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PERSPECTIVE ON A TIMELY POLICY ISSUE

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Using Artificial Intelligence and Quantum Computing to Enhance U.S. Department of Homeland Security Mission Capabilities

The U.S. Department of Homeland Security (DHS) is the third-largest cabinet department in the federal government, bringing together multiple components, including the Federal Emergency Management Agency (FEMA), the Countering Weapons of Mass Destruction (WMD) Office, the U.S. Coast Guard (USCG), and the U.S. Secret Service (USSS), among others. These components are charged with carrying out a diverse array of missions: protecting the United States against terrorism, securing U.S. borders, securing cyberspace and critical infrastructure, preserving U.S. economic security, and strengthening disaster preparedness and resilience.[1] To successfully achieve these missions, DHS must leverage technologies to the fullest extent possible.

DHS employs well-tested technologies to manage the complexity and resource the costs of its missions. However, two powerful emerging technologies—artificial intelligence (AI) and quantum computing (QC)—might have the potential to significantly expand the capabilities available to DHS in the future. AI—in particular, its subfield of machine learning (ML)—is an umbrella concept of using computers to rapidly solve problems for which the development of algorithms by human programmers would be cost-prohibitive or otherwise extremely difficult (Murphy, 2012).

Abbreviations

AI	artificial intelligence
CBP	U.S. Customs and Border Protection
CISA	Cybersecurity and Infrastructure Security Agency
DHS	U.S. Department of Homeland Security
FEMA	Federal Emergency Management Agency
GPT	generative pretrained transformer
GRE	Graduate Record Examination
LLM	large language model
ML	machine learning
NN	neural network
PDE	partial differential equation
PQC	postquantum cryptography
QC	quantum computing
QKD	quantum key distribution
QM	quantum mechanics
QML	quantum machine learning
QS	quantum sensing
QSVM	quantum support-vector machine
SVM	support-vector machine
TSA	Transportation Security Administration
UAV	uncrewed aerial vehicle
USCG	U.S. Coast Guard
USSS	U.S. Secret Service
WMD	weapons of mass destruction

QC attempts to leverage the principles of quantum mechanics (QM) to obtain quantifiable advantages over traditional computing, both in terms of speed and in the ability to solve very complex problems. Unlike previous leaps in the progress or advancement of science, such as the nuclear program or the space program, which were state sponsored, QC is, for the most part, incentivized and pioneered by private and for-profit companies and by academic institutions (Parker, 2021; Parker et al., 2022). AI is more mature than QC as a domain, and research in AI is distributed widely through academia and industry.

Although the full potential of these technologies is far from being realized, DHS can position its components to take advantage of future advancements by considering how mature QC- and AI-based technologies might be used to affect DHS mission outcomes. In this paper, we argue that **QC and AI tools—if their potential is realized—could support DHS missions, making DHS more effective and efficient and improving the lives of DHS staff and other stakeholders**.

Our predictions are contingent on whether successful quantum ML algorithms can be discovered (i.e., shown mathematically or empirically to be advantageous over their classical counterparts) and on whether they can run smoothly on practical quantum devices.[2] Both issues are the subject of very intense cutting-edge research.

In this paper, we briefly explain the concepts of QC and AI and then discuss potential applications to DHS's missions. We conclude the paper with recommendations on how DHS could best position itself to leverage QC and prepare its workforce.

Quantum Computing and Artificial Intelligence

As two fields of science and technology, both AI and QC have gained extreme popularity in addition to their acceptance in the scientific community. AI has proved to be a valuable tool in modern science and computing. QC, which itself is a subfield of the wider quantum information science discipline, is at an earlier stage of development than AI is but is striving to catch up with its AI cousin. In the past decade or so, there have been many attempts at merging the promised advantages of QC into the field of AI, although, to date, these attempts have met with mixed success (Schuld and Petruccione, 2018; see also Biamonte et al., 2017).

Quantum Computing

QC attempts to leverage quantum mechanical phenomena, such as superposition, entanglement, and interference, to obtain quantifiable advantages over traditional, or classical, computing. QM—the theoretical basis of QC—is one of the most successful theories of 20th-century physics, with experimental tests verifying its validity to incredible precision (Griffiths and Schroeter, 2018; Sakurai, 1994). QM is a fundamental theory of nature that describes the subatomic world in which classical (i.e., Newtonian) physics fails. For instance, in QC, the familiar notion of an information bit being exclusively off (0) or on (1) no longer holds. A quantum bit, known as a *qubit*, exists in a superposition of off and on simultaneously—only upon measurement of a qubit is it forced to take a definite 0 or 1 value with specific probabilities, thereby collapsing into a bit.

This superposition allows for *quantum parallelism*, which is the ability of quantum computers to evaluate a function for multiple input values simultaneously. The key to many proven speedups in quantum algorithms is precisely this parallelism (Deutsch and Jozsa, 1992; Nielsen and Chuang, 2010). Indeed, this is a game changer because the solutions to very complex problems can now be encoded in a registry of qubits, and researchers can extract the desired solution or properties from these qubits in a controlled way.

To proceed with this extraction, researchers must turn their attention to other unique notions that do not have classical counterparts, such as entanglement and interference.[3] One outstanding example of such a speedup and extraction procedure is Shor's algorithm for prime factorization, which finds prime factors of an integer with a superpolynomial speedup—an improvement over the best-known classical algorithms.[4] This has very serious implications in cryptography; as a consequence, the National Institute of Standards and Technology is studying a new array of postquantum cryptography (PQC) algorithms that do not depend on integer factorization.[5]

However, the advantages of QC over classical computing are not straightforward. In certain situations, rather than supplying a superpolynomial speedup, QC provides a more modest quadratic speedup. A well-studied search algorithm known as *Grover's algorithm* is such an instance. Many of the quantum algorithms that we discuss in this paper fall into the quadratic speedup category because they are derivatives of Grover's algorithm. Effectively, this means that, if a classical algorithm requires N iterations to produce a result with a certain accuracy, a quantum algorithm could produce this same result in only $O(\sqrt{N})$ iterations, thereby providing a quadratic speedup in runtime.[6]

The next generation of operating systems should be able to determine which tasks should be solved by classical processing units and which tasks should be outsourced to quantum processing units.

As a result, quantum computers are not all-purpose computers that will someday replace ordinary computers. Quantum computers will likely be employed primarily in the most-taxing operations and those most prone to creating bottlenecks (e.g., Kothari, 2020). Indeed, one could think of quantum devices as being powerful engines in a large chain of processes. Therefore, orchestration across computing approaches will be key. The next generation of operating systems should be able to determine which tasks should be solved by classical processing units (including high-performance computers and graphics-processing units) and which tasks should be outsourced to quantum processing units. Even once quantum computers work, there will probably be a breakeven point at which the quantum computer is worthwhile only for tasks that are bigger than some threshold.

