Quantum Computing Governance Principles

INSIGHT REPORT

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Preface

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Quantum computing, though in its early stages, will help provide very significant advances in our computing capabilities. It promises to bring transformative benefits to several industries and have a considerable impact on improving the state of the world in the coming years. Quantum computing brings opportunities and challenges distinct from those of other computing technologies, which necessitates a multidisciplinary global conversation to guide its development and use for the benefit of humanity.

The most appropriate and effective time to consider the impact of a technology is when that technology is still in the design and development phase as this allows for early intervention. The ethical, legal and societal impacts of quantum computing are just beginning to be discussed; however, governance "guidelines" do not yet exist globally.[1]

The Quantum Computing Governance Principles is an initiative of the Governance Workstream of the World Economic Forum's Quantum Computing Network – a multistakeholder network centred on accelerating responsible quantum computing. We have initiated a conversation on the responsible development and use of quantum computing technology now, while it is still being developed, to build trust in the technology and pre-empt possible risks – rather than wait for it to become commercialized and then try to catch up with governance. This initiative aims to understand the opportunities, risks, and social, legal and ethical implications of quantum computing. It seeks to develop appropriate mechanisms that can inform future governance and policy responses for all quantum computing stakeholders such as businesses, governments and academia.

As a first step, we have co-designed a shared set of governance principles to be adopted by the quantum ecosystem. These will serve as a guide to the responsible development and use of the technology, enabling industry and societal applications and mitigating risks. The Forum's principles are the result of a year of intensive discussions, expert interviews, design workshops and wide consultations among a diverse group of experts globally regarding the implications of quantum computing. The Quantum Computing Governance Principles were developed through a comprehensive multistage co-design process involving quantum science and technology experts, business leaders, social scientists, policy-makers and authorities on emerging technology ethics and law drawn from around the world. The objective is to create awareness as a first step and have the quantum computing ecosystem engage in these discussions. As the next step, we will work with stakeholders to adopt these principles. We hope that by getting these principles out in the world, the topic can be debated and the principles refined and taken forward to collaboratively shape how the technology will be used.

Introduction

There is a need for global guidelines to assess and manage the opportunities and risks of quantum computing, providing a shared set of principles for all stakeholders, to shape the technology and benefit humanity.

Quantum computing and quantum information science represent some of the most rapidly advancing and significant emerging technologies today. Worldwide, governments and industry are accelerating their investment in quantum computing research and development, with significant resources being committed to the sector by both public and private institutions. This is evidenced by large national funding initiatives across the globe,[2] as well as increasing venture capital investments in this technology.[3] Quantum computing is also becoming increasingly relevant in national geostrategic and economic considerations.

This new technology presents society with potentially very significant opportunities: certain highly complex problems are currently inefficiently addressed by classical computers. Such problems, which include but are not limited to physical simulation, optimization and factorization problems, are believed to be more efficiently solvable with quantum computers. This is due to the fact that quantum computers can – as the name suggests – harness the fundamental principles of quantum physics such as superposition and entanglement,[4] giving rise to a new information-processing paradigm.

However, as with every new technology, particularly one as transformative as quantum computing, new socioeconomic, political and ethical challenges arise. As the technology develops further, and as we discover wider-reaching applications, the possibility of ethical and governance challenges involving the use and deployment of such technologies increases.

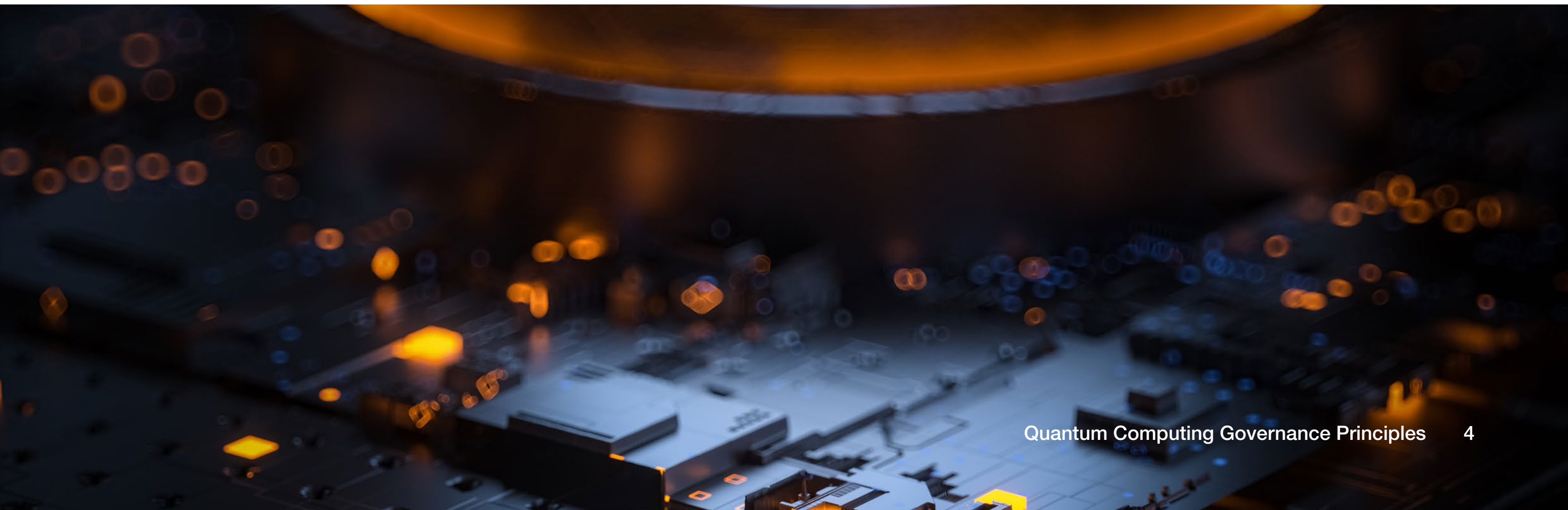
These challenges are interconnected.

First, quantum computing is a new technology. As such, its exact implications are unknown, yet it is widely anticipated that the technology has the potential to have a significant impact on society. With quantum computing introducing a new computing paradigm, existing knowledge about the opportunities and risks of a new technology as well as the necessary understanding to adjudicate between them will, in many cases, be insufficient or at least call for a reassessment of how such opportunities and risks are managed.

Second, since quantum computing will not be used in isolation, but in combination with classical computing technology, problems already being faced in classical computing today might be amplified through the use of quantum methods.

Third, quantum computing is among the technologies that require significant resource investment, giving rise to issues of equity, access and distribution of benefits and risks, especially for under-resourced nations and stakeholder groups.

Ensuring the coherent, cohesive, productive and beneficial use of quantum computing thus requires critical reflection and outreach with an inclusive stakeholder discourse that reaches from technologists to industrial, political and social leadership. This document and the principles outlined are the result of an initial discourse of this kind.



The need for Quantum Computing Governance Principles

Quantum computing is in its early stages. Assuming that the majority of those involved in developing the technology intend it to have a positive impact on humanity, it is vital to have a set of principles on which key stakeholders such as researchers, developers, users and governments can agree. This necessity has motivated the co-design of the Forum's Quantum Computing Governance Principles. The World Economic Forum, as a global forum for political, economic, social and technological stakeholders, is well positioned to be at the forefront of drafting such principles.

This is an ideal time to develop such principles: First, quantum computing is sufficiently advanced for us to have an idea of the areas in which it will start to have an impact and what kind of impact that will be. Second, the technology is not yet so far advanced that such principles can only be retroactive. Third, the socioeconomic ecosystem around quantum computing is no longer in its infancy, but is growing rapidly.

> While advancing rapidly, quantum computing is at an early stage of development, and the ideal time to develop governance principles is now.

While advancing rapidly, quantum computing technology remains at an early stage of development. The engineering challenges facing quantum technology mean that the roll-out of these technologies is likely to differ from that of classical computational devices. Furthermore, the experience of other technologies, such as artificial intelligence (AI), biotechnology and surveillance technologies, has shown that educating stakeholders in the research and development pipeline early about governance issues can avert some of the pitfalls of and mistakes made in prior technology development – such as an absence of assurance mechanisms. Conversely, engaging the quantum stakeholder community early on can also assist policy-makers and governments in ensuring that governance regimes applicable to quantum technologies are workable, feasible and do not inadvertently constrain or impose unnecessary regulatory barriers on the realization of quantum computing's technological potential. Finally, there is a significant opportunity to ensure the timely education of the general public and to start a public discourse on how best to realize the positive effects of quantum computing on society.

Quantum computing gives rise to distinct governance considerations that may not arise in other fields. The Forum's Quantum Computing Governance Principles concern themselves with the opportunities and challenges specific to quantum computing. For example, one area in which it is expected to have an advantage over classical computing systems is the simulation of natural quantum systems (e.g. molecules). This has the potential to significantly accelerate discoveries in fields such as material science. The implications of this challenge the ways in which developments in the area are currently governed. Since existing governance standards do not capture responses to these challenges, the Forum's Quantum Computing Governance Principles have to be distinct from guidelines that govern classical forms of computing.

It may be distinct, but quantum computing is not separate from classical computing. Hence, the Forum's Quantum Computing Governance Principles do, in some areas, touch on other principles. This also holds true for existing industry group standards that cannot easily be applied to quantum technology.

Purpose of the Quantum Computing Governance Principles

The aim of the Forum's Quantum Computing Governance Principles is twofold. Fundamentally, the principles provide a taxonomy to help inform stakeholders and the broader public about the areas in which quantum computing will have an impact and the opportunities and challenges that arise therewith. Furthermore, these principles have been designed to provide guidance for quantum stakeholders horizontally across different sectors and industries, and vertically for policy-makers and investors through to quantum engineers, researchers, software developers and other users.

The utility of governance principles in any field depends on striking a useful balance between their generality and specificity. The broader or more abstract a set of principles, the less utility the principles have in applied settings. Conversely, if principles are too specific, their applicability and generalizability beyond particular use cases is limited.

