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Quantum Technology: Promise, Peril, and Possibility



Michael Kosuda

Colonel, U.S. Army

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ABSTRACT

A second revolution in quantum technology is coming. The potential innovations and capabilities are exquisite, but the basic technology is still undeveloped. This provides policymakers time to grapple with and mitigate the problematic aspects of these technologies. This paper examines the future of quantum technology and argues that government has three essential roles in shaping that future. First, it has an interest in developing quantum technologies. It should invest in basic and applied research to ensure a healthy ecosystem of innovation and prevent a quantum surprise from competitor countries. Second, the government will be crucial to establishing norms and rules governing some applications of quantum technologies, especially ones that must balance government responsibility with individual liberty. Finally, quantum technology has a tremendous potential to cause social disruption. The government will be necessary to lead through transition and prevent or mitigate the worst outcomes while reaching for the potential to create a new order for human flourishing.

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1. Introduction

Quantum theory is over a century old, and we are living in a world created by the first quantum revolution. Something as ubiquitous as a cell phone has billions of transistors, an example of quantum technology foundational to most modern electronics.¹ Today as scientists and engineers delve deeper into the “spooky” world of quantum theory and get better at manipulating quantum properties, we are starting to see the outlines of a second quantum revolution.² This revolution applies previous understanding to develop new disruptive technologies that hold the potential to “alter the quantum face of our physical world.”³ With an estimated \$22.5 billion spent on global research and development in 2021, nation-states, multinational corporations, and investment capital are racing to claim a quantum advantage.⁴

This paper examines the future of quantum technology and argues that government has three essential roles in shaping that future. First, it has an interest in developing quantum technologies. It should invest in basic and applied research to ensure a healthy ecosystem of innovation and prevent a quantum surprise from competitor countries. Second, the government will be crucial to establishing norms and rules governing some applications of quantum technologies, especially ones that must balance government responsibility with individual liberty. Finally, quantum technology has a tremendous potential to cause social disruption. The government will be necessary to lead through transition and prevent or mitigate the worst outcomes while reaching for the potential to create a new order for human flourishing.

¹ Shohini Ghose, “Are You Ready for the Quantum Computing Revolution?,” *Harvard Business Review*, September 17, 2020, <https://hbr.org/2020/09/are-you-ready-for-the-quantum-computing-revolution>.

² When Einstein first observed entangled electrons in action he described it as “spooky action at a distance.” William Hurley, “Quantum Computing, Not AI, Will Define Our Future,” *TechCrunch*, accessed December 26, 2020, <https://social.techcrunch.com/2018/11/17/quantum-computing-not-ai-will-define-our-future/>. Jonathan P. Dowling and Gerard J. Milburn, “Quantum Technology: The Second Quantum Revolution,” *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 361, no. 1809 (August 15, 2003): 3, <https://doi.org/10.1098/rsta.2003.1227>.

³ Dowling and Milburn, “Quantum Technology,” 3.

⁴ “Overview on Quantum Initiatives Worldwide,” Qureca, September 7, 2020, <https://www.quireca.com/overview-on-quantum-initiatives-worldwide/>.

This paper proceeds through four stages. The first provides some of the basic scientific ideas and connections with technology to establish a foundation for the analysis in subsequent sections. The second section consists of futurizing or describing some of the potential futures quantum technology could provide. The purpose of this is to provide material for further analysis and present a forward-looking perspective for policymakers. The third section looks at the potential futures through three different ethical frameworks to uncover concerns that may require government intervention. The final section bins those ethical concerns and provides policy options to address them. Included in the policy section will be an alternate view to account for the potential that not all quantum technologies may be successful. With that road map, we peek behind the veil of the mysterious quantum world.

2. From Science to Technology

“For those who are not shocked when they first come across quantum theory cannot possibly have understood it.” – Niels Bohr⁵

Quantum Theory. To understand the revolutionary nature of the new quantum technology, it is necessary to briefly touch on some aspects of quantum theory that are counter-intuitive and diverge from classical mechanical understanding. Quantum theory “explains the nature of energy and matter on the atomic and subatomic level.”⁶ At this small scale, scientists began to make observations that they could not explain using classical physics. As quantum theory emerged, five principles shocked and challenged the scientific world. Uncertainty, superposition, entanglement, tunneling, and decoherence will become the features that drive the second quantum revolution.

⁵ Manjit Kumar, *Quantum: Einstein, Bohr, and the Great Debate about the Nature of Reality*, Illustrated edition (New York: W. W. Norton & Company, 2011), 1.

⁶ Hurley, “Quantum Computing, Not AI, Will Define Our Future.”

1) **Uncertainty.** “At the level of individual quantum particles, such as electrons or photons (particles of light), it’s impossible to precisely know every property of the particle at any given moment in time.”⁷ When observing an electron, it is impossible to know its location, speed, and direction simultaneously. Uncertainty is not a technological limitation of scientific instruments; it is a law of physics. This uncertainty means that the quantum world deals in probabilities.

2) **Superposition.** The phenomenon that “quantum systems can exist in multiple states simultaneously until observed or measured.”⁸ The most famous illustration of this is Erwin Schrödinger’s cat. In this thought experiment, a cat exists in a box with a Geiger counter that contains a radioactive substance that has a 50% chance of one atom decaying in an hour. If the atom decays, a poison kills the cat. Conventional understanding would, of course, recognize that the cat is either alive or dead. However, when the entire system is expressed as a wave function, the cat exists in both states simultaneously. Only opening the box and observing can determine if the cat lives.⁹

3) **Entanglement.** A quantum property “in which two or more particles remain inexorably linked no matter how far apart they are.”¹⁰ When applied systemically, entanglement has profound differences from our classical understanding of connectedness. Dr. John Preskill from the California Institute of Technology uses the analogy of a book. In a traditional book, you can read one page at a time, and when you have read them all, you can understand 100% of the content. In a ‘quantum’ book, each individual page is entangled with every other page. The particular page will make no sense until you look at them all simultaneously and can understand

⁷ Ghose, “Are You Ready for the Quantum Computing Revolution?”

⁸ Hurley, “Quantum Computing, Not AI, Will Define Our Future.”

⁹ Kumar, *Quantum*, 316.

¹⁰ Kumar, 378.

the interconnectedness. This will have profound implications for how quantum technology handles information.¹¹

4) **Tunneling.** “The ability of a particle to be found in spatial regions from which classical mechanics would exclude it.”¹² At the sub-atomic scale, particles like electrons behave like a wave. When the wave hits a barrier, most electrons will bounce off, but some will continue into the barrier. If it is thin enough, there will be some probability of a wave, albeit a lot weaker, continuing past the barrier.¹³ This will create challenges for engineers trying to control delicate quantum systems.

5) **Decoherence.** “The process that comes about when a quantum state transitions to a classical world state.”¹⁴ This could be when entangled particles separate or when a superposition collapses into a single state. Decoherence makes quantum states fragile and thus presents an engineering challenge for quantum technologies.

The current revolution in quantum technology took off when scientists and engineers stopped thinking of these quantum principles as bugs and started treating them as features.¹⁵ The basic science and engineering ability to harness quantum principles generate the potential for radical improvement in computing, communications, cryptography, imaging, sensing, drug development, and material sciences, among others. Central to many of these technologies is the quantum computer, which illustrates how quantum principles translate into technology.

¹¹ John Preskill, “Quantum Computing in the NISQ Era and Beyond,” *Quantum* 2 (August 6, 2018): 2, <https://doi.org/10.22331/q-2018-08-06-79>.

¹² Dowling and Milburn, “Quantum Technology,” 4.

¹³ Breakthrough, *Maryam Tsegaye, Canada, Physics, Winner: 2020 Breakthrough Junior Challenge, 2020*, <https://www.youtube.com/watch?v=vg2rnjZ19PY&list=LL&index=1>.

¹⁴ Bob Yirka, “Researchers Discover a Way to Avoid Decoherence in a Quantum System,” *Phys.org*, accessed February 23, 2021, <https://phys.org/news/2013-03-decoherence-quantum.html>.

¹⁵ Ghose, “Are You Ready for the Quantum Computing Revolution?”

Quantum Computing Overview

Quantum Information Science (QIS) is an interdisciplinary field that includes computer scientists, physicists, engineers, and mathematicians.¹⁶ One emergent technology produced by QIS is the quantum computer, which applies quantum theory to computer engineering.

Quantum computers are a fundamentally different technology from classical computers. Dr. Shohini Ghose, President of the Canadian Association of Physicists, used a candle and lightbulb analogy. A lightbulb is not just a bigger candle, it is built on a fundamentally more profound understanding of science, and you can't make one from making bigger and bigger candles.¹⁷ The leap in quantum computing is not just faster processing. Quantum computers have applications for solving problems that are impossible using classical machines.¹⁸ One example of this qualitative leap is in the modeling of chemical reactions. Classical computers cannot simulate the action of more than ten atoms.¹⁹ But a quantum computer would be uniquely suited for this task because it would use the same laws of quantum physics that govern the molecules it is simulating.²⁰ As physicist Richard Feynman noted: "Nature isn't classical dammit, and if you want to make a simulation of Nature you better make it quantum mechanical, and by golly, it's a wonderful problem because it doesn't look so easy."²¹ This is the same challenge that interdisciplinary teams are tackling in academic and private industry labs across the globe.