Hardware also places constraints on QC. Several technologies and engineering paradigms exist to produce working qubits: superconductors, ion traps, photonics, annealers, neutral-atom traps, silicon-spin qubits, and (more speculatively) topological qubits and nitrogen-vacancy centers. These technologies (except for annealers) share the same architecture, which is known as *universal gate-based computing*. Current devices from private-sector companies, federally funded research and development centers, and universities produce very noisy qubits, so qubit operations work suboptimally and slowly. This means that, even if an algorithm produces a theoretical advantage, realizing this advantage practically is still difficult because the devices are not yet robust enough. Certain techniques, such as error mitigation and error correction, can help undo the noise to which qubits are prone by their quantum nature. However, these techniques are not fully deployable yet and sometimes add up to the global overhead of the algorithm, thereby reducing its effectiveness in some cases (see, e.g., Google Quantum AI, 2023; Mandelbaum, Steffen, and Cross, 2023; Stamatopoulos et al., 2020; and Woerner and Egger, 2019) for certain theoretical overheads not related to error correction. Devices that are imperfect are known as *noisy, intermediate-scale quantum* computers. Annealers, on the other hand, have a different architecture altogether that is not gate based and does not perform universal calculations, but it excels at discrete optimization and operations research problems.[7]

In sum, we note the following about the current status of QC:

- The only known QC algorithm for AI and ML is Grover's algorithm.
- The theoretical speedup of Grover's algorithm is modest and might well be washed out by all necessary hardware overhead.
- Other QC algorithms for AI and ML might arise in the future, but whether they will is still unknown.

Quantum Computing and Machine Learning

The successes of AI are well documented, and AI has become an indispensable tool in modern computing, whether for commercial, military, or security applications, as illustrated in Krelina (2021) and Quantum Working Group (2021). It thus becomes natural to ask whether QC can further boost ML by providing advantages over classical computing. Given the success of QM in physics on the one hand and the success of ML in computing on the other hand, the expectations of quantum ML (QML) are, in general, disproportionately huge (Schuld and Petruccione, 2018). But although the commercial and business implications of QML are now being explored and addressed, the results have not yet matched the expectations.

For many, AI means ML for big data. This is, however, one of the applications of AI for which QC is the least useful. Any application of quantum algorithms for that type of AI is probably still far in the future, given the need for hardware resources (memory, gate speed, and other concepts we discuss in this paper) and because it is not known yet whether QC would speed up that kind of AI *even in principle* because of such issues as data-loading, as we discuss later.

Assumptions Underlying This Paper

As the preceding discussion illustrates, many technical challenges with AI and QC remain to be solved. Despite these issues, in general, this paper does not focus on timelines or current technology readiness because AI and QC are still in the process of maturing. Our views on how quantum technologies could enhance AI techniques are largely independent of the underlying technology used to produce the quantum devices on which these QML algorithms are going to be run. Instead, for this paper, we assume the existence of a working, or close-to-working, fault-tolerant quantum computer, focusing on what the existence of such a technology could mean for DHS capabilities.

DHS has publicly expressed interest in quantum only for PQC (DHS, 2022). Our views suggest that DHS could expand these interests into other quantum subjects, such as QC and quantum sensing (QS). Informed by our investigations, literature review, and professional experience, we put forward in the conclusion a set of ideas and recommendations that could assist DHS in leveraging QC successfully to protect the United States.

U.S. Department of Homeland Security Missions

Per *The DHS Strategic Plan: Fiscal Years 2020–2024* (DHS, 2019), the department has six primary goals:

- Counter terrorism and homeland security threats.
- Secure U.S. borders and approaches.
- Secure cyberspace and critical infrastructure.
- Preserve and uphold U.S. prosperity and economic security.

- Strengthen preparedness and resilience.
- Champion the DHS workforce and strengthen the department.

For each of these goals, we provide some specific examples of how AI or ML could affect DHS's capabilities. The conclusions in this paper are based on our familiarity with the scientific literature on QC and AI and on our previous and ongoing peer-reviewed scholarship. When possible, we make the connection to QML and develop the potential benefits of providing quantum boosts to ML tasks. Not all instances of technologies' impact will be positive, and, in a few instances, classical techniques are more than enough to provide the needed capabilities or QC simply fails to deliver advantages over classical methods.

As a caution, we emphasize that our attempts at finding instances of profitable uses of QML have *not* been exhaustive, so there could be other examples or situations in which quantum advantages could be important for other DHS activities that are not contemplated in this paper.

Before proceeding, we mention the balance that must be achieved to produce a paper that is informative without being excessively technical. We strove to describe realistic ideas and scenarios in which AI and QM could be merged to alleviate the computational tasks that DHS components must complete as part of performing their duties. Moreover, there is no shortage of technical sources in which quantum algorithms and routines are carefully elaborated, and we refer the interested reader to Barnett (2009); Hidary (2019); Nielsen and Chuang (2010); Rieffel and Polak (2014); Scherer (2019); Schuld and Petruccione (2018); Steeb and Hardy (2018); and Wong (2022). However, these sources tend to emphasize the quantitative aspects of these algorithms and largely ignore potential applications in industry, military, and security.

Counter Terrorism and Homeland Security Threats

The first DHS mission is to counter terrorism and homeland security threats. This mission has four objectives:

- Collect, analyze, and share actionable intelligence.
- Detect and disrupt threats.
- Protect designated leadership, events, and soft targets.
- Counter WMD and emerging threats.

QC and ML together could help DHS accomplish these goals in any of several ways.

Collect, Analyze, and Share Actionable Intelligence

DHS aims to develop "timely and actionable intelligence to accurately assess and prevent threats against the United States" (DHS, 2023). A challenge for providing accurate and actionable intelligence is the glut of information that DHS components receive. DHS's intelligence and domain awareness operations, including those in the Office of Intelligence and Analysis, the USCG, and the National Operations Center, must identify threats by sifting through tens of thousands of vessels operating in U.S. waters, thousands of flights in U.S. airspace, and thousands of tips and alerts filtering up from state and local partners, almost all of which are innocuous noise. Although DHS receives a huge volume of information, it does not collect that information opti-

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mally, pulling in a lot of noise in a way that risks missing important signals.

ML approaches, potentially enabled by QC, could train on these data and help DHS intelligence agents more quickly and accurately identify the needle in the haystack of information they handle every day. Large language models (LLMs) are already adept at integration and analysis of large datasets, as evidenced by the performance of Generative Pretrained Transformer (GPT) 4 on numerous benchmark exams. QC could help optimize intelligence collection, such as from USCG patrols or U.S. Customs and Border Protection (CBP) searches, to better inform intelligence operations. Furthermore, like we do with problems in quantum chemistry, quantum finance, and graph theory, we expect that LLMs could be used to design tailor-made quantum architectures for these intelligence collection problems by using prior knowledge from the relevant research communities.

Detect and Disrupt Threats

Another component of the DHS mission to counter terrorism and homeland security threats is to detect and disrupt threats, such as through the actions that the Transportation Security Administration (TSA) takes to secure airports and airplanes. As stated earlier, mature QC should be able to rapidly optimize patrol, search, and scan strategies at checkpoints, at critical infrastructure locations, and along the borders and approaches. These innovations would aid not only in improving data collection for future intelligence development but also in detecting and disrupting any active threats in the present.

Protect Designated Leadership, Events, and Soft Targets

The USSS has the primary role in protecting leadership, events, and soft targets for the department in most cases, although the Federal Protective Service and the Office of Homeland Security Situational Awareness also play roles in the protection of federal buildings and events, respectively. A key task for each of these components is to conduct risk assessments (of events, facilities, and personnel) to optimize the level of protection that each receives, given limited protection resources.