Quantum computing is an inherently multidisciplinary field, spanning a diverse range of disciplines from physics and mathematics to engineering and computer science. Quantum computing programmes globally also involve a broad range of stakeholders across government, industry, academia and civil society. To reflect this disciplinary and stakeholder diversity and to maximize their impact, the Forum's Quantum Computing Governance Principles were developed through a multistage co-design process involving quantum science and technology experts and thought leaders drawn from across the globe. A consensus decision-making approach was used at each stage of the co-design process to ensure that the principles are reflective of the ambitions and values of quantum computing stakeholders.

Understanding quantum computing as the basis of the governance principles

In curating Forum's Quantum Computing Governance Principles, the following technological assumptions have been made:

A. It will be possible to build a fully programmable universal fault-tolerant quantum computer.

B. Quantum computing will make computation of certain specific problems more efficient and/or precise (e.g. optimization problems etc.).

C. Quantum computing will accelerate computation towards solving problems currently deemed intractable with classical machines (e.g. breaking of currently deployed public-key encryption schemes etc.).

It is important to mention that at the time of drafting the Forum's Quantum Computing Governance Principles there are several fundamentally different technology platforms available (for example: superconducting qubits, silicon spin qubits, ion traps, photonic quantum computing) that may allow the development of a fully programmable universal fault-tolerant quantum computer. Some of these technology platforms are slightly more mature than others, but all of them are still in the development stages and no clear winner is identifiable. Achieving scalable quantum computing with fault tolerance (active error correction during a computation) giving measurable quantum advantage over classical computation is the long-term milestone for the field of quantum computing. The term "quantum advantage" describes the situation where, for a useful problem (with scientific or business value), a quantum computer has a measurable computational advantage (speed/computation time or result precision) over the best-known classical computer or algorithm. To date, the most advanced quantum computing technologies make use of about 100 (non-ideal) qubits (the basic unit of information in quantum computing, analogous to the bit in classical computing), which is significantly short of what is required to run complex algorithms such as Shor's algorithm (theoretically proven to provide measurable speed-up for factoring large integers). Additionally, error correction methods will require a large qubit overhead.

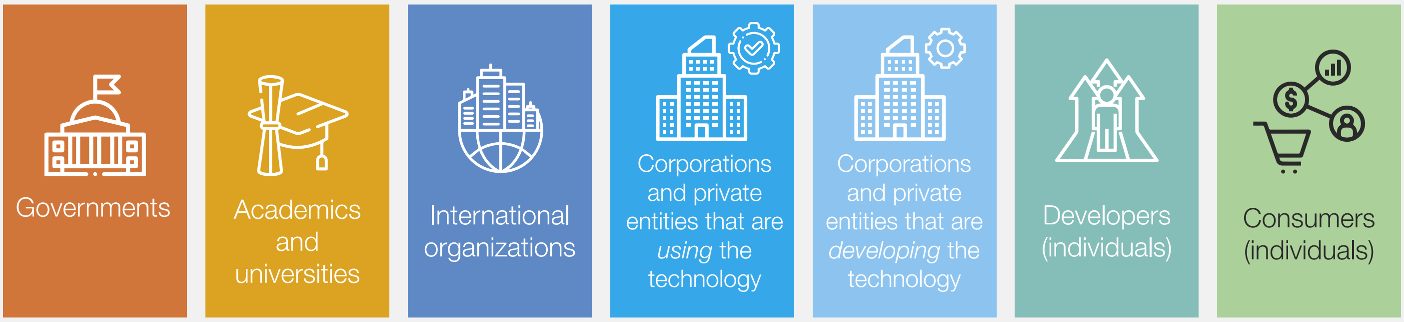
Since quantum computing technologies are rapidly developing, it is of the utmost importance to set out governance principles for this technology. However, these principles will likely not be able to capture all future use cases and should hence serve as a starting point for additional, and more specific, principles.

Quantum computing stakeholders

Who are these principles for and how might they use them?

The Forum's Quantum Computing Governance Principles are designed to be applicable to a diverse range of quantum stakeholders. While there is no single alignment of interests across quantum stakeholder communities, there are areas of commonality among different stakeholder objectives, giving the principles wide applicability. Examples of different stakeholder groups and the ways in which they may practically use the principles are set out below.

FIGURE 1 **Quantum computing stakeholders**



Source: World Economic Forum

– **Governments**: Governments and governmental institutions are the primary stakeholders in any quantum governance programme. In addition to legislative capacities, governments globally play the leading role in setting economic, innovation, science and national security policy agendas that shape quantum development ecosystems. Governments have been and continue to be – directly (via agencies) and indirectly (through funding of universities) – the primary source of funding for theoretical and applied quantum science. Government and public agency stakeholders should consider the Forum's Quantum Computing Governance Principles as a useful starting point when considering frameworks governing policies to regulate and stimulate quantum technologies. These principles can also inform, for example, the steps towards model or practical legislative frameworks and funding imperatives relating to quantum computing science and technology.

– **Academics and universities**: As with many technological innovations, quantum computational technologies have predominantly emerged from theoretical and applied research within academia and universities generally. The university sector remains the one with the highest number of practising quantum researchers, laboratories and research programmes. Maintaining the strength of public higher education institutions in quantum science, and the resulting public benefit, is a key imperative for any governance regime. Universities can usefully adopt and adapt the Forum's Quantum Computing Governance Principles in their research groups, teaching courses and research programmes. In particular, the principles have been crafted with input from academics to provide prompts and context on why and how researchers in quantum domains, including the applied sciences, can and should be conscious of governance principles when undertaking their activities.

– **International organizations**: The multinational nature of quantum research programmes and quantum technological development means that multilateral institutions, both public and private, have an important role to play in encouraging consistent approaches to quantum governance globally. Stakeholders within such multilateral institutions can benefit from the Forum's Quantum Computing Governance Principles when undertaking formal processes relating to, for example, treaties, conventions, protocols and covenants.

– **Corporations and private entities that are *using* the technology**: Quantum computing will likely become a transformative technology for many business sectors. The Forum's Quantum Computing Governance Principles will guide enterprises in their use of the technology. Companies will additionally profit from a lively and growing quantum computing ecosystem due to these principles.

– **Corporations and private entities that are *developing* the technology**: Private and public corporations have traditionally played an important role in the development and commercialization of emergent technologies. This is increasingly being reflected in the quantum arena, with many large technology companies driving innovation in quantum hardware and software. In addition, the quantum start-up community is an emerging and important sector, particularly for software but also hardware. Both established and newly founded quantum enterprises can benefit from considering the Forum's Quantum Computing Governance Principles on a number of levels, including their strategic choices of what application to develop, how to develop it, the ways in which access may be provided to technologies and the degrees to which their activities are transparent to regulators and the wider public.

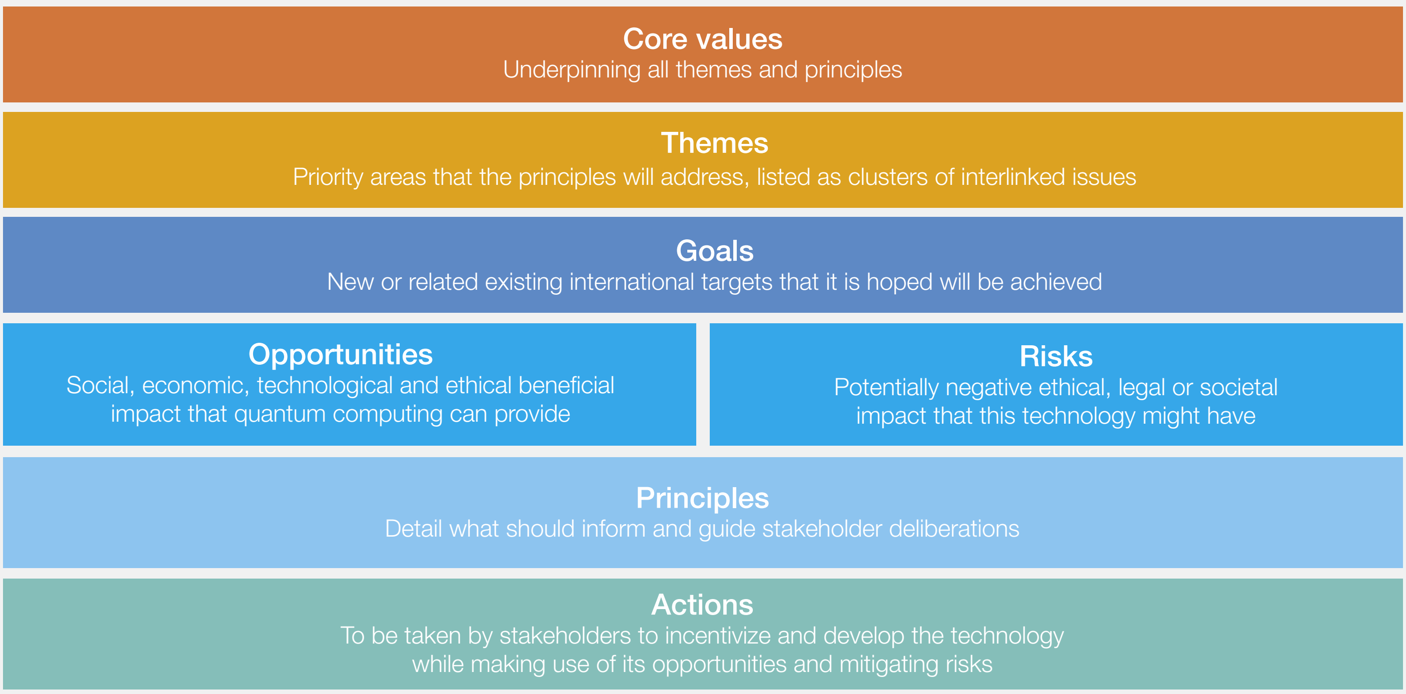
– **Developers (individuals)**: Developers will be vital in harnessing the potential transformative capabilities of quantum computing. The Forum's Quantum Computing Governance Principles will help shape a healthy quantum computing ecosystem, enabling access to education and technology in order to build the required developer workforce. Additionally, developers considering these principles can benefit on various levels, such as when considering how to build applications and how to make them accessible and transparent.

