Quantum Policy

A PRIMER FOR POLICYMAKERS

MAY 2024

→ **Jane Bambauer**[1]

Quantum technologies have received billions in private and public investments[2] and have caused at least some ambient angst about how they will disrupt an already fast-moving economy and uncertain social order. Some consulting firms are already offering "quantum

1 Brechner Eminent Scholar and Professor of Law, University of Florida. Prof. Bambauer previously served as the Deputy Director for Societal Impacts at Center for Quantum Networks, an NSF-supported Engineering Research Center. This report is based on previous work supported by the Engineering Research Centers Program of the National Science Foundation under NSF Cooperative Agreement No. 1941583. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect those of the National Science Foundation.

2 McKinsey & Company, *Quantum Technology Monitor* 2023 (McKinsey & Company, 2023), accessed May 8, 2023, https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/quantum%20technology%20sees%20record%20investments%20progress%20on%20talent%20gap/quantum-technology-monitor-april-2023.pdf; M. Kaur, "Quantum Initiatives Worldwide" (Qureca, 2023), accessed April 29, 2024, https://qureca.com/quantum-initiatives-worldwide-update-2023/.

readiness" services, even though the potential applications for quantum computing, networking, and sensing technologies are still somewhat speculative, in part because the impact of these technologies may be mysterious and profound. Law and policy experts have begun to offer advice about how the development of quantum technologies should be regulated through ethical norms or laws.[3] This report builds on the available work by providing a brief summary of the applications that seem potentially viable to researchers and companies and cataloging the effects—both positive and negative—that these applications may have on industry, consumers, and society at large.

As the report will show, quantum technologies (like many information technologies that have come before) will produce benefits and risks and will inevitably require developers and regulators to make trade-offs between several legitimate but conflicting goals. Some of these policy decisions can be made in advance, but some will have to be reactive in nature, as unexpected risks and benefits will emerge.

Quantum Technologies and Applications

Quantum technologies leverage properties of quantum physics such as superposition and entanglement in order to achieve the performance of a task that classical systems could not do as efficiently or not do at all. Quantum technologies are typically categorized in three core functions: computing, sensing, and communications.[4]

3 World Economic Forum, "Quantum Computing Governance Principles—Insight Report" (World Economic Forum, 2022), accessed February 28, 2023, https://www3.weforum.org/docs/WEF_Quantum_Computing_2022.pdf; C. J. Hoofnagle and S. L. Garfinkel, Law and Policy for the Quantum Age (Cambridge, UK: Cambridge University Press, 2022), doi: 10.1017/9781108883719.

4 Hoofnagle and Garfinkel, *Law and Policy*.

Each of these core functions can then be leveraged for a range of practical applications.

Quantum Computing

Quantum computers may be able to run quantum algorithms that solve a certain subset of problems much faster than classical computers by running more efficient algorithms.[5] Dozens of companies and research laboratories around the world are setting new milestones on increasingly capable quantum computers.[6] The commercial interest often comes from potentially decreasing R&D costs using quantum simulations or solving certain optimization and pattern-recognition problems that classical computers currently cannot solve. Superposition and entanglement potentially allow quantum computers to process multiple solutions simultaneously.[7] Quantum computing therefore has the potential to drive a significant computing revolution.[8] Hybrid computing capacity may help organizations to go beyond analyzing data to discover new ways to solve problems. Specific applications that have been theorized include the following.

5 S. Choi, W. S. Moses, and N. Thompson, "The Quantum Tortoise and the Classical Hare: A Simple Framework for Understanding Which Problems Quantum Computing Will Accelerate (and Which It Won't)," arXiv 2310.15505v1 (2023).

6 M. Brooks, "What's Next for Quantum Computing," *MIT Technology Review*, 2023, accesed May 8, 2023, https://www.technologyreview.com/2023/01/06/1066317/whats-next-for-quantum-computing.

7 M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information*, 10th anniversary ed. (Cambridge, UK: Cambridge University Press, 2010), doi: 10.1017/CBO9780511976667; World Economic Forum, "Quantum Computing Governance Principles."

