canada, and the United Kingdom. This will tear down the firewalls that now prevent cross-pollination within these companies and allow them to accelerate the development of needed quantum capabilities.
5. **Expand OSC funds to facilitate public-private partner investment in quantum manufacturing facilities.** For quantum companies, bridging the valley of death between experimental prototypes and production programs of record means more than simply finding a military service champion. Often, a greater barrier to production at scale will be the cost and time associated with designing, building, and tooling a quantum manufacturing facility. The DOD can lead-turn these challenges through public-private partnerships or investing in government-owned, company-operated manufacturing facilities and laboratories.
6. **Designate quantum as an AFWERX Prime program.** Air Force leaders should establish a "Quantum Prime" program to open the vast array of DAF resources to assist in the maturation of the quantum supply chain, components, and classical control mechanisms. Quantum Prime could be used to mature the quantum supply chain in ways that would benefit military-specific applications, such as photonics and atomic vapor/ultra-high vacuum cells, that cut across quantum modalities and technical applications. Specifically, DAF leaders can match components to urgent QIST capability needs and focus investment on those articles in the supply chain.

Conclusion: key takeaways for senior decision-makers

Winning the quantum capabilities race against China and other adversaries will require a robust U.S. quantum defense industrial base. At the most basic level, this means DOD will need to *buy* quantum technologies. The nascent quantum industry will need specific weapon system form, fit, and function requirements to inform their designs, and this kind of engineering and design pull only comes from the actual prototyping and integration of quantum capabilities. The dynamics of this are no different than any other sector of the defense industrial base.

Ben Fitzgerald, executive chairman of the artificial intelligence startup Rebellion Defense, emphasized that small startup companies need acquisition contracts to de-risk their internal operations, supply chains, and finances and build to the scale of production the DOD needs for a peer conflict: "Delivering innovation and meaningful warfighter capability means getting on … production contracts with regular defense organizations."[69] Research and development contracts are important vehicles to mature an emerging technology, but the uncertainty of crossing the valley of death can deter venture capital or other investors. Moreover, small startups must develop, certify, and mature their supply chains, tooling, production processes, and other oft-overlooked elements of scaled production. Research and development activities can succeed on bespoke hardware, individual relationships, and small teams that are not optimized for production. This means companies must have acquisition contracts "with Big Army, Big Navy, in programs of record and in systems of record, not just with research and development funding on things that might get filled at some point in the future."[70]

The health and creativity of all U.S. defense companies fundamentally depend on DOD acquisition programs. Programs of record matter to the vitality of the industrial base, and this includes programs to acquire quantum capabilities. DOD and the Department of the Air Force must act now to deliberately cultivate a robust and innovative quantum industrial base, understand the underlying science, and make informed decisions that will deliver meaningful capability to warfighters. If DOD does not accelerate the maturation of critical quantum technologies for defense, China will gladly surpass the U.S. quantum enterprise. The costs are too great to fail to win in the quantum enterprise. ✪

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