– **Consumers (individuals)**: Individuals will likely have many touchpoints with quantum computing through direct interaction or indirectly through a third party. The Forum's Quantum Computing Governance Principles will help create awareness of the technology and enlighten the wider public about the guiding principles applicable to this technology's development.

The structure of the Forum's Quantum Computing Governance Principles

The principles are structured as depicted in Figure 2. The governance principles are grouped into nine themes and underpinned by a set of seven core values. The figure emphasizes that all principles are underpinned by a set of core values that apply to all themes. Within each theme, goals, opportunities and risks have been identified that have informed the formulation of the principles and corresponding actions.

FIGURE 2 **Structure of the World Economic Forum's Quantum Computing Governance Principles**



Source: World Economic Forum

This hierarchy of principles highlights how important it is for stakeholders to agree on a specific set of core values that inform all quantum computing stakeholders' actions and decisions.

Readers are encouraged to refer to the structure underlying these principles when reading the detailed consideration of each theme, as this enables a better understanding of the core value's cross-cutting nature.

Core values

The core values are set out below. Please note that these values hold across the themes and individual principles.

- **Common good**: The transformative capabilities of quantum computing and its applications are harnessed to ensure they will be used to benefit humanity.

- **Accountability**: Use of quantum computing in any context has mechanisms in place to ensure human accountability, both in its design and in its uses and outcomes. All stakeholders in the quantum computing community are responsible for ensuring that the intentional misuse of quantum computing for harmful purposes is not accepted or inadvertently positively sanctioned.

- **Inclusiveness**: In the development of quantum computing, insofar as possible, a broad and truly diverse range of stakeholder perspectives are engaged in meaningful dialogue to avoid narrow definitions of what may be considered a harmful or beneficial use of the technology.

- **Equitability**: Quantum computing developers and users ensure that the technology is equitable by design, and that quantum computing-based technologies are fairly and evenly distributed insofar as possible. Particular consideration is given to any specific needs of vulnerable populations to ensure equitability.

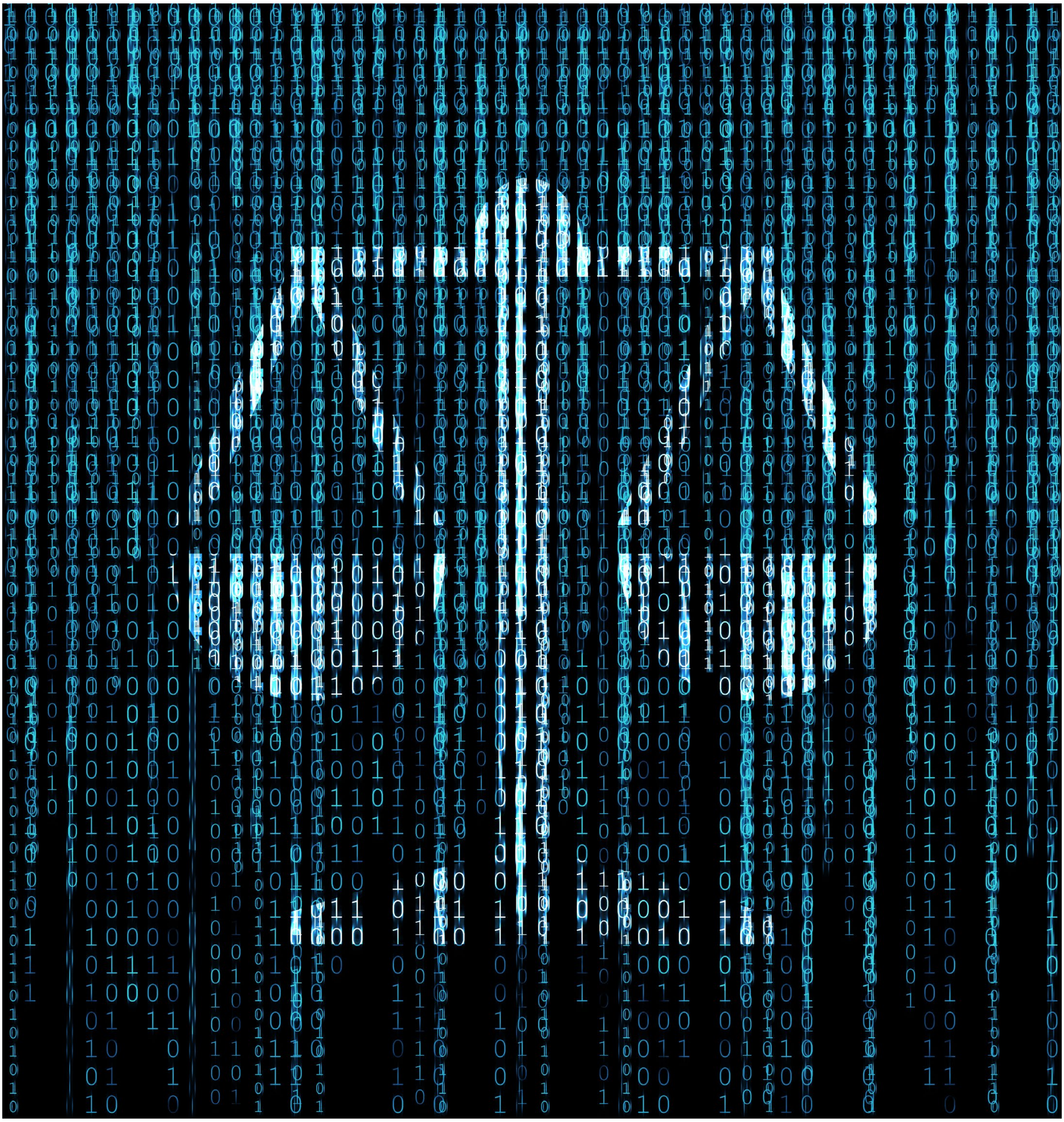
- **Non-maleficence**: All stakeholders use quantum computing in a safe, ethical and responsible manner. Furthermore, all stakeholders ensure quantum computing does not put humans at risk of harm, either in the intended or unintended outcomes of its use, and that it is not used for nefarious purposes.

- **Accessibility**: Quantum computing technology and knowledge are actively made widely accessible. This includes the development, deployment and use of the technology. The aim is to cultivate a general ability among the population, societal actors, corporations and governments to understand the main principles of quantum computing, the ways in which it differs from classical computing and the potential it brings.

- **Transparency**: Users, developers and regulators are transparent about their purpose and intentions with regard to quantum computing.

Themes

Each theme lists a set of principles underpinned by core values; the goals, opportunities and risks inform the formulation of the principles and corresponding actions to be taken by stakeholders.



The themes that define the grouping of the principles are as follows:

1. **Transformative capabilities:** Harness the transformative capabilities of this technology and the applications for the good of humanity while managing the risks appropriately.

2. **Access to hardware infrastructure:** Ensure wide access to quantum computing hardware.

3. **Open innovation:** Encourage collaboration and a precompetitive environment, enabling faster development of the technology and the realization of its applications.

4. **Creating awareness:** Ensure the general population and quantum computing stakeholders are aware, engaged and sufficiently informed to enable ongoing responsible dialogue and communication; stakeholders with oversight and authority should be able to make informed decisions about quantum computing in their respective domains.

5. **Workforce development and capability-building:** Build and sustain a quantum-ready workforce.

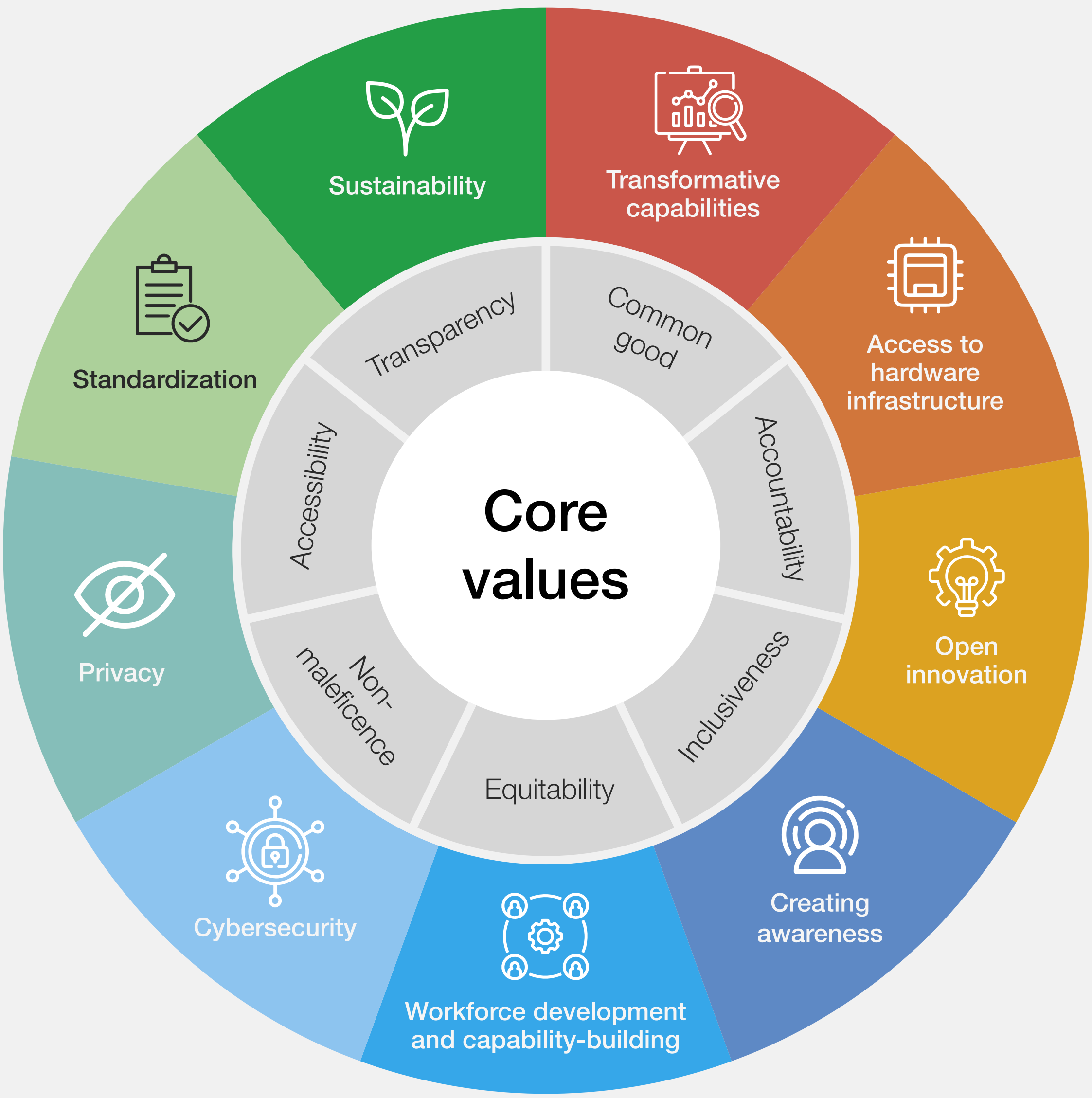
6. **Cybersecurity:** Ensure the transition to a quantum-secure digital world.