8 IBM, *The Quantum Decade*, 3rd ed. (IBM Institute for Business Value, 2021), accessed February 28, 2023, https://www.ibm.com/downloads/cas/J25G35OK; J. Biamonte, P. Wittek, N. Pancotti, P. Rebentrost, N. Wiebe, and S. Lloyd, "Quantum Machine Learning," *Nature* 549, no. 7671 (September 2017), doi: 10.1038/nature23474.

→ Drug Development and Personalized Healthcare

Quantum computers could help researchers design new drugs and understand complex biological systems, leading to more personalized and effective medical treatments. Quantum computing simulations may simultaneously reduce R&D time *and* increase safety by “making target identification, drug design and toxicity testing less dependent on trial and error.”[9]

→ Chemicals and Energy

Quantum computing can discover improved catalyst designs that enable significant energy savings. Some groups are hoping that quantum computing algorithms can help fight climate change by discovering ways to design batteries with higher energy density, cement and fertilizers with lower emissions, or solar panels with greater efficiency.[10]

→ Optimizing Traffic and Improving Logistics

Quantum computers could be used to solve complex optimization problems, leading to more efficient supply chains, better logistics, improved energy distribution, and optimized path planning for self-driving vehicles.[11]

9 M. Biondi, A. Heid, N. Henke, N. Mohr, I. Ostojic, L. Pautasso, L. Wester, and R. Zemmel, *Quantum Computing: An Emerging Ecosystem and Industry Use Cases* (McKinsey & Company, 2021), accessed March 5, 2023, https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/quantum%20computing%20use%20cases%20are%20getting%20real%20what%20you%20need%20to%20know/quantum-computing-an-emerging-ecosystem.pdf.

10 P. Cooper, P. Ernst, D. Kiewell, and D. Pinner, *Quantum Computing Just Might Save the Planet* (McKinsey & Company, 2022), accessed May 8, 2023, https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/quantum-computing-just-might-save-the-planet.

11 Biondi, et al., *Quantum Computing.*

→ Modeling Financial Markets

Quantum computers could be used to better model financial data and make more accurate predictions, leading to more stable and efficient financial markets.[12]

→ Quantum-Assisted Decryption

Among the algorithms that quantum computers can run much faster than classical computers are decryption algorithms such as Shor's algorithm. This algorithm can be used to break the most widely deployed encryption techniques in use today, such as RSA (Rivest-Shamir-Adleman) public key cryptosystems. These will be useful for intelligence and law enforcement investigations, and this is one of the reasons that quantum technologies might be subject to trade restrictions.[13]

Currently, the most functioning quantum computing technologies use fewer than 100 qubits, and most of these have to be put into service to perform error-correction procedures (leaving a much smaller number of "logical" qubits).[14] Quantum computers are expected to grow to 1,000 high-quality physical qubits soon.[15] But this is still many orders of magnitude smaller than the number of qubits needed to run some of the algorithms that get attention. For example, running Shor's algorithm to break modern

12 Biondi, et al., *Quantum Computing.*

13 P. Inglesant, M. Jirotka, and M. Hartswood, *Responsible Innovation in Quantum Technologies Applied to Defence and National Security* (NQIT and UK National Quantum Technology Hub, 2018), accessed February 28, 2023, https://nqit.ox.ac.uk/sites/www.nqit.ox.ac.uk/files/2018-11/Responsible%20Innovation%20in%20Quantum%20Technologies%20applied%20to%20Defence%20and%20National%20Security%20PDFNov18.pdf.

14 Brooks, "What's Next."

15 C. Q. Choi, "IBM's Quantum Leap: The Company Will Take Quantum Tech Past the 1,000-Qubit Mark in 2023," *IEEE Spectrum* 60, no. 1 (January 2023): 46–47, doi: 10.1109/MSPEC.2023.10006669; IBM, *Quantum Decade*.