To make a quantum computer, scientists and engineers seek to exploit the principles of superposition and entanglement to develop quantum bits, or qubits.^{22,23} A classical bit is a switch

¹⁶ "Introduction: A New Quantum Revolution," NIST, March 21, 2018, <https://www.nist.gov/topics/physics/introduction-new-quantum-revolution>.

¹⁷ Shohini Ghose, *A Beginner's Guide to Quantum Computing*, accessed January 2, 2021, https://www.ted.com/talks/shohini_ghose_a_beginner_s_guide_to_quantum_computing.

¹⁸ Chris Wiltz, "Everything You Wanted to Know about Quantum Computing," Design News, December 19, 2018, <https://www.designnews.com/electronics-test/everything-you-wanted-know-about-quantum-computing>.

¹⁹ Wiltz, "Everything You Wanted to Know about Quantum Computing."

²⁰ Ghose, "Are You Ready for the Quantum Computing Revolution?"

²¹ Preskill, "Quantum Computing in the NISQ Era and Beyond."

²² Ghose, "Are You Ready for the Quantum Computing Revolution?"

²³ Wiltz, "Everything You Wanted to Know about Quantum Computing."

that can be either on or off, zero or one. A qubit, however, exists in a superposition of some probability of being one and some probability of being zero at the same time, and this provides “new levers for more powerful ways to communicate and process data.”²⁴ Because qubits can hold many states, they can hold exponentially more data. The second principle at the center of quantum computing is the idea of entanglement. A classical bit is not connected to the other bits; turning it on or off will not affect the adjacent bits. A quantum computer, however, uses entanglement to connect qubits. This leads to an extravagant complexity where just describing “all the correlations among just a few hundred qubits may require more bits than the number of atoms in the visible universe.”²⁵ The potential to exceed the computing power of even the most sophisticated supercomputers is tantalizing. There is, however, a long way to go before realizing that potential.

“To say quantum computing is in its infancy is an overstatement. It’s still in the womb.”²⁶ In many respects, it is like the pre-transistor era of classical computer development before the silicon microchip became the industry standard. Engineering teams are taking different approaches to develop qubits. The University of California at Berkley is using superconducting metals to create electrical oscillator qubits.²⁷ IBM and Google are also using superconducting qubits.²⁸ Other approaches include using “topological” interactions of super-cold electrons (Microsoft); electrons and microwaves (Rigetti Computing); ytterbium ions and lasers (IonQ); and photons in waveguides etched into silicon chips (PsiQuantum) to make qubits.²⁹ These

²⁴ Ghose, “Are You Ready for the Quantum Computing Revolution?”

²⁵ Preskill, “Quantum Computing in the NISQ Era and Beyond,” 3.

²⁶ Irene Qualters, and Taylor Antoinette, “Basic Quantum Research Will Transform Science and Industry,” *Scientific American*, May 17, 2019, <https://blogs.scientificamerican.com/observations/basic-quantum-research-will-transform-science-and-industry/>.

²⁷ Wiltz, “Everything You Wanted to Know about Quantum Computing.”

²⁸ Edd Gent, “IBM Plans to Have a 1,000-Qubit Quantum Computer by 2023,” *Singularity Hub*, September 25, 2020, <https://singularityhub.com/2020/09/25/ibm-plans-to-have-a-1000-qubit-quantum-computer-by-2023/>.

²⁹ “Commercialising Quantum Computers,” *The Economist*, September 26, 2020, <https://www.economist.com/science-and-technology/2020/09/26/commercialising-quantum-computers>.

computers are currently under 100 qubits and have not solved fundamental challenges to scalable quantum computing.

John Preskill of the California Institute of Technology has dubbed this the Noisy Intermediate-Scale Quantum (NISQ) era.³⁰ To deal with the delicacy of quantum states and the properties of tunneling and decoherence, NISQ computers take extravagant measures like supercooling and noise dampening to shield the quantum system. Still, NISQ computers do this imperfectly.³¹ Quantum computing will not reach its full potential until scientists and engineers can apply quantum error correction to stabilize the system and process information. This will require a significant increase in the number of necessary qubits. Reaching that goal will take advances in engineering and material science, meaning that true quantum computers are not on the immediate horizon.³² But when the scientists and engineers do summit the mastery of controlling quantum systems, what will the future entail?

3. Futurizing

With many quantum technologies still requiring advances in basic science and routinely encountering new engineering challenges, the future of quantum tech is highly contingent and frustratingly ephemeral. Before delving into that future, a note of caution is in order. Noted researcher and futurist Roy Amara observed that “humans tend to overestimate change in the near term but underestimate it in the long term.”³³ This observation is now referred to as Amara’s Law. Part of this is due to what another futurist and inventor, Ray Kurzweil, demonstrated; “that humans forecast in linear ways, but change often occurs exponentially.”³⁴

³⁰ Preskill, “Quantum Computing in the NISQ Era and Beyond,” 4.

³¹ Preskill, 5.

³² Preskill, 4.

³³ Christian Crews, “How Far to Look Ahead?,” *Research Technology Management* 62, no. 5 (October 9, 2019): 59, <https://doi.org/10.1080/08956308.2019.1638487>.

³⁴ Ray Kurzweil, *The Singularity Is Near: When Humans Transcend Biology* (New York: Penguin Books, 2006), 11.

With barely an outline of what quantum technology will initially offer, the compounding nature of development will be challenging to forecast. Inevitably, this exercise is likely to both overestimate some futures while underestimating others. However, what will be useful is to probe deep enough to highlight ethical concerns that society needs to address on the front end of this magical trip into a quantum wonderland.

In casting our gaze into the future, it is still prudent to try and ameliorate the effects of Amara's Law. This analysis uses three separate lenses to consider the future of quantum technology. Physicist and theologian Ian Barbour described three perspectives that people use when evaluating technology. The first is "Technology as Liberator," which views technology with enthusiasm, optimism, and as a tool of progress.³⁵ The second is "Technology as Threat," which assumes a pessimistic stance that technology will diminish authentic human experience.³⁶ The final perspective is "Technology as Instrument of Power," which sees technology existing in a social construct determined by human choice.³⁷ This paper sketches some potential futures of quantum technologies in each of Barbour's three perspectives.

To add additional structure in sketching potential futures, this paper adopts a method developed by political scientist Harold Lasswell at the dawn of future studies as an academic discipline. He proposed "five specific tasks for the study of the future. They are 1. The clarification of goals and values. 2. The description of trends. 3. The explanation of conditions. 4. The projection of possible and probable futures if current policies continue. 5. The invention, evaluation, and selection of policy alternatives (to achieve preferred goals)."³⁸ The last step will be deferred until after an ethical interrogation of the potential most critical potential futures.

³⁵ Ian G. Barbour, *Ethics in an Age of Technology*, 1st ed, The Gifford Lectures, v. 2, 1989-1991 (San Francisco, Harper, 1993), 4.

³⁶ Barbour, 10.

³⁷ Barbour, 15.

³⁸ Wendell Bell, *Foundations of Futures Studies: Volume 1 History, Purposes, and Knowledge* (New Brunswick, N.J.: Transaction Publishers, 2003), 49–50.

Three Views of the Future

Quantum Technology as Liberator. Ian Barbour notes that proponents of technology, when projecting into the future, often identify four types of benefits: higher living standards, an opportunity for choice, more leisure, and improved communications.³⁹ Quantum technology offers ample promise in all four areas. This section focuses on the potentials for simulation, medical imaging, and secure networks.

Simulation. One truly revolutionary possibility of quantum technology is the expectation that quantum computers will be able to simulate chemical reactions that are impossible on classical computers. This technology supports the goals of advancing scientific understanding, improving the human condition, and reducing the impact on the environment. With the current NISQ computers, scientists are only able to simulate simple chemical reactions. In 2020 scientists used Google's Sycamore computer to simulate a reaction within a diazene molecule consisting of only four atoms.⁴⁰ While this calculation can be done on classical computers, scientists proved that NISQ computers could produce an accurate result using quantum methods. The power and complexity of quantum simulation will track along with the development of more powerful quantum computers.

Quantum simulation will really take off when fault-tolerant quantum computers become available. Not only will this technology help probe the mysteries of quantum physics, but the potential applications are limitless. Pharmaceutical companies could simulate drug interactions that could accelerate drug development.⁴¹ Paired with genomic information, the processing

³⁹ Barbour, *Ethics in an Age of Technology*, 4–5.