An example of such a risk assessment is the Special Event Assessment Rating system, which determines what federal protective assistance is needed for private events. These assessments are currently conducted using a mix of data analysis and human judgment, but the addition of QC and ML could integrate many more data feeds into the analysis, thus providing a more nuanced and optimized distribution of federal resources and personnel. This would allow DHS to protect more events, facilities, and personnel and provide better assistance to those it currently protects.

During protection operations, there are additional opportunities for the application of these emerging technologies, including the classification of targets of interest (e.g., at a protected event). For instance, noisy, intermediate-scale quantum devices could be used to train a quantum circuit for classification tasks using exponentially fewer parameters than a classical neural network (NN) would require for the same task, with apparently minimal reduction in performance (Schuld et al., 2020). Another example is that fault-tolerant QC devices could be applied to speed up classification tasks by utilizing the many quantum algorithms for linear algebraic routines that have been developed in the literature (Cao, Romero, and Aspuru-Guzik, 2018). These could be executed either centrally at a command center based on sensor feeds or, in the more distant future, at the edge by the sensors themselves.

To identify targets quickly enough that action can be taken to prevent danger to leadership and events, search algorithms must have sufficiently low running time and be usable in combination with classification algorithms. The quantum mechanical properties of information, including entanglement and superposition, have the potential to quadratically reduce the running time of search algorithms. LLMs can be used to design novel quantum architectures that are tailored to various problems, so an LLM-designed quantum architecture tailored to the problem of searching for potential targets would be especially useful in protecting designated leadership, events, and soft targets.

Counter Weapons of Mass Destruction

DHS works to "deter, detect, and disrupt the use of weapons of mass destruction (WMD) and health security dangers as early in the threat pathway as possible" (DHS, 2019, p. 16). This includes emplacing detection capabilities at ports of entry and across the United States and working with international partners to secure potentially dangerous substances and precursors.

Improvements in detection capabilities for WMD using QC could enhance DHS's ability to disrupt WMD pathways at home and abroad. One approach to integrating QC capabilities would involve sending data from classical sensors to a centralized QC capability. However, this would necessitate the transformation of data from classical to quantum so that the data could be used in a quantum algorithm. This transformation—usually termed *loading data onto a quantum device*—is an expensive process. On the other hand, if the data were **already** in quantum form, such as data collected from a quantum sensor (Krelina, 2021; Quantum Working Group, 2021), and, if a quantum algorithm could be deployed almost immediately on this data, the data-loading problem could be bypassed. This QS would allow CBP, the Countering WMD Office, and others to detect chemical, biological, radiological, and nuclear threats more quickly and more effectively and to better resolve alarms in the field. Although this merging concept is still experimental, such a capability being even partially realized could significantly boost the benefits of detecting these types of threats at ports of entry or in metropolitan areas.

Another aspect of DHS's counter-WMD efforts is horizon-scanning for threats from emerging technologies—including potential threats resulting from the use of QC, ML, and AI. For instance, quantum algorithms might be

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employed to accelerate the synthesis of poisons, nerve agents, biotechnologies, and drugs that are harmful or illegal.

These emerging technologies could also have the potential to counter the same threats that they unleash. For instance, QC and AI could be used to design drugs to counter the effects of WMD and other threats. Many advances in drug design have come from AI—specifically, deep NNs and support-vector machines (SVMs), which use large datasets with thousands of molecular descriptors. Because these ML algorithms are computationally expensive, there has been a recent push to use quantum computers to accelerate ML for drug design. For this to work, the set of molecular descriptors must be compressed for use with a quantum computer.

Recent research has uncovered a method for compressing up to hundreds of thousands of molecules for use with SVMs and data-reuploading classifiers on a quantum computer (Batra et al., 2021). Kushal Batra and his colleagues considered sets of molecular descriptors representing coronavirus disease 2019 (COVID-19), plague (*Yersinia pestis*), and tuberculosis. Other research in this area has exploited the fact that quantum-gate parameter exploration offers an advantage over NN parameter exploration because the probabilistic nature of quantum systems enables generation of molecules that would not be explored by a classical generative adversarial network (Li et al., 2021). This idea was used to develop new QML techniques for drug discovery, including a quantum generative adversarial network that learns patterns from the set of molecular descriptors and generates small drug molecules and a quantum variational autoencoder that performs a probabilistic search to generate large drug molecules. Although DHS would not necessarily directly employ these methods to generate new drugs and cures, it could benefit from them and could prepare to help distribute them in an emergency.

Secure U.S. Borders and Approaches

DHS has a critical mission to secure U.S. borders and enforce customs and immigration laws. This mission is complex, in large part because of the sheer size of the interface between U.S. borders and the rest of the world. For instance, CBP actively monitors thousands of miles of territorial borders and 328 ports of entry (CBP, 2023), while the USCG patrols 4 million square miles of territorial waters and exclusive eco-

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nomic zones (National Oceanic and Atmospheric Administration, undated).

Secure and Manage Air, Land, and Maritime Borders

Given the scope of its mission, CBP has a workforce challenge along both the northern and southern borders: CBP has too few agents conducting too few patrols across too much border area. Current operations are personnel intensive, requiring human patrols between ports of entry at all hours of the day and night. This workforce requirement has compounded because of CBP's difficulty in retaining border agents (see, e.g., Gambler, 2019) and the increased number of refugee families attempting to cross the border, which diverts CBP resources away from law enforcement and toward migrant aid and arrest (Morgan, 2019).

To counteract this shortage, CBP has begun to employ autonomous capabilities, and advances in QC and AI could further empower these systems. Since 2012, CBP has used larger MQ-9 uncrewed aircraft to conduct change-detection sweeps along the southern border (CBP, 2022). In addition, CBP has also begun to use small, uncrewed aircraft systems, such as quadcopters, to augment human patrols along the border (CBP, 2018). Although these systems act as a multiplier of the abilities of human surveillance, each of these uncrewed systems still requires an active human pilot. CBP employs static but relocatable *aerostats* (uncrewed and tethered buoyant craft) for land and air surveillance, but these systems act more like unattended sensors than like true autonomous aircraft (CBP, 2021).

As AI advances further, the need for a human pilot might be relaxed, and uncrewed systems could act as true resource multipliers for CBP's limited human capital. However, CBP has tried to use unattended systems as a force multiplier in the past, such as with the Secure Border Initiative, with disappointing results (Hite, 2010; Preston, 2011).

Indeed, widespread use of uncrewed and autonomous aircraft for surveillance might remain hypothetical and far from practical use. The Defense Advanced Research Projects Agency has noted three critical factors that delay the implementation of autonomous systems (Martin, undated):

- Without reliable and high-level autonomy, vehicles require operator involvement, creating a complex human–machine interface and limiting operational gains.
- The unstructured and dynamic nature of environments presents many still-open problems in systems science and engineering.

- ML methods are unpredictable, and the analysis of ML has remained unsatisfactorily nonrigorous.

These factors, together with the inherently speculative nature of QC, make it difficult to know the degree to which QC will offer improvements to the capabilities of AI-driven autonomous systems.

New technologies that combine QC and AI could help realize a more effective implementation of a system like the Secure Border Initiative. To identify where QC and AI might enable new DHS uncrewed aerial vehicle (UAV) capabilities, we adopted the COMP4DRONES hierarchy of UAV components, which breaks a UAV system down into four abstract layers (Hussein et al., 2021):

- planning layer: the capabilities of a UAV system for high-level planning and optimization
- flight management layer: the capabilities of a UAV system for selecting plans based on feedback from the environment
- control layer: the low-level control modes of a UAV that are responsible for executing a flight plan
- sensor and actuator layer: the key technological components that enable low-level control modes and feedback from the environment.