RSA encryption requires over 1,000 logical qubits and thus might require millions of physical qubits.[16]

Quantum Sensing

Quantum sensing leverages entanglement and superposition to offer a much greater amount of sensitivity given a fixed amount of power. Quantum sensors have already contributed to improvements in fields such as positioning, navigation, remote sensing, and biomedical, chemical, and materials sciences.[17] Some examples include the following.

→ Astronomy

Quantum sensors will have a great impact on astronomy. Quantum VLBI can obtain 10 times the resolution of the James Webb Space Telescope with a telescope half the size (and one-hundredth of the cost). A network of a small number of quantum-entangled telescopes in low Earth orbit would get a resolution 100 times greater than the James Webb telescope. This new generation of sensing instruments will deliver deeper knowledge of the early universe, as well as allowing detailed inspection of exoplanets orbiting other stars. The same technology—a network of telescopes in low Earth orbit strung together with a quantum network—could also look *down* instead of up and take ultraprecise images of Earth's surface. These can be used for military intelligence as well as high-precision weather forecasting and mining.

16 C. Gidney and M. Ekerå, "How to Factor 2048 Bit RSA Integers in 8 Hours Using 20 Million Noisy Qubits," *Quantum* 5 (April 2021): 433, doi: 10.22331/q-2021-04-15-433.

17 National Science & Technology Council, *Bringing Quantum Sensors to Fruition* (National Science and Technology Council, 2022), accessed March 4, 2023, https://www.quantum.gov/wp-content/uploads/2022/03/BringingQuantumSensorstoFruition.pdf.

→ Medicine

Quantum-enhanced photonic sensors will allow a 10-fold improvement in resolution using quantum-enhanced atomic-force microscopes (AFMs). In cellular biology, an AFM is used to distinguish cancer cells and normal cells. In molecular biology, AFMs are routinely used to study the structure and mechanical properties of protein complexes and assemblies. We could perform all those tasks with a far higher precision or speed than normally possible, potentially enabling us to image dynamic input (e.g., video rather than still images), which is not possible today.

Quantum-enhanced magnetic-field sensors may be able to achieve 100-fold higher resolution in spatial and temporal imaging of tiny perturbations in magnetic fields, caused for instance by neural signals in the human brain or current flowing in an integrated circuit. This would be useful for brain imaging at a level of granularity that has never been possible. But it can also enable the production of MRI and CT scanners that use a much lower dose of radiation to achieve the same level of resolution, greatly increasing the safety of these diagnostics.

There are also some industrial applications of quantum sensors. They can improve microchip fabrication by enabling better surface measurements for integrated circuit verification and testing. Quantum sensors can also be used for precision agriculture and water conservation and to build scanners that detect and trace evidence of illegal contaminants or contraband.

Quantum Communications

Quantum networks will transmit quantum information between quantum devices to facilitate distributed quantum computing[18] or to create quantum-based security for the transmission of classical communications.

→ Quantum Cryptography

One of the most promising applications of quantum networking is the potential for wide-scale use of quantum key distribution (QKD). QKD security is grounded in the laws of quantum physics to provide a guarantee against surreptitious interception because an unauthorized interception and measurement of entangled particles would be detectable by the source of the quantum key. The European Union has enthusiastically embraced the physics-based security paradigm underlying QKD and is rolling it out as a publicly accessible service in multiple countries. But there is a live debate about the practical necessity and viability of quantum networking for postquantum security in light of the development of classical postquantum strategies. Many well-respected cryptographers, including Peter Shor himself (inventor of Shor's algorithm), believe that classical postquantum encryption will be widely available well before quantum networking is available at scale.

→ Quantum-Networked Computing

Quantum communications networks can also be used in combination with quantum computers to create private automated auctions

18 H. Bombin, I. H. Kim, D. Litinski, N. Nickerson, M. Pant, F. Pastawski, S. Roberts, and T. Rudolph, "Interleaving: Modular Architectures for Fault-Tolerant Photonic Quantum Computing," arXiv (2021), doi: 10.48550/arXiv.2103.08612.

and “blind” computing, where the quantum cloud host can’t eavesdrop on what information is being stored or processed so that proprietary data and trade secrets may be preserved.