⁴⁰ Leah Crane, "Google Performed the First Quantum Simulation of a Chemical Reaction," *New Scientist*, August 27, 2020, <https://www.newscientist.com/article/2253089-google-performed-the-first-quantum-simulation-of-a-chemical-reaction/>.

⁴¹ Hurley, "Quantum Computing, Not AI, Will Define Our Future."

power of quantum computers could synthesize therapies to create or tailor medicine for individuals. Quantum chemists could find cleaner ways of making fertilizer, more efficient solar cells, and perhaps even new carbon capture materials.⁴² To peer even further, as scientists and engineers become more adept at manipulating quantum scale particles, quantum simulation could become part of creating new chemicals, elements, and materials. Perhaps they will even create or discover a more efficient type of rocket fuel that will make extended space flight possible. The ability of quantum computers to simulate quantum dynamics promises to revolutionize scientific understanding and create new possibilities for scientists and engineers to shape the world we inhabit.

It is worth noting that quantum simulation has dual-use properties. Improved pharmaceutical development can also lead to improved poison development. Malicious actors can use the technology for tailored medicine to tailor weapons. The same technology that could develop a new rocket fuel could potentially create new explosives, powerful ones that are harder to detect. This reality validates one historian's observation that "technology is neither good nor bad; nor is it neutral."⁴³ How society treats this technology will determine its impact.

Medical Imaging. A second quantum technology that promises to improve the quality of life is medical imaging. Quantum systems can sense smaller forces with better spatial definition than traditional technologies like X-ray or magnetic resonance imaging (MRI).⁴⁴ The current trend is to make imaging devices smaller but also with higher resolution. One research effort in the

⁴² Preskill, "Quantum Computing in the NISQ Era and Beyond," 13.

⁴³ Melvin Kranzberg, "Technology and History: 'Kranzberg's Laws,'" *Technology and Culture* 27, no. 3 (1986): 545, <https://doi.org/10.2307/3105385>.

⁴⁴ Preskill, "Quantum Computing in the NISQ Era and Beyond."

European Union is using a quantum technique called hyperpolarization to improve MRI sensitivity by a factor of 10,000.⁴⁵

It is not hard to project what the implications are for medical care. Doctors could be able to identify diseases such as Alzheimer's, dementia, and Parkinson's earlier. Understanding what is happening with tissue at the molecular level could revolutionize diagnosis and treatment for cardiovascular disease and cancer, among many others. This technology has tremendous potential to benefit people and improve their quality of life. However, what is not clear is whether enough people will have access to this standard of care for it to have a societal impact.

Secure Networks. A third technology addresses Barbour's last benefit, the value of improved communications. QIS promises to provide virtually hack-proof communications security. The technology at the heart of this promise is Quantum Key Distribution (QKD). It is based on the no-cloning theorem, which states that it is impossible to copy a quantum state precisely.⁴⁶ This is due to the property of superposition, where a quantum particle can be in many states simultaneously. To 'read' the information, an outside observer would have to collapse the quantum state, which would destroy the information and alert those communicating that there was an attempted intercept. This is a different type of cryptography from what is common practice today. Current cryptography relies on challenging mathematical problems such as factoring, which hackers can crack given enough time and computational power. QKD cryptography offers unconditional security because a hacker would have to overcome the laws of physics to crack the key.⁴⁷

⁴⁵ Jonathan O'Callaghan, "Quantum Technology Could Revolutionise the Detection and Treatment of Diseases," *Horizon: The EU Research & Innovation Magazine*, June 24, 2019, <https://horizon-magazine.eu/article/how-quantum-technology-could-revolutionise-detection-and-treatment-diseases.html>.

⁴⁶ Taylor, "Basic Quantum Research Will Transform Science and Industry."

⁴⁷ Eleni Diamanti et al., "Practical Challenges in Quantum Key Distribution," *NPJ Quantum Information* 2, no. 1 (November 8, 2016): 1–12, <https://doi.org/10.1038/npjqi.2016.25>.

In 2016, a Chinese and Austrian collaboration launched the Micius satellite, which established a QKD network between the satellite and multiple ground stations.⁴⁸ Researchers also used QKD over fiber networks which initially had a limited distance. As engineers get better at manipulating quantum particles, they have been expanding the reach of effective QKD. China is developing a QKD network between Beijing and Shanghai (2,000 km), while the United States, Europe, and Japan all have QKD networks in various states of experimentation and construction.⁴⁹

To project forward, quantum cryptography will likely become necessary in securing personal, medical, financial, infrastructure, and classified information. Part of this is due to hacking's future potential, which will be taken up in the next section. But more secure networks have an intrinsic value as well. Improved security can lead to more trust, the kind of trust that can make medical collaboration more effective and financial transactions more fruitful. Of course, the same technology that can safeguard our nation's secrets can also be used to frustrate U.S. technical surveillance, potentially creating space for adversaries and criminals to operate freely.

Quantum Technology as Threat. Skeptics tend to dwell on the negative implications of technological progress. Barbour points out that critics focus on the negative impact on human flourishing with such characteristics as manipulation and worker alienation.⁵⁰ Certain quantum technologies do pose a threat in such areas as hacking, military sensing, and deflationary accelerant.

⁴⁸ Elsa B Kania and John K Costello, "Quantum Hegemony? China's Ambitions and the Challenge of U.S. Innovation Leadership" (Center for a New American Security, 2018), 14–15, <https://www.cnas.org/publications/reports/quantum-hegemony>.

⁴⁹ Diamanti et al., "Practical Challenges in Quantum Key Distribution."

⁵⁰ Barbour, *Ethics in an Age of Technology*, 10–11.

Quantum Hacking. Current cryptography relies on the mathematically complex problem of factoring, that is, breaking a large number into its prime factors (the numbers that, when multiplied together, equal the initial number). Classical computers cannot solve these factoring problems very well, and this provides the basis for most Public Key Cryptography systems securing our internet communications today.⁵¹ Here is where the qualitative change in quantum computers can have a significant impact.

In 1994, the mathematician Peter Shor created an algorithm designed to run on a future quantum computer that could solve factoring problems exponentially faster than the most powerful classical supercomputers.⁵² While the current NISQ computers are not powerful enough to factor large numbers, as computing power increases, Shor's algorithm could have profound implications for our digital infrastructure. The ability to crack security protocols will mean that financial, medical, and security information systems could become compromised. Compromise can occur both in current systems and transmissions and in the exploitation of previously captured encrypted data sets. With data as the critical strategic resource of the information age, we can expect powerful incentives for countries like China to exploit any weakness in encryption to feed their artificial intelligence (AI), quantum computing, and biomedical research efforts.⁵³

Fortunately, the National Institute of Standards and Technology (NIST), which publishes cryptography standards for the federal government, is developing quantum-resistant cryptographic systems.⁵⁴ This research and development aim to create post-quantum cryptography (PQC) that will remain secure even when powerful quantum computers come

⁵¹ Dowling and Milburn, "Quantum Technology."

⁵² "Introduction."

⁵³ Kania and Costello, "Quantum Hegemony," 25.

⁵⁴ Dustin Moody, "The Future Is Now: Spreading the Word About Post-Quantum Cryptography," NIST, November 24, 2020, <https://www.nist.gov/blogs/taking-measure/future-now-spreading-word-about-post-quantum-cryptography>.

online. With NIST guidance expected within the next twenty-four months, there will be a gap in time before they are genuinely needed to secure information. This will present a massive leadership challenge to invest in PQC across federal, state, local, commercial, and private sectors.

Military Sensing. Quantum technology has the potential to disrupt areas of U.S. military advantage. Two such technologies, among many, are quantum radar and magnetic sensing.

Quantum radar uses entangled protons and microwave beams to scan the sky.⁵⁵ Because the protons are entangled, the device can determine if returning signals originated from the system. A stealth aircraft confuses traditional radar by not reflecting radar as well as regular planes. Conventional radar cannot distinguish the minimal radar return from everyday background noise. But a quantum radar could tell which signals were reflected from the aircraft separate from both naturally occurring phenomena and jamming. The entangled proton serves as a round trip receipt. The North American systems are still developing and face significant engineering challenges, but the Chinese have already claimed to have built a quantum radar with a search range of 100 kilometers.⁵⁶ The potential loss of a stealth advantage has significant implications for deterrence (both conventional and nuclear) as well as for the assumptions regarding U.S. fighter development. The diminution of stealth advantage will challenge war planners and system developers who have relied on this technology with great success.

A second area of quantum technology that may challenge U.S. advantage is magnetic sensing. Researchers expect to have highly sensitive magnetometers on the market within five years.⁵⁷ This will have immediate application for navigation aids. They may also be useful in detecting large metal objects like submarines because magnetometers have a high sensitivity to

⁵⁵ Martin Giles, "The US and China Are in a Quantum Arms Race That Will Transform Warfare," *MIT Technology Review*, January 3, 2019, <https://www.technologyreview.com/2019/01/03/137969/us-china-quantum-arms-race/>.