We anticipate that AI methods could augment UAV capabilities at all four layers, while QC would further increase capabilities at the planning and flight management layers.[8] QC would do this by offering computational speedups in finding solutions to optimization and simulation problems. For example, the flight management layer encompasses UAV functions that calculate optimal flight trajectories over terrain using feedback from the environment (Makhanov et al., 2023). A faster means of finding flight paths through complicated environments might allow UAVs to execute more-complex tasks than they currently can with classical technology.

Quantum algorithms that solve systems of differential equations and constrained optimization problems might offer more-accurate or timelier flight path modeling and improve the decisionmaking capabilities of flight management AI. For example, Berry's algorithm for solving linear, first-order differential equations offers a stronger quantum speedup than the best-known classical algorithms do (Berry, 2014), as do several quantum optimization algorithms when applied to combinatorial optimization problems (Jordan, 2022). Grover's algorithm, quantum amplitude amplification (Lathrop, Boardman, and Martínez, 2023), and the quantum evolutionary algorithm (Ming, 2015) are directly applicable to motion-planning problems. AI routines could then use the output of quantum-boosted flight path modeling algorithms to define the state-space breadth-first search or A* algorithm to select between possible flight paths (Paces and Udatny, 2019).[9]

Other examples are the closely related problems of flight path coverage and deconfliction, which occur at the planning layer and involve multiple UAVs. We define the problem of flight path coverage as the question of finding a configuration of UAVs and other supporting resources that allow sufficient presence in an area to accomplish a task. There are technical limiting factors to coverage solutions, such as the maximal flight time and range of a UAV. There are also complicated situational factors. A 2019 study of expanding surveillance infrastructure at the southern border discovered a "funneling effect" of permeable border surveillance: Concentration of resources deterred migrants from attempting border incursions at protected locations but

The capabilities of fully autonomous uncrewed systems are still speculative and likely at least several decades out.

also pushed migrants to attempt crossings in more-remote, less surveilled regions on the border (Chambers et al., 2021). This funnel effect exemplifies why solutions to the coverage problem must be able to adapt to a dynamic environment. It also shows that a suboptimal coverage solution to border surveillance and deterrence can have deadly consequences. A report from the Binational Migration Institute indicates that the funnel effect caused a stark rise in border-crossing deaths from 1990 to 2003 (Rubio-Goldsmith et al., 2006).

The funnel effect is agnostic to the type of technology used for surveillance and will continue to affect the locations of southern border crossings (McClendon, 2021) as long as it is common knowledge that border surveillance is less effective away from resource clusters and towns. Mitigating solutions to the flight path coverage problem using multiple UAVs would require a method of flight path deconfliction. In our context, flight path deconfliction is the process of reducing the risk of midair collision of uncrewed aircraft and other airborne systems (Razzaq et al., 2018).

Finding efficient and reliable methods of flight path deconfliction remains an open problem. ML methods are currently being experimentally applied to complicated systems of uncrewed vehicles, with the goal of coordinating actions and movements (Defense Advanced Research Projects Agency, 2023). Increased simulation and optimization capabilities could allow for efficient real-time management of large groups of UAVs, leading to better coverage for surveillance and deterrence tasks. Algorithms traditionally used in flight schedule optimization could have quantum counterparts, which could yield speedups in calculation time, ideally making classically intractable scheduling problems possible to solve on a quantum computer. However, the capabilities of fully autonomous uncrewed systems are still speculative and likely at least several decades away (Committee on Technical Assessment of the Feasibility and Implications of Quantum Computing, 2019).

Extend the Reach of U.S. Border Security

A nearer-term application of QC to improve border security would be optimization of the placement of fixed and relocatable assets, such as aerostats. CBP has limited infrastructure to support the emplacement of its sensor suites. QC could ensure that this infrastructure is optimally located, given operational cost, weather, geography, and mission purpose. This same approach could also help optimize human patrols. Although AI advancements alone might have limited success in realizing this hypothetical use case, the capabilities allowed by QC but not by classical computing could be key to realizing an autonomous system of UAVs at large scale and to ensuring the reliability and efficiency needed to execute missions.

Enforce U.S. Immigration Laws

When making decisions about the provision of immigration benefits, U.S. Citizenship and Immigration Services adjudicators must make difficult risk assessments based on incomplete and potentially fraudulent information. A current or prospective immigrant might not have intact identification and citizenship paperwork, and lax controls in their home country might allow fraudulent paperwork to be produced. Using QC for risk assessment of investments and borrowers and for fraud detection is already being investigated in the financial sector, although with limited results to date. McKinsey has reported, for instance, that QC is expected to provide only marginal benefits over rule-based heuristics for fraud detection, although AI systems that can incorporate more variables might offer more-substantial improvements (Gschwendtner, Morgan, and Soller, 2023).

Secure Cyberspace and Critical Infrastructure

The Cybersecurity and Infrastructure Security Agency (CISA) is the DHS component with primary responsibility in this mission area. CISA deploys cybersecurity capabilities across the federal civilian network to ensure that federal networked capabilities are resilient to cyberthreats. It also works indirectly with critical infrastructure owners and operators and the respective sector risk-management agencies across the federal government to promote security standards and best practices.

Secure Federal Civilian Networks

QC, with its ability to circumvent common encryption techniques through its parallel computation capabilities, offers both opportunities and risks for cybersecurity. For this discussion, it is important to distinguish between QC, quantum communication, and PQC. Quantum communication employs quantum channels of communication, such as quantum key distribution (QKD), a secure communication technique that implements a cryptographic protocol involving superposition, entanglement, and interference. QKD enables two parties, usually referred to as *Alice and Bob*, to produce a shared random secret key known only to them. This key can then be used to encrypt and decrypt messages. The key feature of QKD that is not found in analogous classical channels is the ability of Alice and Bob to detect the presence of any third party (Eve) attempting to gain knowledge of the key. Indeed, by the very nature of QM, an attempt from Eve to eavesdrop would leave a recognizable signature on the key (Nielsen and Chuang, 2010).

Strictly speaking, PQC is not a quantum technology but a set of the mathematical protocols designed to encrypt information. PQC also provides such functions as authentication and digital signatures (Computer Security Resource Center, 2024). PQC offers opportunities to secure federal networks in a postquantum world. However, PQC protocols have not yet been established or fully deployed. Until PQC is fully standardized, there is a window of risk in which quantum computers could become powerful enough to run Shor's algorithm. In that case, quantum computers could break many of the encryption methods being used to secure sensitive information on federal civilian networks, such as financial transactions, medical records, and personally identifiable information (e.g., biometrics). Terrorists

Terrorists and other sophisticated criminals could use QC to break into secure systems and steal valuable information to use as leverage or even enable widespread identity fraud.

and other sophisticated criminals could use QC to break into secure systems and steal valuable information to use as leverage or even enable widespread identity fraud. Closer to the current horizon is the tactic known as *steal now and decrypt later*, in which malicious actors collecting pre-PQC encrypted data and holding on to those data until Shor's algorithm is realized (Parker and Vermeer, 2023; Vermeer, Parker, and Kochhar, 2022), although it is not easy to predict when this will be possible. It is foreseeable, if still speculative, that advanced AI techniques and algorithms (classical or quantum) could assist in the steal-now part of this process, thereby increasing the necessity to switch to PQC as soon as possible.