7. **Privacy:** Mitigate potential data-privacy violations through theft and processing by quantum computers.

8. **Standardization:** Promote standards and road-mapping mechanisms to accelerate the development of the technology.

9. **Sustainability:** Develop a sustainable future with and for quantum computing technology.

FIGURE 3 **The Forum's Quantum Computing Governance Principles: themes and cross-cutting core values**



Source: World Economic Forum

Theme 1

Transformative capabilities

Goal

Harness the transformative capabilities of quantum computing and its applications for the good of humanity, while managing the risks appropriately.

Quantum computational technologies present the opportunity to tackle many practical problems that are currently infeasible to solve, even with the most powerful classical supercomputers. This section provides guidance to help stakeholders frame their reasoning about and responses to the transformational potential of quantum computing technologies.

Opportunities

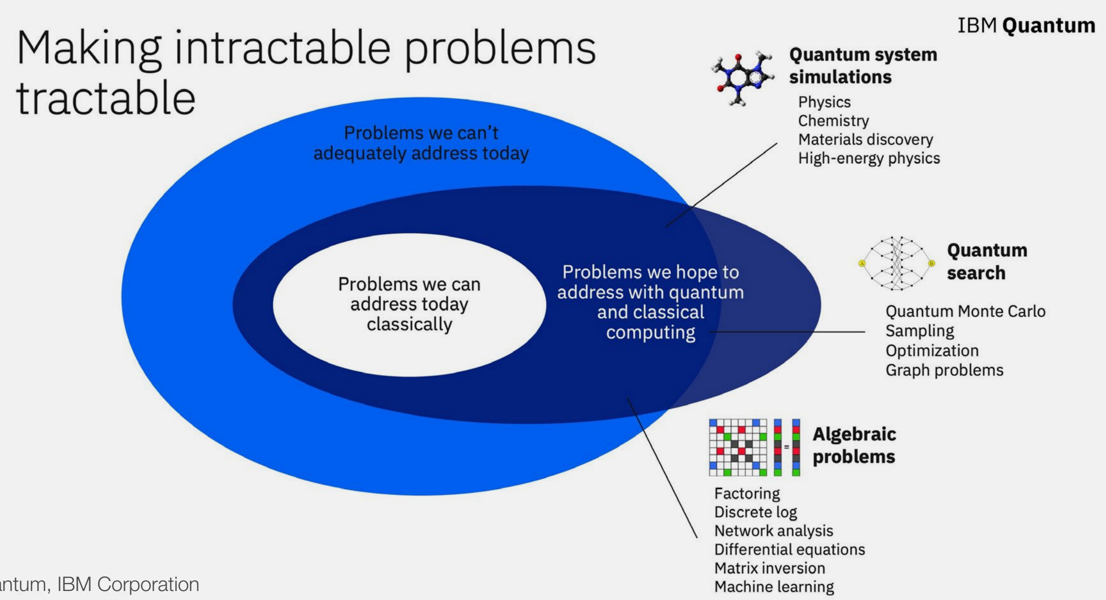
- Quantum science, quantum computation and applied quantum technologies are among the most exciting emergent technologies of the 21st century. While considerable hurdles exist to successfully engineering scalable and fault-tolerant quantum computing systems, the realization of this technology and its transformational impacts are becoming clearer as research accelerates.

- The paradigm-shifting computational differences of quantum computing give rise to extraordinary transformational opportunities. As with all technological change, this comes with potential upsides and downsides. A number of the key transformational impacts of quantum technologies are identified below, followed by an outline of the risks and their respective mitigation strategies.

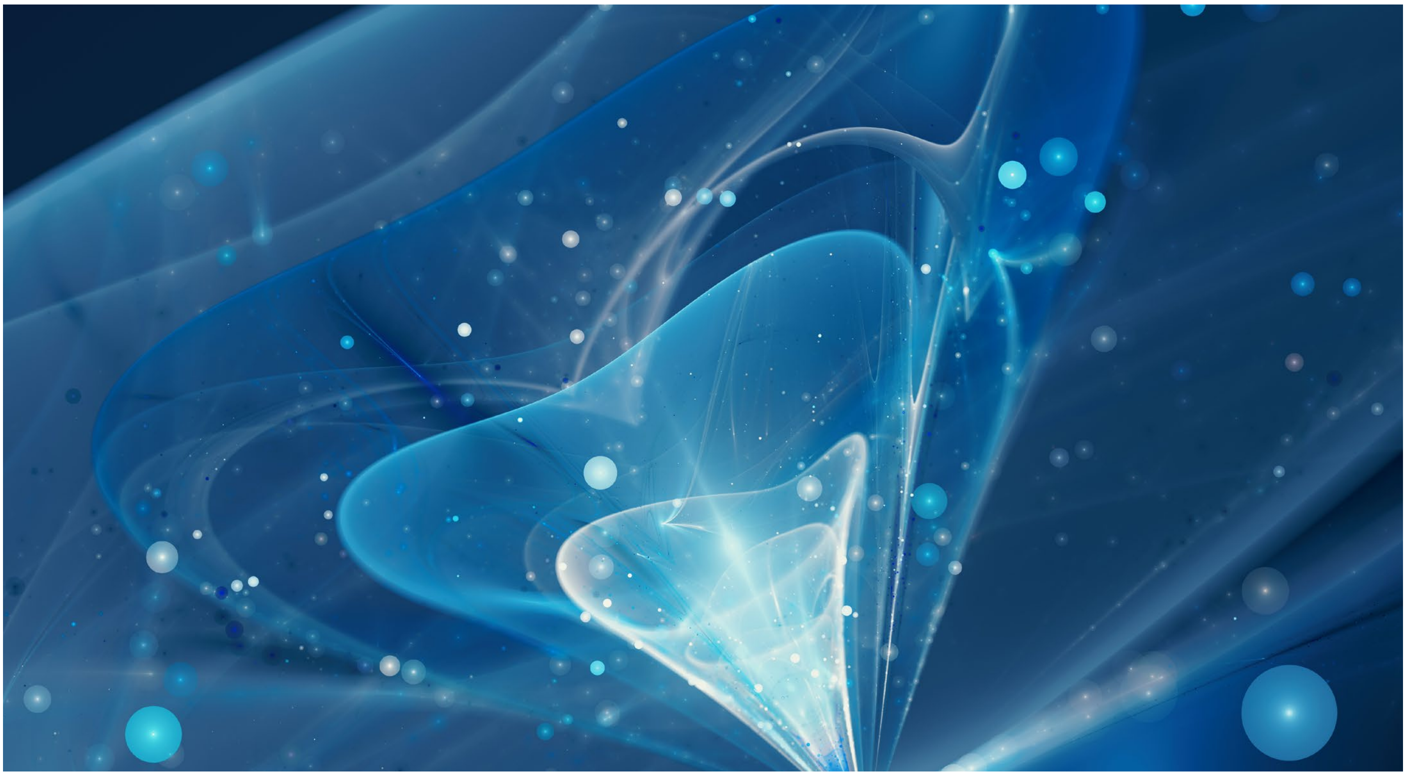
- Quantum computing is likely to have a transformational impact on three specific types of computational problems (see Figure 4). As the graphic highlights, in some cases these are computational problems that can already be addressed with classical computers, but which could be addressed more efficiently with quantum computers. In other cases, the problems are of a type that could be addressed with quantum computers but which are currently deemed intractable with classical computers.

- The three types of problems where quantum computing will have a transformational impact are: the simulation and modelling of quantum systems and processes occurring in nature; search for the ideal or “optimal” solution to a given problem with multiple existing answers; and algebraic problems such as factorization.[5] These types of problems can be found in various fields and sectors, such as chemistry, material science, finance, optimization, logistics, cybersecurity and machine learning, among many others. Hence, quantum computing technologies can have a significant transformational impact on many areas of society.

FIGURE 4 **Potential problems that could be addressed efficiently using a quantum computer to harness its transformational capabilities**



Source: IBM Quantum, IBM Corporation



Risks

- Risk of unknown transformational impact due to a lack of due diligence or impact assessment of quantum technologies.

- Risk of a lack of clear chains of responsibility due to insufficient transformation or change management procedures related to quantum computing technology development or implementation.

- Risks from a failure to identify stakeholders affected by quantum computing technologies, which could lead to adverse impacts on them, and/or resistance to such technologies in a way that hampers their considerable upside. For example, there may be risks of adverse transformational impact, such as if widespread access to quantum decryption resources enabled widespread decryption capabilities.

- Risks from the absence of a proper and comprehensive risk-assessment framework (as exists for other technologies, such as biotechnology), meaning that risks will not be identified or misidentified or will not be identified in a timely fashion to enable response, mitigation and controls to be implemented.