⁵⁶ Giles, "The US and China Are in a Quantum Arms Race That Will Transform Warfare."

⁵⁷ O'Callaghan, "Quantum Technology Could Revolutionise the Detection and Treatment of Diseases."

magnetic anomalies. Researchers from the Shanghai Institute have announced initial success in developing a superconductive magnetic anomaly detection array.⁵⁸ While this program still has technological hurdles, it is not hard to envision that China will reduce some of the U.S. competitive advantages in undersea warfare in the medium to long term. This is especially true in local strategically significant areas like Taiwan and the South China Sea.

Deflationary Accelerant. This last threat category is not about a specific quantum technology but a projection about the technology's impact in aggregate. Even if quantum computers never become commercially available for individuals and remain as exquisite purpose-built machines for big business and government, the speedup in processing power will have significant ramifications for how the economy is structured. Automation first started replacing low-skilled physical labor, and in recent times it is replacing jobs in the knowledge economy.⁵⁹ Technology increases productivity by replacing people.

Quantum technology will accelerate this trend. With massive increases in processing speed for select problems, quantum pairing with AI has the potential to render even more knowledge-based jobs obsolete. Some futurists like Ray Kurzweil remain sanguine about this job obsolescence envisioning jobs lost at the bottom end of the skill ladder replaced by jobs higher up the skill ladder.⁶⁰ While some jobs may be created, it is not entirely clear that the number of jobs created will be equal to the ones lost. A factory will not hire one hundred engineers to tend automation that will replace one hundred factory workers; it would drastically increase labor costs and kill productivity. Businesses only automate when the result is a financial improvement, for example, hiring five engineers and robots to replace one hundred workers. The productivity pay divergence provides evidence. Since 1979 productivity rose 69 percent in the following four

⁵⁸ "Quantum Hegemony," 20.

⁵⁹ Kurzweil, *The Singularity Is Near*, 108.

⁶⁰ Kurzweil, 108.

decades while income stagnated with a mere 11.9 percent increase.⁶¹ Technology is deflationary. Economists project that AI alone will displace one hundred and twenty million worldwide jobs in the next three years.⁶² Quantum technologies promise to add the ability to process new types of tasks, speed up processing, and search big data, which could supersize the job losses due to automation and AI. Barbour highlighted how a narrow focus on efficiency could lead to the instrumentation of the worker and ultimate alienation in the industrial age.⁶³ In a cyber age powered by quantum AI pairing and automation, a narrow focus on efficiency would seek to leave even skilled workers out of the national economic life. The decoupling of wealth generation from labor will have a profound societal impact.

Quantum Technology as Instrument of Power. A third view of technology focuses on the social construction of technological development and posits that technology is an instrument of power whose consequences depend on the social context.⁶⁴ This focus on the interaction between society and technology offers a critical lens to focus on the future of quantum technology. Certain functions of quantum computing led themselves to this investigation. The uses for optimization, surveillance, and social engineering are particularly sensitive to societal interaction and decision-making.

Optimization. One set of problems that classical computers are not well suited for is optimization. A classic example of an optimization problem is: how should FedEx optimize each truck route to deliver thousands of packages most efficiently? When applied to traffic patterns, quantum computing can optimize traffic routes according to current conditions. The Volkswagen

⁶¹ “The Productivity–Pay Gap,” *Economic Policy Institute*, accessed April 10, 2021, <https://www.epi.org/productivity-pay-gap/>.

⁶² Jack Kelly, “U.S. Lost Over 60 Million Jobs—Now Robots, Tech and Artificial Intelligence Will Take Millions More,” *Forbes*, October 27 2010, <https://www.forbes.com/sites/jackkelly/2020/10/27/us-lost-over-60-million-jobs-now-robots-tech-and-artificial-intelligence-will-take-millions-more/>.

⁶³ Barbour, *Ethics in an Age of Technology*, 10–11.

⁶⁴ Barbour, 15.

Group and D-Wave Systems have currently used quantum computing to run pilot programs on traffic optimization in Beijing, Barcelona, and Lisbon.⁶⁵

While researchers don't expect quantum computing to solve the most challenging optimization problems, like combinations or layered optimization, quantum computing may generate approximate solutions much faster than classical computers.⁶⁶ One can envision that with more powerful quantum computers, people will apply optimization to ever more complex societal systems. From the delivery of packages and traffic flow to health care provision, combat operations, fiscal policy, and congressional redistricting, increasing efficiency in all aspects of life is potentially endless.

Here is where the social constriction of how this technology is applied becomes critical. The obvious question is, "Optimized for whom?" Each optimization problem assumes a value to optimize. Is traffic optimized for commuters, commercial vehicles, mass transit, or tourists? Does the medical industry remain optimized for corporate profits, or do people choose to construct a health care system optimized for the provision of care? Does fiscal policy optimize for the few or the many? Is redistricting optimized to express democracy or to undermine it? In this instance, the power of quantum computing cannot be separated from the very nature and structure of power in society.

Surveillance. One feature of quantum computing with several breakout applications is the ability to conduct fast searches of unsorted data.⁶⁷ Data quality is one source of friction in AI and machine learning. Pairing quantum computing with AI holds the potential to overcome some of these challenges. Researchers in China have used a quantum algorithm and a six-qubit computer

⁶⁵ Stephen Gossett, "8 Quantum Computing Applications & Examples," *Built In*, November 18, 2019, <https://builtin.com/hardware/quantum-computing-applications>.

⁶⁶ Preskill, "Quantum Computing in the NISQ Era and Beyond," 7.

⁶⁷ Ghose, "Are You Ready for the Quantum Computing Revolution?"

to extract beneficial information from messy, unstructured data.⁶⁸ One can immediately see the practical applications in areas like medical surveillance and identifying new potentially pandemic-causing outbreaks. Machines will be able to find the proverbial needle in a haystack.

Given expected growth, this capability will incentivize governments, especially law enforcement and intelligence agencies, to collect as much data as possible and have quantum AI evaluate it or monitor it in real-time as the data flows worldwide. This processing power can enable a breadth of surveillance only dreamed of by the East German Stasi. It need not be dystopian, however. Applied within a legal and ethical construct, this capability may help probe the dark web and combat genuine evils like human trafficking, organized crime, and terrorism.

Enhanced digital surveillance will not be limited to governments. Corporations, especially media companies that already have massive amounts of user data, will mine that data to target both advertising and content more efficiently. With already unprecedented power in this arena, quantum-enabled AI's power to shape perception and decision making will call into question the individual's ability to make independent choices.

Finally, as the technology matures and the barriers to entry lower, non-state actors will have new and innovative ways of targeting vulnerable people for radicalization and manipulation. The internet and social media have made this process much easier to accomplish globally through the power of attraction by providing platforms to spread extremist messages. Quantum AI will add the ability to target and groom individual people with the potential to expand recruiting effectiveness exponentially. As it turns out, the difficulty in finding the needle in a haystack can be a break on all kinds of nefarious activities.

Social Engineering. This last technology builds on the surveillance capability of quantum-enabled AI and uses that data to control populations. It could be an extension of the nascent

⁶⁸ Kania and Costello, "Quantum Hegemony," 18.

social credit system that China is developing. This system collects information on corporations and individuals, scores the data according to how closely it adheres to CCP policy priorities, and then provides incentives to align with those priorities. It was nimble enough to “nudge” companies to adhere to COVID closing and opening guidance in 2020.⁶⁹ In its present state, it is far from an Orwellian control mechanism for individuals. The current system is regionally fragmented, suffers from a lack of data consistency, and has relatively modest ambitions.⁷⁰ China is, however, committed to data-driven governance and has more invasive programs such as Golden Shield, Safe Cities, and Police Clouds as part of its surveillance ecosystem. Given time, it is possible to imagine that the quantum-enabled AI could become part of a more coercive system.

In addition to surveillance, a population control system would need an evaluation mechanism to identify selectors for undesirable behavior and a method to deliver both reward and punishment. With a comprehensive enough system, a wayward tweet while in the drive-through line could result in a declined credit card at the window. Financial control, movement control, public blacklists, and red lists (reward) could become powerful tools for shaping behavior in an authoritarian state.

The data processing requirements to build a social control system for a population the size of China would be enormous. To attempt it with only classical computing systems would require prohibitive investments in data storage, supercomputer processing power, and energy production. Here is where quantum computing’s potential for exponential increases in processing speed could help tackle the big data analytical problem. Not only would quantum’s exceptional ability to process unstructured data be required, but its speed would also be necessary to handle the

⁶⁹ “China’s Social Credit System: Speculation vs. Reality,” *The Diplomat*, accessed April 19, 2021, <https://thediplomat.com/2021/03/chinas-social-credit-system-speculation-vs-reality/>.

⁷⁰ “China’s Social Credit System.”

sheer volume of information. This is an example of how a technology that is not inherently problematic can become so when integrated with other elements in a social context shaped by authoritarianism.