Quantum AI could pose other risks to DHS's cybersecurity operations. QC could be used to launch sophisticated cyberattacks, such as distributed denial-of-service attacks (Said, 2023). These attacks could cause significant damage to businesses and critical infrastructure. Indeed, QC is a strong candidate to assist ML techniques in reaching their best performance for cybersecurity. A well-known ML algorithm, SVM, can have its performance boosted by employing quantum *optimization* concepts. The resulting algorithm is called a quantum SVM (QSVM). In turn, QSVMs can efficiently—in a quantifiable sense—detect distributed denial-of-service attacks on smart microgrids. Reversing this operation (i.e., outperforming classical SMVs to detect attacks with QSVMs) could lead to very dangerous attacks on U.S. critical infrastructure, such as airports, maritime airways, power grids, and nuclear plants (Krelina, 2021; Vermeer, Parker, and Kochhar, 2022). Legislation has been introduced to research how quantum applications and QC can make the U.S. electric grid more resilient, secure, and efficient (Cornyn and Padilla, 2023). The key parties in this endeavor are subject-matter experts in a coalition between the U.S. Department of Energy and DHS.

It is imperative to simultaneously develop programs that consider the cybersecurity landscape through both offensive and defensive lenses. In the same way that U.S. researchers would benefit from quantum advances to strengthen cybersecurity defenses, malicious actors could use these same technologies to craft more-effective malware, novel attack threats, and more-creative evasion techniques.

Strengthen the Security and Resilience of Critical Infrastructure

QC offers potential benefits to improving the security and resilience of critical infrastructure. Quantum optimization could improve load-balancing across a network, allowing U.S. infrastructure to operate more efficiently, even in the face of concerted attacks across the network. QC might also improve the value of risk assessments for both CISA and owners and operators, allowing each to better deploy its limited resources to secure the most-critical nodes for each sector.

At the same time, another potentially worrisome use of QC is that QC algorithms could boost other well-known ML algorithms, such as NNs, random forests, decision trees, and *k*-nearest-neighbor algorithms, to develop new and more-powerful methods for conducting warfare, such as launching coordinated attacks on multiple targets (Krelina, 2021; Schuld and Petruccione, 2018). This could disable key nodes of the U.S. critical infrastructure network, such as power plants and communication centers. The underlying mechanisms have previously been touched on, and they involve faster and more-robust linear algebra, such as matrix operations. Adversaries of the United States could then use these boosted QML algorithms for hacking elections, causing widespread blackouts, sabotage, cyberextortion of owners and operators, and other forms of cyberterrorism.

Preserve and Uphold U.S. Prosperity and Economic Security

DHS is also tasked with the preservation of the prosperity of the United States. The four objectives supporting this mission area are to enforce U.S. trade laws, safeguard the U.S. transportation system, maintain U.S. waterways, and safeguard the U.S. financial system. Each of these objectives is led by a different DHS component (CBP, TSA, the USCG, and the USSS, respectively), and other DHS components play a role in each mission. All might benefit from improvements in QC and AI.

Enforce U.S. Trade Laws

Enforcement of U.S. trade laws is already largely automated, via rule-based targeting using such systems as the Automated Commercial Environment system and the Automated Targeting System. These systems accept entry information for cargo and conveyances from importers and carriers and compare this information with that in databases of derogatory information (e.g., the Terrorist Screening Database). These systems also compare the entry information to rules "based on CBP Officer experience, trend analysis of suspicious activity, law enforcement cases, and raw intelligence" (CBP, 2017, p. 1). These systems use the rules and derogatory information to flag entries for manual review by customs officers.

AI enabled by QC could provide better targeting capabilities to help customs officers flag the riskiest or most-suspect entries for deeper manual review or inspection. AI and ML could develop more-robust and -nuanced rules that incorporate the hundreds of fields that CBP collects on different entries and can evolve these rules in real time as the threat changes. QC, on the other hand, would provide much greater computing power to CBP than classical computing capabilities can and might be able to more adeptly assess

Quantum sensors could be used instead of or alongside computed tomography to detect the presence of trade amounts of explosives in luggage or cargo.

the hundreds of thousands of entries per day that CBP must process.

Safeguard the U.S. Transportation System

A key challenge for TSA is detecting prohibited items, especially explosives, in checked luggage and accessible baggage. TSA currently uses computed tomography sensors to detect these items in checked luggage and, in many cases, carry-on baggage. Computed tomography is more effective than previous methods but, because it must take many two-dimensional images of the same bag, is slower than those methods.

Quantum sensors could be used instead of or alongside computed tomography to detect the presence of trace amounts of explosives in luggage or cargo (Garroway et al., 2001). Quantum imaging could also be used to create high-resolution images of luggage or cargo, which would make detection of potential threats easier. This would allow TSA to speed up the screening of baggage without sacrificing the effectiveness of the scan.

Maintain U.S. Waterways

The USCG maintains the safety and security of U.S. waterways through human patrols and uncrewed sensors (e.g., buoys). Although these operations cannot be replaced by AI or QC capabilities (a quantum computer cannot execute a water rescue), the laydown and efficiency of these patrols and sensors might be optimized by leveraging QC-enhanced portfolio management. In other words, the optimization of infrastructures along with the security and reliability of networks could be boosted by employing the quantum methodologies of portfolio optimization (Boyd and Vandenberghe, 2018) and operations research. Through such a process, the safeguarding of U.S. assets would be translated into operations research problems in which certain functions are optimized (e.g., the use of certain cutters or personnel) subject to constraints (e.g., availability, reliability, or even external factors, such as weather). Quantum search algorithms could also enable a more effective search-and-rescue operation for missing vessels or individuals at sea.

Safeguard U.S. Financial Systems

Financial institutions, such as investment banks, hedge funds, and insurance companies, have demonstrated interest in understanding how QC will affect their lines of business, especially in generating profits or hedging risk (Orús, Mugel, and Lizaso, 2019). Quantum tools can also assist DHS in enforcing financial regulations and identifying potential counterfeiting.

For example, credit card companies and retail banks are pursuing supervised and unsupervised QML algorithms to detect fraudulent charges (Grossi et al., 2022). Likewise, ML problems involving discrete-valued inputs (e.g., true/false/inconclusive, financial/nonfinancial anomaly) appear frequently in financial and industrial settings. In fact, categorical features are known to be critically important for ML tasks in financial and health care applications (for applications of variational QML to categorical data, see Hancock and Khoshgoftaar, 2020; Herman et al., 2023; and Jing, 2019). These same methods could be employed to detect anomalous transactions that indicate money laundering, counterfeiting, and illicit finance.

Large datasets of images are also employed in the detection of counterfeit bills, a task entrusted to the USSS. QC in the field of image processing is expected to provide a quadratic speedup compared with its classical counterpart (Anand et al., 2022). The use of QC image processing could translate into a time decrease in the detection of fake bills.