→ Entangled Synchronized Atomic Clocks

Having well-synchronized clocks across multiple devices is critical to the efficient functioning of everything from GPS to Internet communications. Today, these devices have to be resynchronized from time to time, and small inaccuracies can garble messages or lead to other errors. But if those atomic clocks used quantum networks to share entanglement resources, synchronization would be faster and less error-prone.[19] Quantum-based “position, navigation, and timing devices” could be used as highly reliable navigation systems for submarines and other devices, too, without the need for externally provided guidance through GPS. This would allow navigation to continue unobstructed when a vehicle is underground or underwater, and it would also remove the threat of signal jamming by adversaries.

A Pragmatist View of the Quantum Policy and Quantum Ethics Landscape

Scholars and think tanks have already begun to articulate the ethical and social values that should be embedded in the design, distribution, and use of quantum technologies. For example, a report by the World Economic Forum uses the following core values: the use for common good, ensuring human accountability, inclusiveness, equitability, nonmaleficence, transparency,

19 Y. Yang, G. Chiribella, and M. Hayashi, “Quantum Stopwatch: How to Store Time in a Quantum Memory,” *Proceedings of the Royal Society A: Math. Physical and Engineering Sciences* 474, no. 2213 (May 2018): 20170773, doi: 10.1098/rspa.2017.0773.

and accessibility. Mauritz Kop has advocated using fairness, benevolence, nonmaleficence (avoiding harm), autonomy, and sustainability as guideposts for the ethical development of quantum technologies.[20] And TU Delft's report has identified security, safety, resilience, trust, privacy, equal access, and net neutrality as key values for a responsible quantum Internet.[21]

These are excellent values, but stated in the abstract, and with seeming supremacy over the values of innovation, dispersion, and timely adoption, they cannot provide concrete guidance for real-world decisions that policymakers and developers will have to make. Thus, this report tries to identify all of the societal interests—including the interests in successful development—that will need to be balanced. When an application pits values against each other—for example, when an application that increases privacy will also increase the opportunities for malevolence—policymakers will have to set priorities and be honest about the trade-offs. In most cases, it is too early to settle the policy questions related to quantum technologies, let alone codify those policies into law. But it is not too early to start an accounting of the potential social problems that will arise with new quantum technologies and an inventory of potential responses. The following societal interests should receive some weight and consideration among lawmakers wanting to promote the responsible development of quantum technologies.

20 M. Kop, "Why We Need to Consider the Ethical Implications of Quantum Technologies," *Physics World*, December 17, 2021, accessed May 8, 2023, https://physicsworld.com/a/why-we-need-to-consider-the-ethical-implications-of-quantum-technologies/.

21 P. Vermaas, D. Nas, L. Vandersypen, D. E. Coronas, *Quantum Internet: The Internet's Next Big Step* (TU Delft, 2019), accessed May 8, 2023, https://qutech.nl/quantum-internet-magazine/.

Incentives to Innovate and Avoiding Opportunity Costs

There is always a beneficial use that serves as the backdrop of discourse on ethical technologies.[22] Technological innovation has improved and will continue to improve human health and well-being. Quantum-based technology may unleash productivity gains in a range of applications across many sectors of the economy, including health, transportation, and national security. But the development, commercial viability, and economic sustainability of these technologies is by no means certain. Industrial policy that creates incentives for quantum R&D and commercialization (e.g., through direct public investment or through IP rules) can increase the pace and intensity of development. Conversely, rules that impose demanding procedures or requirements can delay or quash innovation.

I start with this societal consideration because it can get lost in the mix when other social goals are discussed. For example, Kop recommends regulating quantum technologies so that "the benefits and risks . . . must be equally distributed across all members of society and across developed and developing countries in equal measure."[23] These are excellent goals (I include them below), but a realistic approach cannot lose sight of commercial viability as a prerequisite for the eventual equitable distribution of quantum benefits.