Toward a Quantum Future

What will a quantum future look like? Ultimately, we don't know because the future has not been written yet. There are important decisions to make at the individual, corporate, and societal levels to create that future. However, looking through the lenses of technology as liberator, threat, and instrument of power has provided the barest of glimpses about what those decisions may be. From a governmental perspective, which technologies and outcomes should benefit from public funding and why? What, if any, role does government play in mediating the effects of technology on society? Where does the government need to guard against malicious use to defend the nation and the values that animate it? What are the ethical obligations of people and government in shaping the social context of technological development? We assess these potential futures from an ethical perspective to open the aperture on these and similar questions. See Appendix 1 for a summary table of quantum technology and potential futures.

4. Ethical Interrogation

Approach. This analysis applies three ethical perspectives to the futures described above, focusing on government rather than individuals or corporations. This is to scope the present inquiry to identify the ethical considerations that will lead to policy alternatives in the next section. The analysis will apply Deontology (hereafter referred to as duty ethics), Utilitarianism, and Ethics of Care in the following manner.

Duty Ethics. This lens focuses on the state's responsibility, asking "what is the government's duty" regarding this technology. Duty ethics will pay attention to the logic for any

ascribed duty consistent with the principles of universalizability and treating people as ends in themselves. Because the focus is at the state level, the notion of duty will come from conceptions of the national interest. This lens will not be concerned with outcomes.

Utilitarian Ethics. This lens will focus on how government policy shapes quantum technologies' outcomes with a bias toward maximizing the benefit for the greatest number of people. The utilitarian view will be concerned with how government policy shapes and distributes gain as well as how it avoids or mitigates harm.

Ethics of Care. This lens addresses weaknesses in the first two ethical frameworks.⁷¹ Care will broaden the perspective from a subject (government) – object (technology) view to consider the more comprehensive systemic relationships over a longer time horizon. It will cast the government in the role of the “one who cares” and will inquire about the state’s responsibilities in that role.

Quantum simulation. This application of quantum computing has such a broad application from basic research, to pharmaceuticals, to material design, to the green energy transition. This array of applications has attracted significant corporate and venture capital interest, so one could ask if it is even necessary for the government to play a role in its development. In this respect, the qubit is very much like a transistor in the 1950s. It was fundamental to many of the emerging technologies of the time, and the military fostered development by funding infrastructure, stressing engineering development, and fostering industry standardization.⁷² To gain a technological advantage, or maybe even just parity, the military will need access to this capability. From an economic perspective, it is necessary to have an industrial capacity to ensure

⁷¹ For example, care ethics can address the ax murderer problem from duty ethics where it would be wrong to lie to an ax murderer asking if his intended victims are in your house. Care ethics would recognize the priority of protecting those in the house over the abstraction of never lying. Care ethics can also balance utilitarian ethics when it sacrifices a minority for majority benefit, it will include the relationships and importance of all constituencies.

⁷² Merritt Roe Smith, *Military Enterprise and Technological Change: Perspectives on the American Experience*, (Cambridge, MA: MIT Press, 1985), 275.

resiliency and capacity. What does all this mean? Venture capital will chase fast profits and is likely to focus on software rather than capital-intensive computing hardware. Corporations have demonstrated a similar propensity to offshore production and focus on software. It would not be in the national interest to rely on foreign manufacturers to produce the technology or let a foreign competitor gain a material advantage. From this interest, one can imagine a duty to foster basic and applied research and maintain a domestic industrial capacity. The principle behind this duty is that it is the government's responsibility to invest in technology that will strengthen national and economic security and whose absence would place the country at a severe disadvantage.

From a utilitarian perspective, William Hurley, former chair of the Quantum Computing Working Group for the Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA), has argued that the most significant benefit will accrue through open-source collaboration.⁷³ This will clash with the value of intellectual property for corporations but can be mediated, especially in areas of government financing. There is a second concern regarding malicious actors and the potential to exploit the dual-use nature of quantum simulation. Given the broad areas of application and the likely numbers of organizations involved, this will have to be a risk that governments and communities of practice actively managed. Management will be easier if the government is actively engaged in the field, and the risk will not be diminished if the government should forgo involvement or limit its access.

Finally, from a care perspective, one could inquire about the impact of this technology on society. Will the public have access to the benefit – especially of publicly funded research? Or, will corporations capture the benefits of social risk (investment) by privatizing profits? Clearly, private interests will accrue profit, but with public funding comes the potential to share profits or for government use in socially but not commercially relevant areas.

⁷³ Hurley, "Quantum Computing, Not AI, Will Define Our Future."

Medical Imaging. At first glance, this quantum technology would seem to have a weaker claim on the national interest than simulation. Biotechnology also has an established and thriving commercial sector that would argue against the need for government involvement. If, however, one considers that advanced medical devices are one of the ten sectors China is attempting to dominate, government involvement may be appropriate to ensure that the market remains fair and that the United States has a domestic capacity so as not to rely on authoritarian regimes for access to care.⁷⁴

The utilitarian perspective is less ambiguous. This technology offers tremendous potential to reduce human suffering, and therefore the government should invest in both basic and applied research. The utilitarian view would also seek to expand access and availability of this technology to the largest number of people to maximize gain. This will conflict with the medical industry and the values of commercial freedom that seek to maximize profit while not necessarily being concerned with access. A utilitarian could counter that a healthier population would benefit industry as well as society at large.

A care perspective will also seek to broaden access and ask more fundamental questions about the structure of society. Is it just to construct a system that forces people to choose between financial ruin and access to advanced technology? Is it right to allow suffering, diminution of living standards, and early death in a land of plenty?

Secure Networks. Secure networks are the circulation system for a knowledge economy. The centrality of secured communications for economic and national security imperatives would argue for a strong national interest and hence government responsibility in developing this capability. The analysis from duty ethics above would suggest that perusing this technology is

⁷⁴ Congressional Research Service. *“Made in China 2025” Industrial Policies: Issues for Congress*, (Washington, DC: CRS, 2020), 3.

indeed imperative. While secure networks are critical to governments, businesses, and individuals, the sun also shines on the wicked. The same technology that preserves privacy can conceal malicious activities. Since the government also has a duty to protect its citizens from criminal and threat activity, it may have to regulate the construction and operation of quantum networks. For example, quantum networks may not replace the entire internet. Still, there may be value in more limited applications for hardening local networks like control of nuclear power plants or highly classified networks. As the Colonial Pipeline cyber-attack in May 2021 demonstrated, insecure networks can have massively disruptive effects over a short time horizon.⁷⁵ Suppose society seeks a broader application of quantum networks. In that case, the point-to-point security that quantum entanglement brings would be subject to all the other nodes required for network connectivity. It is entirely conceivable that the government will use similar laws and techniques to surveil foreign threats. Also, a quantum network would not address the weakest link in any system, the operator. In any event, criminals and threat actors will always exist. The more central duty is to seek the highest forms of protection for those functions that underpin society.

The utilitarian perspective would focus on the potential gains in commerce, medicine, and security stemming from the trust secured communications engenders. In this view, secure networks are the critical infrastructure that governments invest in for the common good.

A care perspective would be concerned with access and equity in focusing that gain. If public spending results in localizing and focusing wealth on a limited selection of the population, the government intervention would fail in its responsibilities for the whole.

⁷⁵ Andy Greenberg, "The Colonial Pipeline Hack Is a New Extreme for Ransomware," *Wired*, May 8, 2021, <https://www.wired.com/story/colonial-pipeline-ransomware-attack>.

Hacking. The government has a clear responsibility to pursue post-quantum cryptography (PQC). The guiding principle behind that duty is the government's responsibility to provide security from malign actors in the international system. The obligation to protect, however, extends beyond merely passive measures. Data networks are central to societal health and human flourishing. Therefore, hackers who would steal, corrupt, or hold hostage the functioning of those networks represent a clear and present danger. The government will have to develop hacking tools to understand and counter threat vectors with active measures. In this sense, the government's duty to pursue hackers is no different from seeking out criminals and terrorists. Hackers can be one or the other or both simultaneously.

A utilitarian view would also recognize the benefit of using quantum computing to hack threat systems and information. This would increase the capability of intelligence and security organizations.

A care perspective would want to ensure that PQC is available to the commercial sector and private individuals, so the society as a whole is more resilient in a digital world. However, there is a tension between the value of protecting individual information and the importance of being able to hack and exploit threats. One can imagine the government resolving this in a manner similar to the current digital security architecture where there is a baseline protocol and classified information is afforded additional measures.