Quantum finance involves more than ML. Other fields of AI, such as simulation and optimization, are also very much affected by QC. QC, being inherently probabilistic, can be leveraged to perform Monte Carlo simulations and extract properties of these simulations (such as their distribution and moments), again, with quadratic speedups (Montanaro, 2015). A natural application of this technique would be pricing financial derivatives and exotic options in which heavy duty use of Brownian motion is employed (Alghassi et al., 2022; Certo et al., 2023). As with ML, the terminology could quickly be adapted to the regulatory space, and DHS could use it to counter illicit finance.

The bottom line is that it is plausible that the techniques of quantum finance (ML, simulation, and optimization) could be quickly repurposed for the safety of the United States. In general, one can expect near-quadratic advantages in these cases, making quantum finance a strong candidate for early exploration at DHS.

Strengthen Preparedness and Resilience

Another mission of DHS is to strengthen preparedness and resilience in the face of natural disasters. FEMA has the lead role for this mission, but other components, such as the USCG, also have roles to play. This mission consists of four components: building a national culture of preparedness, responding during incidents, supporting outcome-driven community recovery, and training and exercising first responders. Each of these might be able to benefit from QC and ML.

Building a National Culture of Preparedness

To build a national culture of preparedness, FEMA supports communities in becoming self-sufficient before natural disasters through predisaster mitigation efforts, building (and rebuilding) infrastructure to make it more resilient to disasters, and otherwise helping communities prepare for future disasters.

These actions could all be supported by an enhanced ability to forecast natural disasters, and ML is a perfect

> QC offers opportunities to improve the physical modeling of the systems representing the weather.

fit for this task. There is a large body of research on using ML to forecast disasters. For instance, deep neural operators have been used to forecast pandemic spikes, structural failures, wildfires, and rogue waves (Pickering et al., 2022). Another example is a hybrid ML method based on SVMs and *k* means that is used to detect flood-affected areas from satellite images with high accuracy (Akshya and Priyadarsini, 2019). A third example is an ML model that combines random forests with object-oriented image analysis for landslide detection in several areas that recently experienced landslides (Stumpf and Kerle, 2011). In each of these examples, aerial imagery provided the data on which the model based its forecast.

QC has also been proposed as a way to speed the training of NNs. QC could be used in the training of disaster forecasters that use NN models (e.g., the deep neural operator model that was used to forecast pandemic spikes, structural failures, wildfires, and rogue waves).

AI and QC improvements could also benefit preparedness by improving weather prediction capabilities. Accurate predictions of severe weather events would allow decision-makers to issue safety announcements that could save lives (Teitelbaum, 2013).

Accepted models for weather forecasting are dynamic in nature. A powerful technique is that of numerical weather prediction (National Weather Service, undated). This is a field of fluid dynamics and thermodynamics that employs some of the thorniest differential equations in the whole of science (Broomé and Ridenour, 2014; Pu and Kalnay, 2018). Weather is a chaotic system (Bannister, undated). This means that any dynamical system that is a candidate for weather prediction will be extremely sensitive to initial conditions: A small change in those initial conditions will translate itself into extremely different behaviors in the system.

QC offers opportunities to improve the physical modeling of the systems representing the weather. These are typically partial differential equations (PDEs). If one could turn such a PDE into a workable Schrödinger equation,[10] the advantages would become noticeable. Universal quantum devices based on gates excel at solving the Schrödinger equation. Usually, one solves the Schrödinger equation exponentially quickly and then reads the solution (i.e., the function that models the weather or some properties of this function), with a quadratic speedup coming from employing derivatives of Grover's algorithm, such as quantum amplitude estimation (Nielsen and Chuang, 2010). Although there are serious obstacles along the way, such as the nature of the boundary conditions of these differential equations, this seems to be a direct path through which QC could boost weather prediction (Cooper et al., 2022; Deloitte Consulting, 2023).

Unfortunately, most PDEs—in fact, the great majority—cannot be transformed to the Schrödinger equation.[11] However, the solutions to these equations can instead be approximated using linear algebra operations (broadly speaking), and, with some mild caveats, quantum algorithms can usually perform linear algebra rather efficiently. An example of such PDEs is the set of Navier–Stokes equations, in which quantum techniques that do not necessarily require a transformation to the Schrödinger equation have also been proposed in, for example, Budinski (2022) and Gaitan (2020).[12] Other tools, such as quantum approximation-optimization algorithms (Farhi, Goldstone, and Gutmann, 2014) and the Harrow, Hassidim, and Lloyd algorithm (Harrow, Hassidim, and Lloyd, 2009) for solving linear systems of equations, also assist in this task, but some care is needed (Aaronson, 2015; Carrera Vazquez, Hiptmair, and Woerner, 2022) to achieve the promised quantum advantages. In addition, variational quantum techniques (Endo et al., 2020; Kubo et al., 2021; Yuan et al., 2019) are also powerful tools to simulate PDEs. Variational quantum algorithms are techniques of finding approximations to the lowest energy levels or ground states of quantum systems based on initial guesses or ansatzes. At the policy level, this quantum boost could open the window to predicting weather beyond the current one- or two-week upper bound.[13]

Another technique that could be employed in weather prediction involves AI (Weather Company, 2023). This technique requires training large amounts of historical data to detect patterns. However, this is not an easy task for a quantum device. As described earlier, at a quantum level, loading a classical data set into a quantum register for a quantum computer to perform a quantum algorithm on these data is an extremely difficult task (Salton et al., 2022; Cortese and Braje, 2018; IBM, undated). In fact, this task is so difficult that it is not entirely clear yet whether this data-loading problem might ruin any subsequent advantage provided by the QML algorithm mentioned earlier. Therefore, it seems unlikely at this point that AI techniques used for weather prediction will benefit from QC.[14] The challenge of data-loading is not limited to recommenders and AI for weather prediction. It applies to nearly the entire field of QML. If these are negative results in these two applications, they are negative results for nearly the entire field of QML and nearly everything discussed in this paper about QML. Therefore, this problem needs to be addressed in future theoretical research.

Respond During Incidents

During natural and human-caused disasters and other kinds of emergencies, DHS provides support, search-and-rescue assets, communication systems, and technical assistance. In particular, both FEMA and the USCG help local authorities with search and rescue during disasters.

QC and ML could improve DHS search efforts. As noted earlier, quantum search algorithms offer a quadratic speedup in run time compared with classical search algorithms, and LLMs can be used to generate quantum architectures that are tailored to specific search problems. Moreover, ML methods, such as NNs, can be used to detect objects in images, and QC can be used to speed up the training of the NNs that are used for object detection.

Additionally, as discussed in the previous section, ML and QC can be used to help DHS forecast disasters, which would allow the department to respond more quickly and thoroughly during incidents. In the case of biological emergencies, such as pandemic outbreaks, ML methods, such as deep neural operators, can be used to forecast spikes, and QC could be used to speed up the training of the NNs in the forecasting model.

ML and QC could help FEMA develop better flood maps to reduce future risk and decrease the costs associated with future weather disasters.

Support Outcome-Driven Community Recovery

In the aftermath of a catastrophe, FEMA assists communities in restoring infrastructure, economic activity, social services, housing, and other functions. These restoration efforts aim to reduce future risk and decrease disaster costs through, for instance, incentives to obtain flood insurance policies. Having more-accurate flood risk maps could allow FEMA to support communities in rebuilding and recovering more resiliently. As mentioned earlier, ML and QC could help FEMA develop better flood maps to reduce future risk and decrease the costs associated with future weather disasters.