22 B. Jones and L. Summers, "Calculation of the Social Returns to Innovation," https://www.nber.org/papers/w27863.

23 Kop, "Why We Need."

Winning the International Economic Arms Race

The US government has spent $3.75 billion on quantum technology developments, and the European Union has spent $8.4 billion. These figures are dwarfed by the $15.3 billion investment that China is believed to have made.[24] The development of quantum technologies is being conducted, to some degree at least, as an arms race, no doubt because of the espionage and national security uses of the technologies. Chinese trade restrictions and export controls are a part of the national quantum strategy, and the distrust is mutual. Right now, there is waning political interest in nurturing economic interdependence with China.[25] The east-west rivalry has ambiguous effects on the goal of innovation. Arms races can induce large investments of money and national pride into scientific development, which can speed up the development process. But top-level expertise in quantum is scarce, so political separation of the major research hubs could also lead to knowledge silos and delays in the discovery process.

24 McKinsey & Company, *Quantum Technology Monitor*; Kaur, "Quantum Initiatives Worldwide"; European Quantum Flagship, *Strategic Research Agenda* (European Quantum Flagship, 2020), accessed March 4, 2023, https://stage.qt.eu/media/pdf/Strategic_Research-_Agenda_d_FINAL.pdf; M. Riedel, M. Kovacs, P. Zoller, J. Mlynek, and T. Calarco, "Europe's Quantum Flagship Initiative," *Quantum Science and Technology* 4, no. 2 (February 2019): 020501, doi: 10.1088/2058-9565/ab042d.

25 C. T. Holter, P. Inglesant, R. Srivastava, and M. Jirotka, "Bridging the Quantum Divides: A Chance to Repair Classic(al) Mistakes?," *Quantum Science and Technology* 7, no. 4 (September 2022): 044006, doi: 10.1088/2058-9565/ac8db6; T. Roberson, J. Leach, and S. Raman, "Talking about Public Good for the Second Quantum Revolution: Analysing Quantum Technology Narratives in the Context of National Strategies," *Quantum Science and Technology* 6, no. 2 (January 2021): 025001, doi: 10.1088/2058-9565/abc5ab.

Managing Risks to Safety, Financial Security, and Social Stability

Many of the specific applications described in part I raise potential risks related to health, safety, and financial security. Moreover, just as we saw with computing and with the classical Internet, the growth of quantum technologies will cause some disruption to labor markets and social norms in several domains all at the same time. Managing risks during a time of rapid technological change will be a challenge. There are some advantages of regulating technology well before mass adoption (the FDA model, e.g.), and there are other advantages to regulating technology only after it has had the chance to be adopted and explored (Internet platforms and Section 230 immunity, e.g.).

We should expect lively policy debates about whether quantum technologies ought to be "born free" or "born in captivity."[26] If lawmakers regulate the harmful uses of a new technology too late, they risk not only missing out on protecting the victims of those risks but also possibly running into problems of political economy if there are firms with a vested interest and significant motivation to obstruct health and safety regulation.[27] However, regulating too early runs its own risks. These include not only potentially obstructing innovations that can help society, but also attracting protectionist regulation and legislation based on the lobbying of guilds and professional societies that would otherwise provide better, cheaper, and more accessible quantum

26 A. Thierer and A. Marcus, "Guns, Limbs, and Toys: What Future for 3D Printing?," *Minnesota Journal of Law, Science & Technology* 17, no. 2 (June 2016): 805–54.

27 D. Acemoglu and P. Restrepo, "The Wrong Kind of AI? Artificial Intelligence and the Future of Labour Demand," *Cambridge Journal of Regions, Economy and Society* 13, no. 1 (May 2020): 25–35, doi: 10.1093/cjres/rsz022; D. Acemoglu, "Could We and Should We Reverse (Excessive) Automation?," in *Combating Inequality: Rethinking Government's Role* (MIT Press, 2021), 163–70.

services to the end users. For example, if quantum computers are able to run high-quality drug simulations and produce personalized pharmaceuticals, obviating the need for traditional clinical trials, legacy firms that benefit from the old model will rush to regulate.[28]