- Risks from failing to realize the full problem-solving potential of quantum computing due to the often non-overlapping expertise required in both quantum technology and target application domains.

Principles

- Efforts should be made to encourage the use of the transformative capabilities of this technology to benefit humanity.

- Managing the transformational impacts of quantum computing should be informed by an understanding of the technical details of such transformation, the requirements for development and the interests of stakeholders involved, including those managing these transformations, and the consumers and communities affected by them, including their rights and responsibilities.

- Communications about the transformative capabilities of quantum computing and their mechanisms should be understandable by the intended users.

- Quantum computing programs should be subject to risk-management protocols that clearly identify chains of responsibility for the strategic or impactful direction of their development, along with risks involved for different stakeholders.

- Efforts should be made to ensure that the development of quantum computing involves broad interdisciplinary collaborations.

Actions

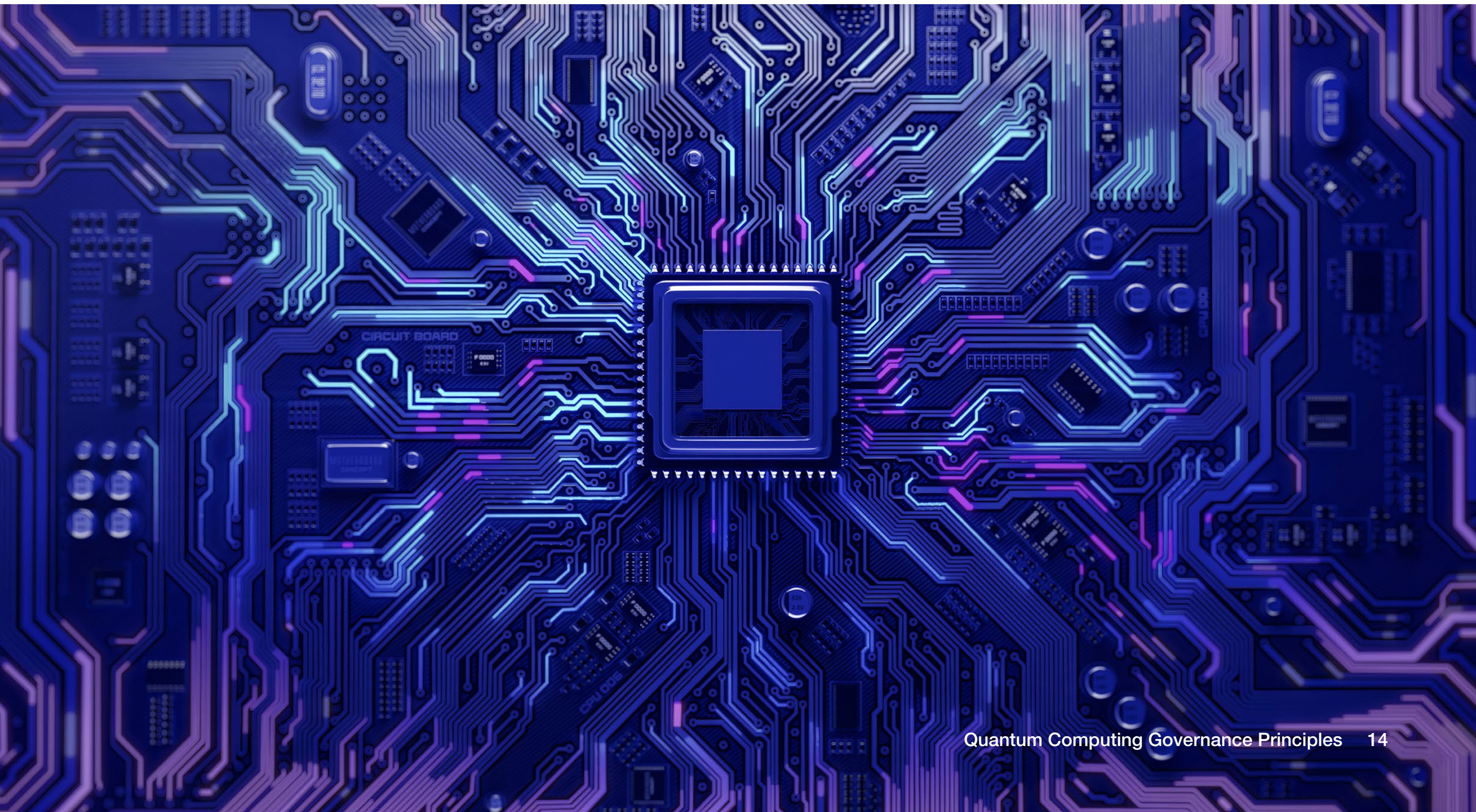
- Identify technical impact: identify key technical transformative impacts of relevant quantum computing technologies, including detailing likely development pathways and timelines, together with examining how such innovations differ from current technological practices and the likely consequences.

- Identify developmental requirements: identify the necessary and sufficient conditions to develop quantum computing technology projects, including economic resources (capital and labour markets), funding sources (public and/or private sector), regulatory requirements, developmental milestones and time frames, along with prospective ownership of and access to such technologies.

- Map stakeholders: map key stakeholder groups involved in or affected by the transformative capabilities of quantum computing identified above, including the decision-makers, the intermediate and end users of the technologies, and the economic and social stakeholders (such as industries, sectors or community groups) likely to be affected.

- Conduct impact assessment: undertake a formal opportunity and risk evaluation process associated with the deployment of quantum computing technologies. Identify potential industry applications, applications for common good and stakeholder engagements that it can enable. Use frameworks (including internationally standardized approaches) that account for acceleration of the risks of other emerging technologies in the post-quantum era.

- Incentivize stakeholders:
  - Public investment: governments globally remain the primary drivers of direct financial investment in quantum technologies, primarily due to the potential security and defence impacts. Incentivizing continued and increased investment in quantum computing technologies will require governments to understand the broader benefits (beyond narrow defence imperatives).
  - Private investment: private-sector and start-up investment in quantum computing technologies has grown significantly over the past couple of years. Major technology companies such as Google, IBM and Microsoft and others have been joined by start-ups such as PsiQuantum, Rigetti and IonQ among others. Governments can incentivize further development of quantum computing investment markets by aligning policy, taxation and investment policies to promote the sector. In particular, because many quantum technologies remain unproven and have longer realization timelines than classical technologies, investment frameworks should incentivize long-term investment in the sector.
  - Capital and labour markets: incentives for the public and private sectors should also be considered, along with ways to incentivize the increase in available capital for investment in quantum computing technologies. Such incentives should also be coupled with measures to mitigate or deal with labour-market supply-side constraints caused by a fundamental lack of skilled trained quantum practitioners to meet potential global demand.



Theme 2

Access to hardware infrastructure

Goal

Ensure wide access to quantum computing hardware infrastructure.

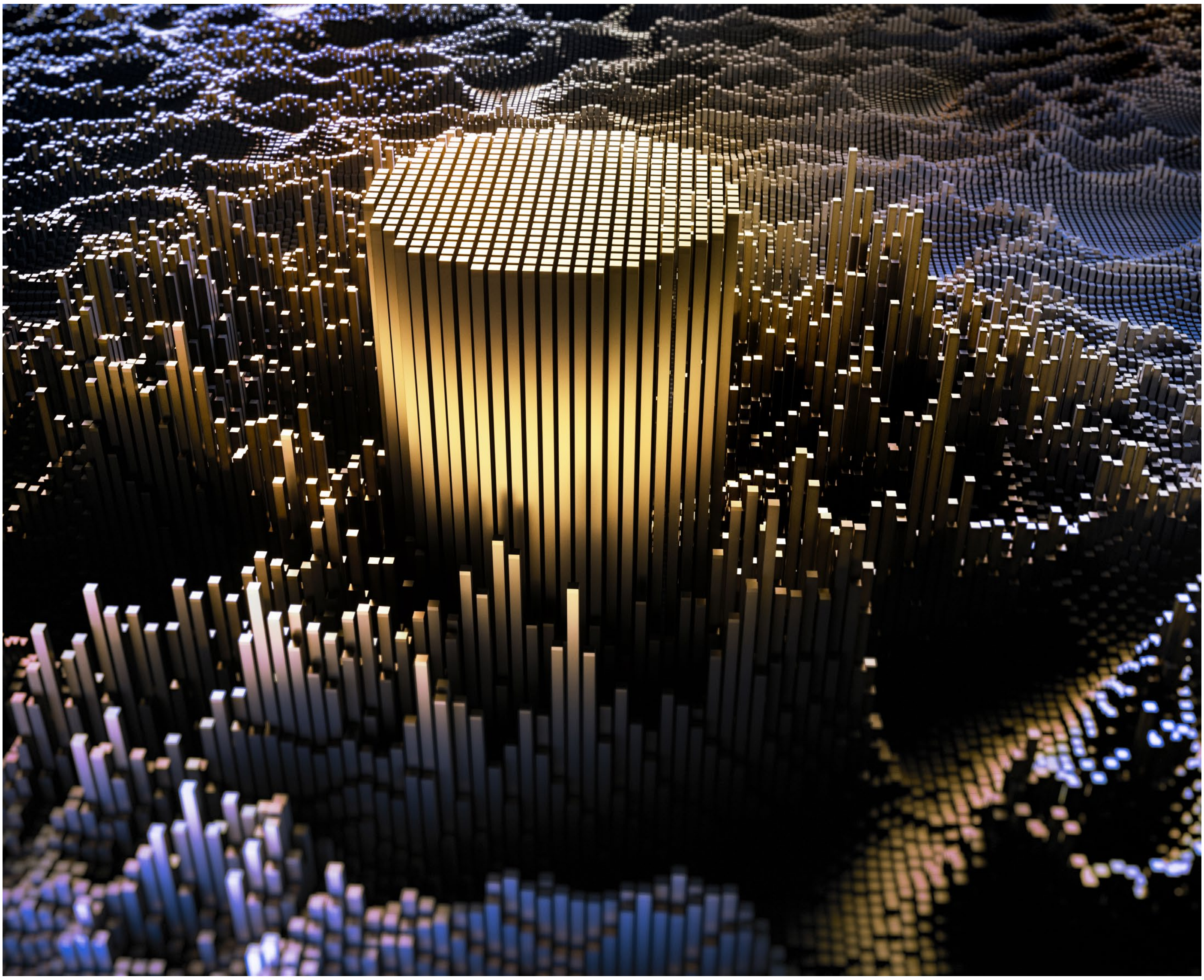
Opportunities

– Timing: quantum computers are not yet widely deployed. This creates an opportunity to enable wide access to hardware infrastructures.