Train and Exercise First Responders

Part of the DHS mission to strengthen preparedness and resilience is to strengthen local networks and reinforce the skills of first responders, including emergency planning methods. For any location in the United States, ML and QC might be used to help DHS forecast the nature, magnitude, and other geophysical features of future disasters that will affect the location. Given a disaster forecast for a specific location, DHS could use that forecast to tailor its training of the first responders at the location. In particular, DHS would be able to use the forecast to reinforce skills in the first responders that are relevant to the disasters that are forecast at their locations and to better help the responders plan for emergencies.

Champion the U.S. Department of Homeland Security's Workforce and Strengthen the Department

The sixth and final DHS mission is to champion its own workforce. This involves the standard departmental governance and management, maintaining a high-performing workforce, and optimizing mission-support efforts. QC and LLMs could combine to assist the DHS workforce in several ways, which we describe in this section.

LLMs are an emerging technology that can augment workflows in numerous domains and that might help DHS improve performance of each of these tasks. Although they are still unable to solve difficult mathematical and quantitative problems, LLMs can achieve near–human-level performance on many writing and research tasks, and their performance has been improving rapidly. For example, OpenAI's LLM GPT-4 can perform in the 90th percentile on the Uniform Bar Examination, 88th percentile on the Law School Admission Test, 80th percentile on the Graduate Record Examination (GRE) Quantitative Reasoning section, and 99th percentile on the GRE Verbal Reasoning section. The performance of OpenAI's previous GPT model, GPT-4 Turbo was in only the 10th percentile on the Uniform Bar Examination, the 40th percentile on the Law School Admission Test, the 25th percentile on the GRE Quantitative Reasoning section, and the 63rd percentile on the GRE Verbal Reasoning section (OpenAI, undated). Given their rapidly improving performance on these benchmarks, LLMs are becoming a useful tool for automating tasks that would be much more time-consuming for a human to complete.

ML can be performed using a combination of quantum computers with high-performance classical computing and graphics-processing units. In particular, QC has been proposed as a method for large-scale training of neural architectures, even when there are few reliable resources (Liang et al., 2023). For example, researchers have used Grover's quantum search algorithm to compute sparse-attention matrices, which can be used to speed up the training of LLMs (Gao et al., 2023).

Strengthen Departmental Governance and Management

Strengthening DHS's governance and management includes "applying thorough and sound analytic studies to identify and implement the best solutions for the Nation's investment in homeland security" (DHS, 2019, p. 52). LLMs have already been employed in survey research (Jansen, Jung, and Salminen, 2023), automatic summarization (Liu et al., 2023; Zhang et al., 2023), text classification (Sun et al., 2023), and text generation (Chung, Kamar, and Amershi, 2023). Each of these tasks could be used to enhance analytic assessments of DHS investments.

Another challenge for DHS governance is filtering the right information up to decisionmakers to help them make informed decisions. Not all DHS information systems interoperate, and there are many instances of siloing. This often prevents information from reaching decisionmakers when needed. It is unclear, however, whether AI technologies could alleviate this problem (e.g., Shlezinger et al., 2021; Soldati et al., 2023).

ML techniques could be employed with historical data to find out the effects of siloed communication in prior situations. One would expect these effects to have resulted in delayed responses to critical problems. Although declaring that to be the case would be too speculative at this stage, the tasks of finding, training, and deploying these ML algorithms would likely benefit from a quantum perspective. However, the uncertainty and feasibility of this mission make determining the mission's priority difficult.

Develop and Maintain a High-Performing Workforce

Another part of the DHS mission is to develop and maintain a high-performing workforce. This includes engaging the workforce and improving satisfaction while maintaining employee performance.

LLMs can optimize employee performance and save work time while taking on repetitive tasks. In particular, LLMs can perform many tasks that are tedious for human employees, and their adoption could lead to higher employee satisfaction. For instance, LLMs are already adept at summarization, text classification, and text generation. LLMs can also assist with human communication and, in certain situations, can make communication more accessible to human understanding by making text clearer, more understandable, and, at times, more empathetic. DHS could begin to integrate LLMs for such tasks as note-taking, rote data analysis, and news summarization.

Additionally, DHS agents in the field or command centers might experience overwhelming cognitive load due to the diversity of information feeds at their disposal. Different AI tools could be leveraged to reduce this cognitive load and automate the manual work involved in using these systems. One such AI approach is the introduction of recommender systems or engines. These engines have found their application in the more mundane world of entertainment, in which a user faces an overwhelming number of entertainment choices at their disposal. Recommender systems train previous data on the user's choices and patterns. This involves reinforcement learning; multicriterion, multidimensional recommender systems; risk-aware systems; and location-based recommendations (Ricci, Rokach, and Shapira, 2021).

The literature on quantum recommender systems is mixed. In promising work in 2016, Kerenidis and Prakash showed that a quantifiable advantage could be achieved by employing quantum singular-value estimation ideas (Kerenidis and Prakash, 2016).[15] However, Tang (2018) shows that classical computers could provide "nearly" the same performance as the Kerenidis–Prakash algorithm, thereby delivering a checkmate on the overpromises of QML. Classical AI recommender systems are still a valuable tool for DHS agents, but the benefits of quantum boosts are not known to be substantial.

Optimize Support to Mission Operations

The final component of the DHS mission to champion its workforce is to optimize support to mission operations. This includes "providing operators and personnel with the equipment, training, technology, legal counsel, partnerships, and research to more effectively execute their responsibilities" (DHS, 2019, p. 55). As part of this support, DHS aims to

> leverage existing technologies to combat immediate and emerging threats; [coordinate] joint operations; closely [monitor] operational needs to identify new statutory needs; [identify] joint requirements and acquisition needs; and [ensure] that DHS activities comply with civil rights, civil liberties, and privacy requirements. (DHS, 2019, p. 55)

In addition to reaping the benefits of quantum-augmented LLMs (discussed previously), DHS can realize mission-support benefits from LLM-augmented quantum algorithms. As stated earlier, quantum algorithms could be used to more quickly optimize objectives, given a set of constraints, and such optimizations could be applied to maximize the allotment of resources or choices among a set of investments. Additionally, some research has focused on applying LLMs to quantum architecture design (Liang et al., 2023). Specifically, Zhiding Liang and his colleagues developed and implemented a Quantum GPT-Guided Architecture Search model to propose ansatz quantum architectures and evaluate them with benchmarks in the domains of quantum chemistry (estimation of molecular ground-state energy for lithium and water), quantum finance (portfolio optimization), and graph theory (max cut and the traveling salesperson problem). The researchers found that, after

AI tools, if they attain their full potential, could make DHS more effective and efficient and improve the lives of both its personnel and its stakeholders.

a small number of iterations, they were able to obtain an ansatz with performance comparable to that of state-of-the-art quantum architectures. LLMs can design well-performing quantum architectures in part because they can use prior knowledge of the relevant research community to tailor the architecture and the initial parameter guesses to the problem at hand. In particular, an LLM could use the collective knowledge of the homeland security community to tailor quantum architectures in support of DHS mission operations.

Discussion and Conclusion

In this paper, we have illustrated ways in which QC could enhance AI tools that DHS employs or could employ in the performance of its duties as these emerging technologies mature. These tools, if they attain their full potential, could make DHS more effective and efficient and improve the lives of both its personnel and its stakeholders.