Even when technology does precisely what it is intended to do, the process of creative destruction will leave behind people who had invested their training or savings into the previous systems. Losses and anxiety from technological disruption (whether from quantum technologies or others) could justify a "transition relief" program to provide an economic safety buffer for workers or communities most affected by the disruption. Designing a good program is no trivial task. Scholarly discussions about the desirability of transition relief after a legal or social shock show diverging views on whether a relief scheme can address transitory needs without excessively distorting or undermining individual incentives to adapt.[29]

Equitable Access to Quantum Technologies

The law and ethics community is rightly concerned with gaps in access to technologies that wind up serving as an engine of health and prosperity. These gaps often emerge along socioeconomic and racial lines, and they span not only differences in literal (technical) access to technologies but also gaps in practical access when financial or educational barriers present an obstacle.

28 B. Yandle and A. Smith, *Bootleggers & Baptists: How Economic Forces and Moral Perusasion Interact to Shape Regulatory Politics* (Cato Institute, 2014).

29 L. Kaplow, "An Economic Analysis of Legal Transitions," *Harvard Law Review* 99, no. 3 (1986): 509–617, doi: 10.2307/1341148; S. Shavell, "On Optimal Legal Change, Past Behavior, and Grandfathering," *Journal of Legal Studies* 37, no. 1 (January 2008): 37–85, doi: 10.1086/588264; J. S. Masur and J. R. Nash, "The Institutional Dynamics of Transition Relief," *New York University Law Review* 85, no. 2 (201): 391–456.

During the initial rollout for quantum technologies, while they are both expensive and potentially difficult to use except by individuals with technical expertise, access gaps are inevitable. Mitigating the duration and impact of these access gaps should be a high priority. However, we should expect tense, good faith debates over how, and how quickly, to reduce access gaps and whether the more direct costs of equitable-access programs should be borne by the public or by industry (and their customers).

Competitive Markets

The initial costs of some of the critical components of quantum technologies (such as quantum computers or quantum memory and repeaters) and the path dependency of certain practices (such as technical protocols) mean that there is a high probability that a small number of companies may dominate the quantum technology marketplace, at least in the beginning. But if that dominance is maintained for reasons that have little to do with adding to consumer value (e.g., because of network effects or aggressive acquisition of startups), the societal goals described above–innovation, minimizing opportunity costs, and equitable access in particular–will be undermined. Economists with a good handle on the economics of the computing and communications industries will need to use the particular features of quantum technology marketplaces and apply antitrust and competition principles to them.

The Right Type of Privacy

Some quantum technologies increase privacy, while others diminish it.

Pervasive satellite imaging of Earth's surface using quantum telescopes would enable the surveillance to occur in public (at least, when the weather allows). Satellite imaging from currently available commercial satellites does not allow for enough resolution to make out an individual in any given image, as Google Earth demonstrates. Satellite imaging technology used in military satellites is believed to be high-enough resolution to make out identities and details of people, but these of course are not widely available.[30] As networked quantum sensors become available at smaller sizes and lower costs, we should expect high-resolution aerial images to become commonplace. This will raise questions about privacy expectations. Under existing European law, commercial firms would have to avoid collecting high-resolution images of people in public, but US law has been reluctant to recognize limitations on photography in public.

The use of quantum computing for decryption is, quite obviously, a privacy-diminishing application. It will surely have a mixed effect on society. While these tools could enable a range of legitimate uses by state actors who have followed necessary procedures, the technology can also be exploited by state and private actors who have illegitimate personal, financial, or political motivations. Thus, postquantum preparedness should be a paramount interest for policymakers. NIST has embraced a suite of classical encryption methods known as Post Quantum Cryptography that are believed to be secure from quantum computer attacks. And the deployment of quantum key distribution will help reinforce communications channels against attacks. Nevertheless, the temporal scope of this problem is unusual. The data and communications that we are

30 S. Brown, "Satellite Surveillance May Be Less of a Privacy Concern than You Think—for Now," *CNET*, 2019, accessed May 8, 2023, https://www.cnet.com/science/turns-out-satellite-surveillance-only-sounds-like-a-major-privacy-concern/.

producing today, and that we have already produced and stored in RSA-encrypted form, are under the threat of a "gather now, decrypt later" attack.[31] Thus, we need a practical strategy to handle the fallout from the monumental data breaches that may have already been set in motion. This will require updated authentication systems and resilience against blackmail or identity fraud.