– Funding structure facilitates incentivization: private corporations depend to an extent on public funding and academic collaborations for the development of quantum computers, which enables the establishment of an incentive structure that promotes wide access.

– Solving complex problems – together: quantum computers can potentially find solutions to problems that cannot be addressed classically (such as material simulations for new drugs or materials for carbon capture, routing optimization in the transport industry). The solutions to such problems can best be found through a large and diverse group working together. Enabling wide access to the technology means that quantum computers can potentially be used to solve these problems.

– Workforce enablement: quantum computers are reliant on a developing workforce; to educate and train them, knowledge needs to be shared more widely, and hence there is an opportunity to convince corporations developing quantum computing to grant wider access beyond purely commercial considerations.



Risks

- Due to the high cost and technical expertise associated with quantum computers, only a handful of actors are able to build them, and hence there is a risk of monopolization of quantum computing. This raises the question of equal access to the technology, and how benefits will be distributed. In a worst-case scenario, quantum computing could exacerbate existing divides. When the economic opportunities of quantum computers are realized, countries and corporations that have invested heavily will benefit. The ability to invest early will contribute greatly to widening socioeconomic gaps globally. In case of global conflict, if there is a monopoly on the technology, monopoly-holders could decide to shut down their systems and create global restrictions.
- The uneven distribution of skills and knowledge to work with and on quantum computing hardware can further contribute to exacerbating existing – and creating new – inequalities in terms of technology access.
- If there is a monopoly of knowledge of quantum computing hardware residing with only a few corporations and research institutions, this could lead to a power imbalance vis-a-vis national governments (regulators) as well as competitors and the public at large. This could also have negative geopolitical implications.

Principles

- Efforts should be made to provide wide access to quantum computing hardware.
- International efforts should be made to ensure equal access to quantum computing hardware, shared benefits and prosperity.
- Access to quantum computing should be equitably shared; it should not be monopolized.
- Compliance with United Nations Sustainable Development Goals (SDGs) 9 (Industry, innovation and infrastructure) and 17 (Partnerships for the goals) should be ensured.
- Regulators and national governments should be enabled to make informed and comprehensive trade determinations and technical assessments in order to make decisions related to accessing quantum computing hardware and investments therein.

Actions

- Governments should:
  - If investing in developing quantum computing hardware, also consider providing access to members of the public – e.g. via cloud access. This also requires the development of appropriate regulations regarding access purposes.
  - Acquire access to quantum computing hardware to be distributed to public institutions and to members of the public.
- Private corporations should be incentivized to make a subset of their systems publicly accessible.
- User associations should be created with the aim of sharing hardware to use for their respective purposes and hence should be independent from quantum computing hardware providers.
- Funds should be (over-)distributed to countries with less ability to fund programmes for hardware development so that they can gain traction in building skills nationally and for universities and companies to be enabled to work on hardware development themselves.
- Programmes should be established that ensure quantum computers (hardware) and access to them are globally distributed to give countries that are not part of the quantum computing development process access to the technology.
- Regulations need to be established that govern the creation and distribution of intellectual property (IP) generated through access.

Theme 3

Open innovation

Goal

Encourage collaboration and a precompetitive environment, enabling faster development of the technology and the realization of its applications.

Opportunities

- There is an opportunity to create a global quantum community by fostering worldwide interest in collaboration from research and industry. This could result in universal open projects.

- It is important to create strong existing international collaboration networks – today, entities such as the World Economic Forum and professional societies such as the Institute of Electrical and Electronics Engineers (IEEE) provide opportunities to nurture international collaboration networks in quantum computing – e.g. the Forum's Quantum Computing Network, and the IEEE Quantum Initiative. These existing international collaboration networks can be used to anchor collaborative projects.

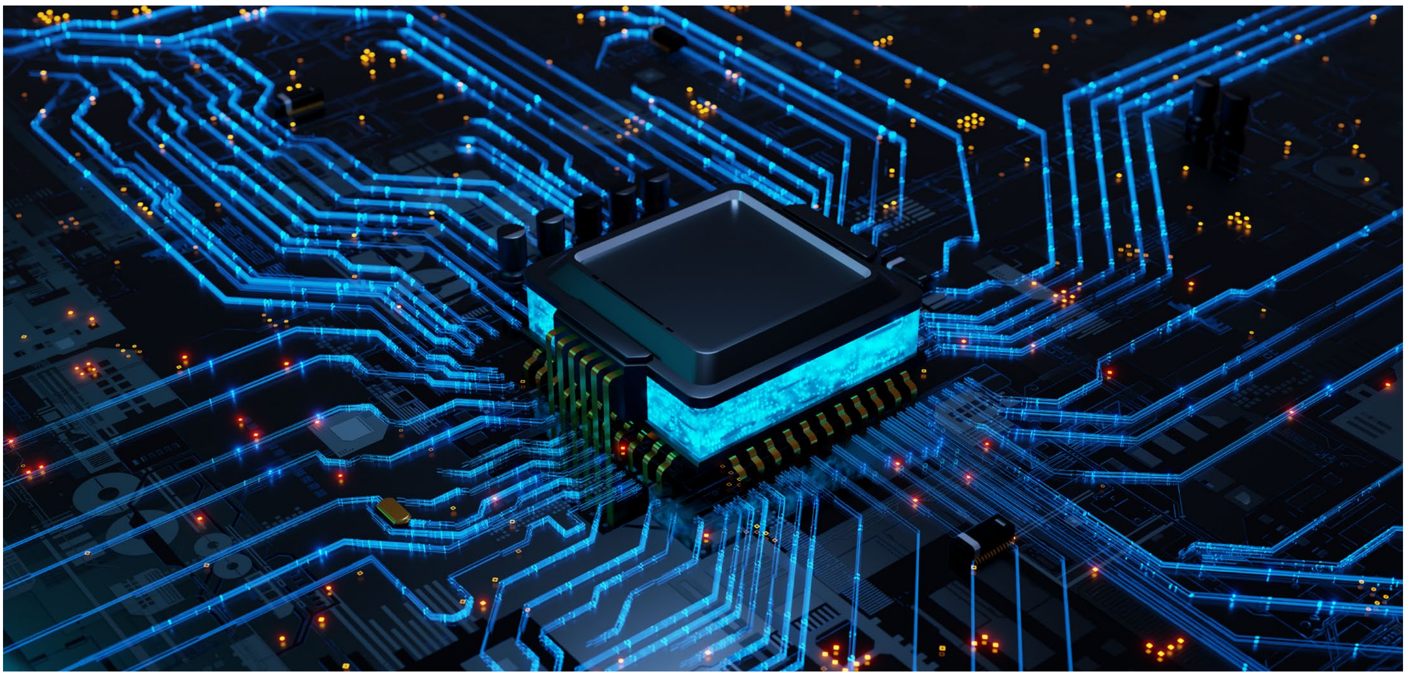
- Launching open innovation platforms and networks will enable joint projects and open-source projects.

- Stronger and more robust development of the quantum computing technology ecosystem is needed. As ecosystem players collaborate around the world, there is an opportunity to cross-validate positive results and find unique and multiple possible solutions to problems and roadblocks. This will add a layer of resilience and robustness to the quantum computing technology ecosystem.

- Broader markets and stronger adoption of quantum computing technologies are required. Quantum computing is in the early development stage. The areas of market opportunity creation and market adoption require nurturing. As success is gained in solving specific industry-affecting problems, this can easily be replicated across the world, helping create a broader market. Examples of success stories will create positive competition for early adoption and create more successful adoption stories (since learnings can be shared).

- When an open innovation environment is created, it becomes easier to identify areas that need standardization. People working together on open projects are able to reach consensus on the challenges much more easily. This creates an opportunity for standardization efforts to follow research and development work very closely.

- Focusing on visible practical use cases as open projects can incentivize industry adoption faster and also help in growing the community of developers and researchers



Risks

- Lack of collaboration can lead to risks such as: lack of clarity on the progress of the technology; disproportionate power in the hands of the few; access issues; lack of focus on applications with social good; development of harmful applications.

- Lack of scientific incentive to collaborate could hamper progress. There is a need to balance the commercial value of building in isolation vs. collaborating on roadmaps together.

- Lack of transparency of technological outcomes could blur the understanding of progress and lead to lost momentum and delays.

- Few funding agencies allow for transnational activities. Many risks identified here span companies and national boundaries. These sometimes run counter to sovereign/ commercial interests.

- If the development of quantum computing moves to a few nation states and larger organizations, there is an increased risk that the most socially beneficial use cases, such as combating climate change, will be deprioritized in favour of applications that confer a competitive or geostrategic advantage to a particular group.

- Patents given to basic knowledge discoveries (e.g. microscopic behaviour in complex materials, proteins, biological cells etc) will further privatize knowledge.

- The potential of accelerated progress is lost in the absence of collaboration and leverage of collective intelligence across the globe. Quantum computing is demanding; it requires the best minds around the world to work together.

- With open innovation, data privacy also becomes a major risk, with data being shared across borders for use cases and research.

Principles

- The quantum computing ecosystem should drive collaboration by either leveraging existing international initiatives or creating new ones with the charter for open innovation.

- Mechanisms of trust should be established between sharing parties.

- Research outcomes should be transparent, especially when they are high-impact and global.

- The quantum computing ecosystem should drive global equitable skill development in its field.