The question is whether DHS can realize this potential. A mix of private and other governmental actors are funding research to advance the science of QC and AI. These include Amazon, D-Wave, Google, IBM, IonQ, Microsoft, PsiQuantum, Rigetti Computing, QC Ware, Quantinuum, and Xanadu. Current scientific and business consensus indicates that QC will be at least partially successful in solving *some* demanding and computationally challenging tasks in AI, simulation, and optimization. Many of these problems correspond to challenges DHS faces across its mission space.

DHS does not need to be a primary research and development funder in this space to be an early beneficiary of advances in this technology. In this section, we describe some of DHS's opportunities to leverage ongoing and future advances in these emerging technologies.

Create an In-House Quantum Team

One option could be the creation of a quantum-fluent team within the Science and Technology Directorate to find problems at DHS that are computationally taxing and that create severe bottlenecks and to map these problems to quantum algorithms (a process known as *quantizing*) to prepare for ways in which these problems can be solved, at some scale, using future quantum devices. Because well-established entities are already developing the most-powerful algorithms, DHS does not need to reinvent the wheel or invest directly in advancing the science of QC. Having a smaller in-house team of scientists at DHS who can understand and repurpose these algorithms would likely be sufficient. Moreover, technical expertise in the manufacturing of quantum hardware is a scarce resource and one that is subject to increasing export controls. Therefore, the actual deployment of the algorithms on hardware could also be outsourced to U.S.-based technology companies, such as Amazon, D-Wave, Google, IBM, IonQ, Microsoft, PsiQuantum, Rigetti Computing, QC Ware, Quantinuum, and Xanadu.

Outsource the Department's Quantum Needs

Another possibility is for DHS to outsource its quantum needs to a combination of universities, think tanks, and private-sector companies. For instance, DHS could take the following approach:

1. Outsource the consulting services for finding taxing computational bottlenecks to a global system integrator.
2. Have the mapping and quantization of the problem performed by another organization or academic institution.
3. Have the new quantum solution executed by a private company that owns and maintains quantum devices.

The advantage of such an approach is that it would foster a mutually beneficial relationship between the public, private, and academic sectors and stimulate quantum research in the United States. See also Parker (2023) for a perspective on quantum collaborations.

Monitor Progress and Prepare the Workforce

The timing of DHS realizing the potential of these emerging technologies is also tricky. Several road maps place quantum advantages in the 2020s or 2030s (Google Quantum AI, undated; IBM, undated). Unfortunately, there is no consensus on this point, and existing road maps stem largely from private-sector companies that might have vested interests in attracting investment. Although DHS likely cannot do much on its own to speed scientific process on QC and AI, it can monitor progress in these fields and prepare its workforce accordingly. (An exception could be if DHS could deploy PQC algorithms as soon as they are vetted by the National Institute of Standards and Technology and the cryptography and intelligence communities.)

Closing Thoughts

In conclusion, QC and AI have promising applications for DHS in cryptography, communication, cybersecurity, espionage, WMD, financial markets, autonomous weapons, and weather prediction. Realizing this combined potential will require identifying difficult computational problems that can be mapped to quantum algorithms and that offer some advantage over classical algorithms. DHS should strategize how to pursue these possibilities to more quickly and effectively employ quantum algorithms and AI.

Notes

[1] According to *The DHS Strategic Plan: Fiscal Years 2020–2024* (DHS, 2019), the department has a sixth, inward-focused mission to strengthen itself and its workforce.

[2] An algorithm is a set of instructions for a computer to accomplish a task.

[3] Entanglement is a property of nature that takes place when several qubits are generated and then interact with each other in such a way that the overall state of each qubit can no longer be described independently of the state of the other qubits, even when these qubits are separated by extremely large distances. As its name suggests, entanglement means that the system of qubits is now intimately connected and that interesting and valuable correlations between these qubits can be exploited in quantum algorithms. Interference is the effect of manipulating the proportions of off and on of the qubits for the purpose of amplifying desired measurement results and mollifying undesired quantum by-product effects. Interference is critical to manipulating a system of qubits into configurations can that be put to effective use in quantum devices.

[4] Shor's algorithm can factor an integer N in polylogarithmic time. In other words, the running time of Shor's algorithm is a power (polynomial, rather) of $\log N$, which is a hefty improvement over known classical methods. *Superpolynomial* means asymptotically greater than any polynomial.

[5] For more, see Computer Security Resource Center, 2024.

[6] Here, we have employed the *big O* notation, which indicates order of magnitude, effectively implying that Grover produces a speedup advantage in the order of magnitude of the square root of N.

[7] Another way to say this is that annealers do not solve the Schrödinger equation (i.e., cannot solve chemistry and physics problems), so they cannot be used outside optimization without first *heavily* reworking the problems at hand.

[8] We also foresee that QS could offer improved capabilities at the sensor and actuator layer of UAV operation.

[9] As Paces and Udatny explained, the A* algorithm uses

> estimation of the cost to get from the actual state to the goal state in order to speed up the search process. The estimation is called heuristic. The algorithm is designed mainly to find a fast solution to one destination. (§ III[E])

[10] The Schrödinger equation is the governing master equation of quantum evolution of a closed system, and its solution provides essentially all one can know about the quantum system being investigated.

[11] Should the dynamical-system PDEs not be amenable to be written in Schrödinger form, one could still attempt switching or enlarging the problem to a more general PDE (also known as an *embedding protocol*) that happens to be of Schrödinger form, such as demonstrated in Gonzalez-Conde et al. (2021); see also Alghassi et al. (2022) and Alhajjar et al. (2023). This enlargement represents a compromise because it requires solving a more general problem and therefore necessitates careful extraction of the desired subsolution within the larger problem. This extra care could erode any potential quantum advantages.

[12] Navier–Stokes equations are a set of PDEs that express momentum and conservation of mass in Newtonian fluids. They take viscosity into account. Many scientific and engineering phenomena, including the weather, ocean currents, water flow in a pipe, and air flow around a wing, can be described using Navier–Stokes equations.

[13] After about one week, chaos kicks in again and weather becomes essentially unpredictable.

[14] If the weather data were to be collected with a quantum sensor and if the data were *already* in a quantum register, the situation would improve, and AI techniques would become more useful.

[15] Singular-value analysis is an advanced linear algebra technique adept at inverting matrices and solving systems of linear equations with applications in physics, signal processing, ML, and other fields.

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About This Paper

Building on research in quantum machine learning, we investigated the effect of quantum-enhanced artificial intelligence within the context of the six U.S. Department of Homeland Security (DHS) missions. For each mission, we illustrate how quantum boosts could help DHS perform its computational duties more efficiently. We also explain some situations in which quantum computing does not provide benefits over classical computing. Last, we provide recommendations to DHS on how to leverage quantum computing. This paper should be of interest to policymakers, researchers, and others working on quantum computing or artificial intelligence.

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This research was conducted in the Management, Technology, and Capabilities Program of the RAND Homeland Security Research Division (HSRD). HSRD operates the Homeland Security Operational Analysis Center, a federally funded research and development center sponsored by DHS. HSRD also conducts research and analysis for other federal, state, local, tribal, territorial, and public- and private-sector organizations that make up the homeland security enterprise, within and outside the Homeland Security Operational Analysis Center contract. In addition, HSRD conducts research and analysis on homeland security matters for U.S. allies and private foundations.

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