Military Sensing. Here again, there is a clear responsibility to develop the technology necessary to defend against likely threats. If U.S. forces are to remain competitive, they must counter-threat advances in stealth, subsurface warfare, and antisatellite technology. Quantum radar and advanced magnetometers hold promise here. As stealth technology proliferates, quantum radars will reduce the temptation to rely on stealth as a first-strike weapon in nuclear and conventional *fait accompli* scenarios. Advanced magnetometers will not turn the ocean

transparent but could add an important sensor to the array of anti-subsurface warfare technologies. Finally, with a demonstrated capability to shoot down satellites, the magnetometer may be the elusive non-Global Positioning System navigation aid that keeps warfighters functional should that critical system falter. While these are not revolutionary technologies, they are essential in the coevolution military technology, and it would be irresponsible to cede the field to competitors. Finally, these technologies are likely to have significant spinoff civilian applications. Better navigation aids can make commercial air and maritime travel safer. One could even imagine the magnetometer as a critical safety component in self-driving vehicles on land. Duty ethics would also endorse developing these technologies for their civilian uses as well.

A utilitarian would see benefit beyond just military competition noting the dual-use applications of these technologies to navigation and medical imaging, among others. For these reasons, a utilitarian perspective would also support investment in basic and applied research.

A care perspective would have similar concerns about the benefit apportionment of any government-subsidized technology mentioned above. It might also inquire about the opportunity costs of continuing to build exquisite stealth platforms if that technology is about to relinquish its advantage. Eisenhower expressed this view when he observed that it is not only money being spent, but also “the sweat of its laborers, the genius of its scientists, [and] the hopes of its children.”⁷⁶

Deflationary Accelerant. The responsibility of the state to the individual in economic matters is not settled in the United States. Clearly, elected leaders feel compelled to direct government intervention in moments of crisis like the Great Depression, Great Recession, and

⁷⁶ Dwight D. Eisenhower, “April 16, 1953: Chance for Peace | Miller Center,” October 20, 2016, <https://millercenter.org/the-presidency/presidential-speeches/april-16-1953-chance-peace>.

COVID-19 Pandemic. But these are temporary, ad hoc, and hotly debated. The economic disruption of quantum technology holds the potential to be something different. If technology causes a significant separation between labor and wealth, there will be a systemic shift where the assumptions of laissez-faire capitalism are no longer applicable. This would not be a temporary crisis but the instantiation of a permanent class of unemployed or underemployed people. What is the government's duty? Proponents of small government, and consequently the concentration of wealth, would argue that there is no duty. Government is for security and to facilitate free enterprise. Charity is the province of private and religious organizations. This is a political position and not an ethical one. But if asked about the imperative that a government should ignore the suffering, privation, and early death of its citizens, the duty to intervene becomes clearer.

Utilitarianism would also hold a bias toward intervention. Not only would the lack of intervention lead to individual suffering, but it could also be deleterious to the social fabric holding society together. The government should intervene to stabilize society, thus creating the best outcome for the greatest number of people.

A care perspective would not only favor government intervention but might also imagine the construction of a new system with more potential for human flourishing. Just like the shift to an agrarian society that freed people from the relentless pursuit of hunting and gathering to create specialization, science, civilization, and culture, a labor force liberated from the machines of wealth creation has a yet unseen human potential if not ignored and exploited. This would need to include a reimagining of the social contract.

Optimization. Optimization is a product of quantum computing and software development. Therefore, acquiring the capability will be a matter of funding basic research already discussed and working with contractors to develop applications. Duty ethics will be concerned with how

the government applies optimization. It must take care in optimizing social systems to avoid treating people instrumentally or as a means to an end. The system engineering for the Three Gorges Dam on the Yangtze River is an example of optimization (without quantum computing) for performance without regard for the 1.3 million people displaced by the project.⁷⁷

With potential applications from the municipal level to across the federal government, there is significant potential gain. From a utilitarian perspective, maximizing access will be a concern, especially if quantum computers remain exquisite purpose-built machines. One can imagine any number of public-private, federal-state-local schemes to share computing power when smaller localities face an optimization challenge.

Care ethics highlight the responsibility of those applying this technology to those who are affected by it. Therefore, care ethics could inform community of practice norms or regulatory regimes for government and corporate actors employing quantum optimization. There will be natural incentives to optimize for costs or time, even if it at the expense of human costs.

Surveillance. Intelligence and security agencies will want to deploy this enhanced capability with as few restrictions as possible. Duty ethics will recognize the imperative that governments must secure the nation and its people. Still, unrestricted surveillance would fail the universalizability principle because it would run afoul of values surrounding individual liberty. This ethical situation is not different in kind from those faced with current surveillance technology, and Congress will have to craft rule sets with equal care.

Both governments and corporations will find powerful applications for this capability. Here a utilitarian view, absent a second ethical lens, may prove problematic as there is no inherent break on utilitarian logic when there is an appeal to the greater good.

⁷⁷ Mara Hvistendahl, "A Revered Rocket Scientist Set in Motion China's Mass Surveillance of Its Citizens," *Science*, March 14, 2018, <https://www.sciencemag.org/news/2018/03/revered-rocket-scientist-set-motion-china-s-mass-surveillance-its-citizens>.

Care ethics could provide a second check on this technology. This perspective would not only be concerned with government use but would also question corporate use. Both have access to massive amounts of data, and greater surveillance capacity could lead to profiling and exploitation. Care ethics would seek rule sets that protect against potentially malicious applications.

Social Engineering. Duty ethics would prohibit the development of this type of technology in the United States because it is incompatible with the vision of government as described by law. It is impossible to universalize the principle that the government should exercise such a high level of control under a constitution that specifically limits government control.

A utilitarian view may challenge the categorical dismissal of social engineering technology. One can point out that social engineering takes place continuously. If a gas station can incentivize the purchase of a sixty-four-ounce soda, why should the government be prohibited from incentivizing better choices? Wouldn't the country be better off if its citizens were fitter, healthier, more educated, etc.? Free people can argue about government incentives like cigarette taxes. It is quite another to instantiate a system of surveillance and coercion.

Care Ethics would also focus on protecting the individual from government coercion. Still, it would broaden the scope to ask if the presence of this type of system in other countries presents a danger to free people generally. Suppose one proceeds from the premise that individual liberty is a human right, and that freedom is indivisible. In that case, the country should seek to establish norms across democratic countries and oppose such systems in authoritarian and totalitarian regimes.

A View from Delphi

The ethical perspectives of duty, utility, and care provide instances of ethical peril and disruption, but also possibility. The briefest of investigations suggests that the ethical concerns

can be binned in several categories. First, some aspects of quantum technology require government promotion for security, economic, or social reasons. A second bin groups technologies where an ethically informed government should seek to establish democratic norms and regulations to protect individual freedom and autonomy. Finally, aspects of quantum computing could be profoundly disruptive and will challenge society to confront fundamental assumptions about the role and purpose of government. This category also includes areas where values come into conflict with each other such as the tension between surveillance and individual liberty. These three areas will form the framework for policy recommendations in the next section.

One final note before leaving the ethical analysis regards virtue ethics.⁷⁸ This paper has not used virtue ethics as a primary lens to view the future of quantum technology. This was partially an effort to avoid the trap of anthropomorphizing government. Governments are not moral agents, but the individuals in them are. In this respect, virtue ethics will serve two critical functions in bridging ethical observations and policy development. First, as communities and policymakers develop norms and regulations, the rule-makers must be people of character. This ensures that the new rules serve the public interest and not some narrower sub-set of self-interests. Character and the ability to discern the proper functions of technology and law will be necessary to negotiate and resolve competing tensions so that the rule sets do not create harmful unintended consequences. A second critical function that virtue ethics will serve is addressing the social disruption quantum technology can trigger. It will be essential to have a clear vision of eudaimonia or human flourishing to orient on solutions.⁷⁹ Here there is a direct connection between the ancient debates about the *summum bonum*, the role of the state and individual, and

⁷⁸ Aristotle, *Nicomachean Ethics*, trans. Terence Irwin, 2nd ed. (Indianapolis: Hackett Publishing Company, 1999).

⁷⁹ Aristotle, Book I, CH 7.

the reevaluation that a quantum disruption will cause.⁸⁰ Virtue ethics will be essential to navigating these fundamental questions. See Appendix 2 for a summary table of quantum technology and ethical concerns.

5. Policy Development

Society will shape the future of quantum technology. The ethical implications of the technology suggest that government, as representative of the people, has a role to play in three crucial ways. Government is vital to developing the technologies, establishing rules and norms, and providing a venue for politics to decide among competing values.

First, the U.S. government should continue to fund both basic and applied research in quantum computing, quantum information science, medical imaging, and military sensors. Part of this is to ensure a threat competitor does not gain an advantage from a leap-ahead technology. Another important aspect is that the United States will want to cultivate a vibrant quantum ecosystem. Quantum computers may not settle on one standard design. Researchers and engineers may build different types of quantum computers for various applications. In this environment with nascent technology, an entrepreneurial approach with varied streams of inquiry will be necessary to remain competitive. Finally, as demonstrated by the number of patent applications, the United States is leading in quantum computing. China, however, is leading in quantum cryptography and communications, which suggests increases in government funding in these areas may be appropriate.⁸¹

A second important role for the government is in establishing norms and rule sets for the application of quantum technology. Here it is vital to adhere to the two principles contained

⁸⁰ Plato, *The Republic*, trans. Benjamin Jowett (Buffalo, NY: Prometheus Books, 1986), Book I.