- The issuing of open-source versions of prototype use cases should be encouraged.

Actions

- Institutionalize international-level rewards for collaborative research and/or projects.

- Include quantum computing-led sustainability solutions on the agenda of international institutions, thus leveraging existing incentives for sustainability to push for collaboration in quantum computing.

- Establish a sharing/trusting code providing relevant use-case scenarios that affect society or groups beyond a single organization or community, e.g. epidemics, cybersecurity, global catastrophic events.

- Address privacy concerns arising due to open innovation through privacy principles.

- Develop opportunities in the quantum computing community and among other stakeholders to spur the creation of positive anchors in the ecosystem.

Theme 4

Creating awareness

Goal

The general population and quantum computing stakeholders are sufficiently aware, engaged and informed to enable ongoing responsible dialogue and communication; stakeholders with oversight and authority are enabled to make informed decisions about quantum computing in their respective domains.

Opportunities

- Quantum computing stakeholders currently have a unique opportunity, given the early stage of quantum computation development and adoption, to build trust with the general population by creating awareness about quantum computing. Seizing this opportunity would help stakeholders to anticipate and mitigate any potential risks that might arise from a lack of awareness or overhype.

- There is an opportunity to debunk current quantum computing myths and dispel hype, and to put mechanisms in place (such as public awareness campaigns and engagement with trusted news media outlets) to either reduce the potential harm of new myths and hype that may arise in future or prevent their occurrence. The current relative lack of awareness and knowledge about quantum computing technologies[6] presents a valuable opportunity to generate informed, trusted dialogue and responsible debate between the general population and quantum computing stakeholders. Capitalizing on this opportunity to invest in educating a quantum-literate public may help abate any potential proliferation of anti-science or anti-intellectual sentiments.

- To mediate the risk of uninformed public information campaigns, opportunities to generate data gathered with rigorous social science methodology can be encouraged and supported. A data-informed approach would enable nuanced, directed communication and public engagement strategies to help debunk quantum computing myths and potentially mitigate risks that may germinate from misinformation and conspiracy theories.

- Quantum computing stakeholders can seize current opportunities to encourage social media platforms and government public communications to build in mechanisms to safeguard against misinformation contagion.

- While recent reports (e.g. the *Quantum Technologies: Public Dialogue Report* published by the UK Research and Innovation Engineering and Physical Science Research Council)[7] have found there to be a lack of awareness and knowledge of quantum computing, there are also some indications of interest from the general public through targeted engagement initiatives such as Quantum Shorts by the Centre for Quantum Technologies[8] and The BIG Bell Test citizen science experiment.[9] Using this and similar opportunities may contribute to a readiness among stakeholders to adopt quantum computing in their domains and industries.

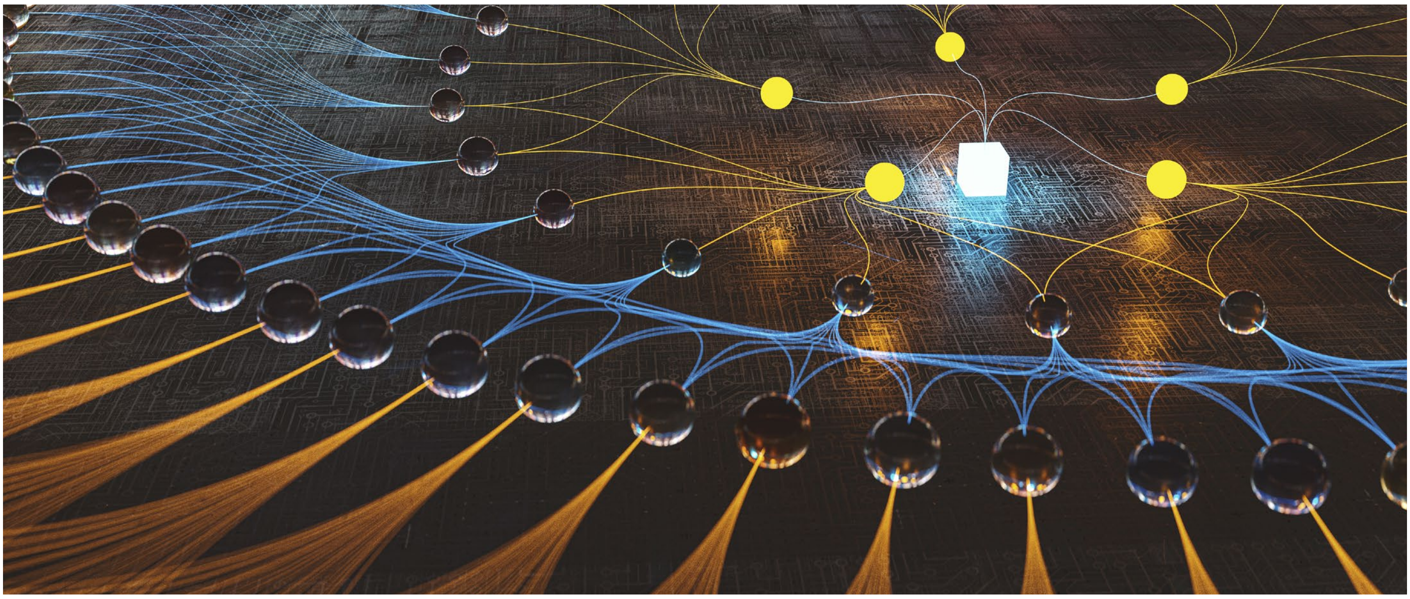
- There is an opportunity for quantum computing stakeholders to adopt learnings from successful science and technology public awareness campaigns connected to other technological innovations that have had wide societal impact.

- Training future-generation quantum scientists and engineers in science communication may support public trust and engagement in dialogue with quantum computing stakeholders.

- Open dialogue and engagement with the public about quantum computing may contribute to socially responsible and ethical development and use of quantum technologies, as an informed public may expect this technology to be used for the common good and public benefit.

- Efforts at proper communication could favour mutual, trusting discussions between the general public and the scientific field; this, in turn, could have an amplifying beneficial effect, ensuring the general public "trust the experts" to achieve broader social goals. At the same time, this would hinder unsustainable business models exploited by bad actors trying to maximize short-term profits through dishonest marketing at the expense of erosion of public trust.

- There is an opportunity to take deliberate action to encourage and facilitate collaboration and the sharing of diverse perspectives and opinions among different quantum computing stakeholders. Creating opportunities for engagement of this kind may help generate balanced dialogue and public knowledge in terms of the exchange of ideas, scientific facts and information about the scientific process behind the development of quantum computing.



Risks

– A lack of public engagement and awareness of quantum computing may hinder opportunities to increase knowledge and build trust between quantum computing stakeholders and the general population.

– Misinformation about quantum computing may create unwarranted fears. Given that knowledge about quantum computing and how it works is not (yet) widespread, misinformation may become prolific in the community. This may lead to unwarranted fears and scepticism.

– Protest groups may attempt to misrepresent quantum computing science and technology. Lessons can be learned from other technologies, such as the attacks on 5G mast towers in the UK,[10] the anti-vaccination movement and the attempted bombing of IBM's nanotechnology laboratory in Zurich in 2010.[11]

– Quantum science employees or quantum computing organizations may be at risk of reputational or physical harm from protests by anti-technology groups.

– A lack of public trust in, or understanding of, quantum computing may affect its uptake or funding in some sectors or communities.

– From an economic or investment perspective, hype around an asset or industry is potentially problematic. A large portion of investment in start-ups, new technologies or even existing assets is based on hype. Venture capital may, for example, be driven by hype to invest in a range of technologies, only some of which pay off – yet those that do pay off reap returns for investors and benefits for society at large. Quantum researchers naturally eschew hype because they tend to prefer rigour, but investment dynamics are not driven by the level of mathematical certainty or precision one expects in academia. Thus, quantum hype may in fact be an advantage or necessity to achieve widespread interest in the technology. However, in the long term, relying on hype to drive investment in quantum computing is more likely to do harm than lead to positive uptake.

– Hype may lead to an overreaction from policy-makers, possibly resulting in the nationalization of quantum computing developments and capabilities.

– There are significant risks that any public awareness efforts to dispel hype could, in fact, feed misinformation or underdeliver on the aim of increasing general knowledge. As raised in the opportunities and actions sections of this theme, awareness campaigns should be data-driven and informed by scientifically rigorous social science methods and science communication expertise. Unrealistic expectations of progress could lead to a perception of under-delivery, which could consequently restrict funding and lead to a slowing in the progression of quantum computing science and adoption, invoking a "quantum winter" (for example, as occurred in AI development on multiple occasions)[12,13]

– Individual actors from across the private and public science and innovation sectors benefit from hype, making it harder to dispel.

– Growing distrust in the usefulness of quantum computing can lead to underestimating risks in other areas, particularly in cybersecurity. For example, some stakeholders may be ambivalent about the capabilities and impact of quantum computing on existing technology, such as cryptography, which may have significant and detrimental future impacts on cybersecurity and privacy.

Principles

- Dialogue and communication about quantum computing should accommodate diversity in the general population's understanding and potential capacity to learn more about quantum computing and their motivations for engaging in quantum computing dialogue.

- Language and communication methods relating to quantum computing should be as widely accessible as possible and appropriate for the target audience.

- The language used in raising public awareness and the methods and content of communications should be transparent, responsible and not intentionally deceptive or unduly speculative.

- Public communication about quantum computing should be conducted by trusted experts or informed science communicators with the aim of building and engendering trust in the technology.

- Public communication about quantum computing should be based on scientific fact and represent both risks and benefits while being guided by the values of common good and non-maleficence.

Actions

- Encourage and direct the creation of public awareness guidelines and policies based on the core values of the Forum's Quantum Computing Governance Principles, especially inclusiveness, accessibility and transparency.

- Create opportunities for the general population to learn and engage in open and trusted dialogue about the potential uses and applications of quantum computing.

- Demonstrate the responsible, accessible and ethical use of quantum computing in use cases in public forums to promote the technology and encourage public trust.