Quantum-based communications security will increase user privacy. The drawback with this is that quantum-based encryption does not allow law enforcement to intercept the messages of criminals or enemies of the state even if they have a warrant. The intelligence and law enforcement community will have a quantum version of the "going dark" problem that they are facing today, as more and more services (including all communications on Apple devices) move from centralized encryption to device-side end-to-end. The privacy guarantee of a quantum network channel plus the power of a quantum computer is a dangerous combination if hackers and other malfeasors engage in quantum-assisted crime. These crimes include decrypting pre-quantum encrypted data and communications as well as discovery of new poisons or biological weapons. Owners of quantum computers may need to develop (or may need to be required to develop) a verification and vetting process before clients get access to quantum computing services. This, however, will undermine the openness and vibrancy of those services.

A Well-Prepared Workforce

As is the case with machine learning and computer engineering more broadly, the supply of workers with appropriate math and science

31 H. Kristjánsson, R. Gardner, and G. Chiribella, *Quantum Communications Report for Ofcom* (Ofcom, 2021), accessed February 28, 2023, https://www.ofcom.org.uk/__data/assets/pdf_file/0012/222600/Quantum-Communications-report-for-Ofcom.pdf.

skills and with an interest in quantum-specific applications is woefully insufficient to meet demand.[32] History has shown that the usual method of inducing supply to meet demand (namely, by paying more) does not work very well in the labor market because some decisions, such as what to study in college or whether to offer associate's degrees in a particular technical trade, occur well before the firms have a need for large numbers of workers. Thus, there is a societal need to incentivize and support the study of quantum information science (or, perhaps, more broadly STEM and technology-related professional programs). This is one of the few social goals that runs into little conflict with other goals. Thus, the one recommendation I can make today without reservation is **a significant government investment to cultivate STEM-related skills and interests beginning in K-12 programs and extending all the way to graduate school and postgraduate training.**

In addition, given that science talent is *already* in short supply, and given that science education is a long-term project, it will be necessary for the United States to also act decisively and strategically in its immigration policy. (Indeed, since visa application fees often fund US education programs in STEM, the education and immigration strategies work hand-in-hand.[33] Thus, to grow and retain a well-prepared workforce now, lawmakers should consider **modifying immigration law** by creating more pathways for foreign students studying STEM at US universities to stay and work in the US after earning their degrees and by expanding the

32 Hoofnagle and Garfinkel, *Law and Policy*.

33 T. Barkley, J. Morales, and J. T. Smith, *What Policies Promote Abundance?* (Center for Growth and Opportunity at Utah State University, 2022), https://www.thecgo.org/research/what-policies-promote-abundance/; US Department of Labor, "H-1B Skills Training Grants," US Department of Labor, accessed March 29, 2022, https://www.dol.gov/agencies/eta/skills-grants/h1-b-skills-training.

H-1B visa program or creating new immigration programs for high-skilled immigrants.

Conclusion

A measured regulatory frame for quantum technology would aim to minimize risks related to safety, competition, and distributional fairness without suppressing the development or viability of a technology that has the potential to generate profound benefits in health, environmental sustainability, communications privacy, materials science, and a wide variety of other domains. When formulating and suggesting ethical principles that should guide quantum R&D, policymakers should stay vigilant of the trade-offs that are involved.

There is no consensus on the way that ethical principles and social goals should be managed when they are in conflict. Policymakers should be wary of sweeping generalizations of what “innovation” or “ethical technology” requires unless those values have been translated into realistic predictions of the impact on human rights and welfare and unless the priorities between conflicting goals are made clear.