⁸¹ Kania and Costello, "Quantum Hegemony," 13.

within duty ethics of universality and treating people as ends in themselves. This approach will help ensure that rules are just. This is a fundamental duty and the reason that free peoples form governments. Also, for a government to serve its function, it must provide necessary and wholesome laws. This would fulfill the telos, or ultimate purpose, of government which virtue ethics require for the proper ordering of a just society. In hacking, optimization, surveillance, and social engineering, the United States should work with other liberal democracies to establish ethical norms for their development and employment. Domestically, Congress will have to develop rules and regulatory regimes for government agencies and corporations to protect individual liberty and uphold the rule of law. The government has done this in the past with intelligence capabilities. Still, the inability to successfully establish rule sets for social media suggests that this effort will require vigorous attention and potentially augmented committee expertise to navigate the multitude of issues involved.

A further aspect of establishing rule sets is for the executive branch to develop a policy toward countries using or considering these tools for authoritarian control. Should the government treat coercive social control systems as a violation of human rights and push against it like genocide and religious repression? The answer will depend on the context and issues in play at any given time. The executive will also have to address policy toward countries trending toward authoritarianism. China has no problem exporting its tools for social control, and one can imagine a contest between liberal democracies and authoritarian regimes over what the world order should look like.

A final role for the government is to help mitigate the social disruption resulting from the aggregate impact of quantum technology on society. The potential economic disruption of separating labor from wealth generation will strain and possibly even break the current U.S. liberal market economy. This will concentrate wealth and generate many unemployed and

underemployed people, which will further rend the fabric of the nation. But that future is a choice, and what is politics if not the argument over choices. An eighteenth-century focus on individual liberty is not wrong. Still, it may be insufficient to imagine a social compact that reaps the benefits of decoupling people from the machines of production. Quantum technology can precipitate a crash and suffering, or it can lead to a soft landing with enough human capital intact to flourish in a new emergent economy.

An Alternate View

The success of quantum computing is not the only possible future policymakers may encounter. Some scientists argue that development beyond rudimentary NISQ computers to commercially viable quantum computers is impossible. The problem reduces to manipulation and error correction in exquisitely complex and sensitive quantum states. Mikhail Dyakonov, a researcher in theoretical physics from the University of Montpellier, noted that a quantum computer that could rival classical ones would need at least one thousand qubits. Rather than the binary status of transistors, the qubit exists in a superposition described by quantum amplitudes. To process information, the computer uses quantum gates to alter these values in a precise manner. This is where the promise of vast data storage in a qubit becomes a crippling liability. For the system to function, “a useful quantum computer *needs to process a set of continuous parameters that is larger than the number of subatomic particles in the observable universe.*” (emphasis original)⁸² Here is a helpful reminder that a qubit hinges upon the ability to control something as small as a single electron or photon. These quantum particles are highly susceptible to environmental conditions, even the noise of the machine itself. These physical factors induce error. The theoretical solution for error correction is to add more qubits. This, of course,

⁸² Mikhail Dyakonov, “The Case Against Quantum Computing,” *IEEE Spectrum: Technology, Engineering, and Science News*, November 15, 2018, <https://spectrum.ieee.org/computing/hardware/the-case-against-quantum-computing>.

compounds the problem. These engineering challenges lead Dyakonov and others to conclude that the physical quantum computer will not meet the requirements for qubits demanded by quantum computing theory.⁸³

If this is the case, then the most revolutionary aspects of quantum technology will not materialize. Quantum simulation and downstream applications to theoretical physics, material sciences, and pharmaceutical development will not experience a revolutionary leap. Optimization and unstructured big data will continue to befuddle system engineers. On the positive side, intrusive surveillance, coercive social engineering, and the accelerated job loss will also fail to threaten the world in quite the same way. What will be left of quantum technology is medical imaging, cryptography, secure networks, and quantum sensors. These are all significant technologies that will have a societal impact requiring policy attention. It just will not be the disruption that could threaten the system.

This possibility raises a difficult conundrum for policymakers. Is the quantum revolution overhyped? Could funding and prestige entice researchers to dedicate lifetimes to a futile quest? Are tech giants like Google and Microsoft engaged in a mutually destructive arms race? Are private equity, corporations, and governments worldwide captured by the initial stages of a hype curve? All of these things are unlikely to be true simultaneously. So what is a policymaker to do?

First is to put the apparent impossibility of quantum computing into perspective. This is the very edge of basic science and engineering. It is an exploration in a place no one has been before, and there is no preexisting map or theory to illuminate the way. This work is hard. It is not certain in which direction the subsequent discovery will come. Fortunately, scientists have similar experiences to draw upon. John Preskill noted that during the development of classical computing, often experimentation led to valuable discoveries and could only be explained later

⁸³ Dyakonov, "The Case Against Quantum Computing."

by theory.⁸⁴ This would seem to be an appropriate dynamic given that scientists and engineers are knocking about at the edge of human understanding. This dynamic also argues for a robust research ecosystem with many irons in the fire. It is impossible to predict where efforts in noise mitigation will go. If the circuit-based quantum computer that Dyakonov critiques ultimately do prove unattainable, researchers are also pursuing adiabatic computing with quantum annealers.⁸⁵ With so much of the science and engineering unsettled, even the very makeup of the qubit itself, it is too early to call the expedition failed.

Second, in a practical sense, policymakers cannot afford to be pessimists. With competitors willing to put almost fifteen billion dollars into a single research laboratory, can politicians cede ground to those who would boldly take the field and do the hard work?⁸⁶ Turning away is capitulation and potential relegation to second power status.

6. Conclusion

The second revolution in quantum technology is coming. The potential innovations and capabilities are exquisite, but the technology is still undeveloped. This is good because it provides policymakers time to grapple with the more problematic potentials in this class of technology. In the short run, the U.S. government should continue funding both basic and applied research across the broad spectrum of quantum technologies. This can be calibrated to account for corporate and private equity investment strengths, but it must also ensure that significant gaps do not occur with competitor countries. In the medium term, the United States and other liberal democracies will have to establish international norms and governance concerning several applications like hacking, optimization, surveillance, and especially social

⁸⁴ Preskill, “Quantum Computing in the NISQ Era and Beyond,” 8.

⁸⁵ Preskill, 8.

⁸⁶ Kania and Costello, “Quantum Hegemony,” 10.

engineering. It would be better to work through societies' interests before the technology becomes available rather than to deal with the consequences after having had an opportunity to do damage. Finally, in the long run, society may have to face the idea that some of the fundamental assumptions that have led to extraordinary wealth in the industrial age may no longer provide a stable civilization. The social disruption quantum technology could visit upon the nation does not have to be a cause for ruin; it could also be the catalyst to imagine a new order where society spends human capital on true flourishing.

Appendix 1 Table of Quantum Technology and the Future

		Technology	Future
Technology as Liberator	Simulation	-Quantum computing application -Simulate quantum mechanical systems like chemical reactions	-Advance quantum physics basic research -Develop new materials, green technology, pharmaceutical development
	Medical Imaging	-Quantum mechanics to increase resolution -Increase MRI by a factor of 10,000	-Ability to understand what is happening at the protein level
	Secure Networks	-Quantum cryptography -Quantum networks	-Quantum Key Distribution -Satellite and ground fiber networks
Technology as Threat	Hacking	-Quantum computing application -Crack current encryption protocols	-Compromise past, current, and future data -Post Quantum Cryptography (in time?)
	Military Sensing	-Quantum Radar -Magnetometers	-Identify stealth aircraft -Non-GPS navigation -Subsurface warfare detection
	Deflationary Accelerant	-Aggregate effect of quantum technologies -Combined with AI accelerate job obsolescence	-Separate labor from wealth creation -Chronic unemployment/ underemployment -Market economy no longer supports a functioning society
Technology as Instrument of Power	Optimization	-Quantum computing application -Search unstructured data	-Improve efficiency of societal systems (traffic, voting, health care, financial). -Model combat operations
	Surveillance	-Quantum computing application -Search unstructured data	-Pair with AI, surveillance state or security tool -Find bad actors on dark web
	Social Engineering	-Quantum computing application -Pairs surveillance with incentives (carrots & sticks)	-Data driven governance -Digital coercion

Appendix 2 Table of Quantum Technology Ethical Concerns

	Duty	Utility	Care
Simulation	-Maintain technological advantage/parity	-Open-source vs intellectual property -Dual use	-Who benefits from public funding?
Medical Imaging	-Maintain technological advantage/parity	-How to maximize use for greatest number	-Access (equity) -Insurance industry vs health system
Secure Networks	-Maintain technological advantage/parity	-Treat as required infrastructure for knowledge economy	-Ensure Access
Hacking	-Promulgate Post Quantum Cryptography (PQC)	-Maintain technological advantage/parity (ability to hack)	-Protection PQC
Military Sensing	-Maintain technological advantage/parity	-Promote civilian dual use	-Opportunity costs?
Deflationary Accelerant	-Is there a state duty to the individual?	-Maintain social stability	-Individual suffering -Social contract (new possibility)
Optimization	-Application -Treat people as ends in themselves	-Maximize use at all levels of government	-Responsibility to those affected -Norms and regulation
Surveillance	-Balance liberty and protection -Duty to regulate industry?	-Promote intelligence and security use	-Balance liberty and protection -Protect from industry misuse
Social Engineering	-Prohibit U.S. development	-Isn't this happening anyway?	-Protect from coercion -Establish international norms

Areas for the government to promote development (black font)

Work to establish norms and rule sets (blue font)

Mitigate the disruptive effects of quantum technology (red font)

Bibliography

- Aristotle. *Nicomachean Ethics*. Translated by Terence Irwin. 2nd ed. Indianapolis: Hackett Publishing Company, 1999.
- Barbour, Ian G. *Ethics in an Age of Technology*. 1st ed. The Gifford Lectures, v. 2, 1989-1991. San Francisco, Harper, 1993.
- Bell, Wendell. *Foundations of Futures Studies: Volume 1 History, Purposes, and Knowledge*. New Brunswick, N.J: Transaction Publishers, 2003.
- Breakthrough. "Maryam Tsegaye, Canada, Physics, Winner: 2020 Breakthrough Junior Challenge." September 21, 2020. Video, 2:58.
<https://www.youtube.com/watch?v=vg2rnjZ19PY&list=LL&index=1>.
- "China's Social Credit System: Speculation vs. Reality." *The Diplomat*, Accessed April 19, 2021. <https://thediplomat.com/2021/03/chinas-social-credit-system-speculation-vs-reality/>.
- "Commercialising Quantum Computers." *The Economist*, September 26, 2020.
<https://www.economist.com/science-and-technology/2020/09/26/commercialising-quantum-computers>.
- Congressional Research Service. *"Made in China 2025" Industrial Policies. Issues for Congress*. Washington, DC: CRS, August 11, 2020. Accessed January 11, 2021.
<https://crsreports.congress.gov/product/pdf/IF/IF10964>
- Crane, Leah. "Google Performed the First Quantum Simulation of a Chemical Reaction." *New Scientist*. August 27, 2020, Accessed March 4, 2021.
<https://www.newscientist.com/article/2253089-google-performed-the-first-quantum-simulation-of-a-chemical-reaction/>.
- Crews, Christian. "How Far to Look Ahead?" *Research Technology Management* 62, no. 5 (October 9, 2019): 59–62. <https://doi.org/10.1080/08956308.2019.1638487>.
- Diamanti, Eleni, Hoi-Kwong Lo, Bing Qi, and Zhiliang Yuan. "Practical Challenges in Quantum Key Distribution." *NPJ Quantum Information* 2, no. 1 (November 8, 2016): 1–12.
<https://doi.org/10.1038/npjqi.2016.25>.
- Dowling, Jonathan P., and Gerard J. Milburn. "Quantum Technology: The Second Quantum Revolution." Edited by A. G. J. MacFarlane. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 361, no. 1809 (August 15, 2003): 1655–74. <https://doi.org/10.1098/rsta.2003.1227>.
- Dyakonov, Mikhail. "The Case Against Quantum Computing." *IEEE Spectrum: Technology, Engineering, and Science News*, November 15, 2018.
<https://spectrum.ieee.org/computing/hardware/the-case-against-quantum-computing>.
- Eisenhower, Dwight D. "Chance for Peace." April 16, 1953. Transcript.
<https://millercenter.org/the-presidency/presidential-speeches/april-16-1953-chance-peace>.

- Gent, Edd. "IBM Plans to Have a 1,000-Qubit Quantum Computer by 2023." *Singularity Hub*, September 25, 2020. <https://singularityhub.com/2020/09/25/ibm-plans-to-have-a-1000-qubit-quantum-computer-by-2023/>.
- Ghose, Shohini. "A Beginner's Guide to Quantum Computing." Filmed November 2018. TED video, 9:56. https://www.ted.com/talks/shohini_ghose_a_beginner_s_guide_to_quantum_computing.
- . "Are You Ready for the Quantum Computing Revolution?" *Harvard Business Review*, September 17, 2020. <https://hbr.org/2020/09/are-you-ready-for-the-quantum-computing-revolution>.
- Giles, Martin. "The US and China Are in a Quantum Arms Race That Will Transform Warfare." *MIT Technology Review*. Accessed February 12, 2021. <https://www.technologyreview.com/2019/01/03/137969/us-china-quantum-arms-race/>.
- Gossett, Stephen. "8 Quantum Computing Applications & Examples." *Built In*, November 18, 2019. <https://builtin.com/hardware/quantum-computing-applications>.
- Greenberg, Andy. "The Colonial Pipeline Hack Is a New Extreme for Ransomware." *Wired*. May 08, 2021. <https://www.wired.com/story/colonial-pipeline-ransomware-attack>
- Hurley, William. "Quantum Computing, Not AI, Will Define Our Future." *TechCrunch*. 17 November, 2018. <https://social.techcrunch.com/2018/11/17/quantum-computing-not-ai-will-define-our-future/>.
- Hvistendah, Mara. "A Revered Rocket Scientist Set in Motion China's Mass Surveillance of Its Citizens." *Science*. March 14, 2018. <https://www.sciencemag.org/news/2018/03/revered-rocket-scientist-set-motion-china-s-mass-surveillance-its-citizens>.
- NIST. "Introduction: A New Quantum Revolution." Last updated March 21, 2019. <https://www.nist.gov/topics/physics/introduction-new-quantum-revolution>.
- Kania, Elsa B, and John K Costello. "Quantum Hegemony? China's Ambitions and the Challenge of U.S. Innovation Leadership." Center for a New American Security, 2018. <https://www.cnas.org/publications/reports/quantum-hegemony>.
- Kelly, Jack. "U.S. Lost Over 60 Million Jobs—Now Robots, Tech and Artificial Intelligence Will Take Millions More." *Forbes*. October 27, 2010. <https://www.forbes.com/sites/jackkelly/2020/10/27/us-lost-over-60-million-jobs-now-robots-tech-and-artificial-intelligence-will-take-millions-more/>.
- Kranzberg, Melvin. "Technology and History: 'Kranzberg's Laws.'" *Technology and Culture* 27, no. 3 (1986): 544–60. <https://doi.org/10.2307/3105385>.
- Kumar, Manjit. *Quantum: Einstein, Bohr, and the Great Debate about the Nature of Reality*. Illustrated edition. New York: W. W. Norton & Company, 2011.
- Kurzweil, Ray. *The Singularity Is Near: When Humans Transcend Biology*. New York: Penguin Books, 2006.

Moody, Dustin. “The Future Is Now: Spreading the Word About Post-Quantum Cryptography.” *NIST*, November 24, 2020. <https://www.nist.gov/blogs/taking-measure/future-now-spreading-word-about-post-quantum-cryptography>.

O’Callaghan, Jonathan. “Quantum Technology Could Revolutionise the Detection and Treatment of Diseases.” *Horizon: The EU Research & Innovation Magazine*, June 24, 2019. <https://horizon-magazine.eu/article/how-quantum-technology-could-revolutionise-detection-and-treatment-diseases.html>.

Qureca. “Overview on Quantum Initiatives Worldwide.” September 7, 2020. <https://www.qureca.com/overview-on-quantum-initiatives-worldwide/>.

Plato. *The Republic*. Translated by Benjamin Jowett. Buffalo, NY: Prometheus Books, 1986.

Preskill, John. “Quantum Computing in the NISQ Era and Beyond.” *Quantum* 2 (August 6, 2018): 79. <https://doi.org/10.22331/q-2018-08-06-79>.

Smith, Merritt Roe. *Military Enterprise and Technological Change: Perspectives on the American Experience*. Cambridge, MA: MIT Press, 1985.

Taylor, Irene Qualters, Antoinette. “Basic Quantum Research Will Transform Science and Industry.” *Scientific American*. May 17, 2019. <https://blogs.scientificamerican.com/observations/basic-quantum-research-will-transform-science-and-industry/>.

Economic Policy Institute. “The Productivity–Pay Gap.” Accessed April 10, 2021. <https://www.epi.org/productivity-pay-gap/>.

Wiltz, Chris. “Everything You Wanted to Know about Quantum Computing.” *Design News*, December 19, 2018. <https://www.designnews.com/electronics-test/everything-you-wanted-know-about-quantum-computing>.

Yirka, Bob. “Researchers Discover a Way to Avoid Decoherence in a Quantum System.” *Phys.org*. Accessed February 23, 2021. <https://phys.org/news/2013-03-decoherence-quantum.html>.