- Incentivize responsible language and scientific factualism in public communications about quantum computing, especially for spokespeople and science communicators, and discourage the adoption of unscientific or overhyped language.

- Establish forums and opportunities for open dialogue between journalists and media organizations and quantum computing experts. This dialogue would aim to encourage and support responsible media representations of quantum computing, and enable trusted partnerships between experts and the media.

- Manage the expectations of the general population and other stakeholders in terms of the capabilities, limitations and potential future opportunities of quantum computing.

- Ensure public dialogue and communication is balanced in presenting and discussing both the potential risks and the benefits of quantum computing.

- Create and facilitate opportunities for different quantum computing stakeholders to engage in diverse, open and trusting dialogue with other groups, e.g. among stakeholders from different sectors; between members of the general population and quantum computing experts or informed science communicators; and between quantum computing enthusiasts and pessimists.

- Design and conduct social science surveys, focus groups and interviews with the quantum computing stakeholder community to ensure an objective and data-informed approach to public awareness guidelines, policies and other interventions aimed at generating science-based, accessible information in the public domain about quantum technology.

Theme 5

Workforce development and capability-building

Goal

Build and sustain a quantum-ready workforce.

Opportunities

- There is a need to increase the understanding of how quantum-adjacent industries will be affected by the technology and use that insight to develop appropriate training programmes and educational pathways for current and future workforces affected by the potential changes.

- Various levels of knowledge are needed, ranging from those who are part of the development of quantum computing to those who will be affected by this technology and who might want to understand it at a level relative to their function. In addition to quantum physicists, the future quantum workforce will comprise quantum engineers, technicians, computer scientists and professionals with backgrounds in areas such as product management, marketing, sales, business and communications.

- There is an opportunity for public-private partnerships to develop and redesign interdisciplinary STEM education for young people and offer reskilling or development programmes for the current workforce.

- Greater collaboration is required between industry and academia in developing post-secondary quantum computing education programmes to suit future industry workforce needs.

- A national quantum education programme should be developed.

- Public-private collaborations would be of benefit on quantum computing education and professional development, specifically addressing the diversity imbalance.

Risks

- Lack of a trained quantum workforce could lead to missed job opportunities and lack of interdisciplinary dialogue on both the development and application of quantum computing.

- Lack of diversity in development of the quantum workforce is to be avoided.

- There is difficulty in transitioning the current workforce to a quantum workforce, from both a technical and mindset perspective.

- There is also difficulty in understanding the full impact of quantum computing as the technology evolves and use cases and applications are still being discovered and/or validated.

- Lack of equitable access to quantum computing education is a risk.

Principles

- Schemes to develop the quantum workforce should be created.

- Education should address the present and future impacts of quantum computing on society and incorporate responsible innovation values.

- Cooperation between industry, governments and academia should be encouraged to ensure education is accurate and standardized without compromising scientific integrity.

- Different methods of learning should be respected, addressed and accommodated.

- Education should be easily accessible.

- Education should begin with the youngest citizens.

Actions

Workforce development:

- Educate and train leaders and decision-makers involved in quantum computing on responsible innovation values to ensure technology is developed fairly and in ways that preserve human rights.
- Ensure that organizations developing or adopting quantum computing technology provide free and easy access to education for their workforces that addresses the impact of this technology on their personal and professional lives.
- Develop and run nationwide schemes to upskill for jobs developing and using quantum computers, as well as writing quantum software.
- Incentivize private corporations to participate in upskilling partnerships.

Capability-building:

- Establish quantum computing courses in secondary-school curricula (including basic lessons about what quantum computing is, what it is capable of and the basics of quantum programming).
- Train the trainers: create outreach campaigns for secondary-school teachers.
- Incorporate education about applying and identifying the potential impacts of quantum computing into non-scientific postgraduate programmes in disciplines such as business, law and public administration.
- Develop globally accepted and/or accredited coursework and materials for further education.
- Establish a global, trusted platform on which the public can access free educational resources on quantum computing with the assurance that the information it contains is not overhyped, incorrect or self-serving.
- Create public and private funding opportunities for diverse groups of students and researchers.
- Establish scholarship schemes promoting diverse access to quantum computing (interdisciplinary access, under-represented minorities, emerging economies).

Theme 6

Cybersecurity

Goal

A transition to a quantum-secure digital world.

Opportunities

- This is the right time to be proactive to address cybersecurity issues due to advanced quantum algorithms.
- There is a need to address the impact of quantum computing on cybersecurity from all perspectives, as the technology evolves.
- Migration to cryptographic agility and a quantum-resistant digital infrastructure may be an opportunity to also amend existing suboptimal cybersecurity solutions, from which current infrastructures suffer extensively.
- Increasing awareness and upgrades in information security could increase confidence in online transactions and help digital and economic growth.
- There is an opportunity to consider network engineering from a new perspective to address cybersecurity requirements. This has to be in line with the approach of future quantum communication technologies.

Risks

- Attacks may be made on communications by intercepting messages in transit – which are generally exchanged using quantum-vulnerable solutions – decrypting them and accessing the content.
- Attacks may be made on data stored in the cloud by breaking currently deployed public-key encryption schemes.
- Validation and authorization mechanisms could break down due to quantum computing, since they rely on existing encryption methods, e.g. it would become possible to break the integrity of digital signatures and entities and enable forgeries and impersonations.
- Destabilization of governance protocols in emerging infrastructures such as blockchain networks relying on proof of work (e.g. Grover's algorithm providing a potential advantage for mining) or other consensus mechanisms (by attacking the authentication layer) could occur.
- Malicious development of quantum computing capabilities can happen "in the dark", enabling attacks that cannot be immediately detected.
- Without quantum-resistant security solutions, all regulations and laws regarding privacy, data management etc. would be impossible to uphold.
- An unharmonized transition to a quantum-secure world could lead to a "balkanization" of digital infrastructures due to, for example, incompatible standards.
- Advances in quantum error-correction technology could reach a "breaking point", at which point scaling up the quantum memory necessary to mount quantum attacks suddenly becomes much easier.
- Quantum superposition attacks might pose an immediate threat to certain cryptographic solutions traditionally considered resilient to such attacks, such as hash functions or block ciphers.

Principles

- International standards and scientific research should be relied on to develop and evaluate quantum-resistant solutions.

- The development of open quantum-resistant algorithms and protocols should be promoted and encouraged.

- Quantum computing stakeholders should be mindful of the evolving proliferation of cyber risks posed by quantum computers.

- Stakeholders should promote and encourage the adoption of future-ready cryptographic solutions through crypto-agility, where cryptographic algorithms can be seamlessly changed in a plug-and-play fashion to resist attacks by quantum computers.

Actions

- Incentivize security research, hacking and discovery.

- Prioritize the adoption of quantum-resistant cybersecurity.

- Create strong systematic awareness programmes about the potential risks to cybersecurity with business, government and institutional leaders.

- Make assets in public and immutable ledgers (e.g. blockchain networks) protected with cryptography quantum-secure as a matter of urgency.

- Secure communications using quantum-resistant solutions, following guidelines set by standards organizations.

- Enable quantum-native telecom infrastructures using quantum random number generator (QRNG) and quantum key distribution (QKD) protocols, quantum memories and quantum repeaters.

Theme 7

Privacy

Goal

Mitigate potential data privacy violations through theft and processing by quantum computers.

Opportunities

There are opportunities to:

- Increase individual awareness about the threats to data privacy posed by quantum computers in order to prepare them for the quantum era.

- Prevent quantum communication networks from allowing certain parties to access personal data or personally identifiable information (PII), as happens with some existing classical networks.

- Improve the protection of personal data with quantum-secure encryption to prevent data breaches by quantum computers.

- Develop quantum-secure protocols and mechanisms to protect emerging large databases of sensitive personal data including genomic and biometric data.

- Develop regulatory policies to ensure personal data protection in the quantum era.

Risks

- There is a risk of hacking of data in transit and data stored containing personal data or PII that is not protected with quantum-secure cryptography by exploiting cyberthreats posed by quantum computers.
- Another risk is the ability to run powerful data analysis algorithms to forecast, infer or induct unconsented or unauthorized information from datasets containing personal or PII information by combining quantum computers with other technologies such as AI.
- The technology could be used by authoritarian regimes or powerful organizations to expand surveillance, encroach on privacy or violate civil liberties.

Principles

- Stakeholders should be aware of the impact of cyber risks posed by the advent of quantum computers in breaking encryption standards currently used to protect PII.
- Stakeholders should be cognisant of the risk of quantum computers being used to infer personal information about individuals or populations without their explicit consent, and of this being done more efficiently than current state-of-the-art technology.
- With regard to the collection and storage of PII, stakeholders should be mindful of the likelihood that enhanced quantum processing may render current data privacy techniques ineffective.
- The protection of the individual should be the first priority when deploying quantum-resistant infrastructures.

Actions

- Embed privacy-preserving techniques into the design of digital solutions, including protection with quantum-resistant cryptography, and anonymization and de-identification techniques.
- Implement post-quantum cryptographic standards as soon as possible, e.g. National Institute of Standards and Technology (NIST) standards.
- Raise public awareness about the urgency of the quantum cybersecurity threat to personal data.
- Provide detailed information about how data will be stored and processed, how it is safeguarded from attacks by quantum computers, how it will be managed and its intended use.
- Ensure that sensitive data is properly protected immediately to prevent its future decryption and release.
- Make sure current regulations allow for the fact that that quantum computing may unlock potentially privacy-violating insights from very large datasets that were previously assumed to be impossible to access based on the capabilities of classical computers.
- Bolster research into mitigation techniques to prevent quantum computing from enhancing opaqueness of predictive models and algorithmic biases.
- Put in place governance and regulations around the growing collection and analysis of human genomic data, given the long lifetime value of such data and the potential incentives for bad actors to exploit the technology.
- Reassess and strengthen anonymizing and de-identifying techniques for datasets that contain personally identifiable data to protect it from attacks by quantum computers.
- Prevent quantum-resilient infrastructures from allowing certain parties to access personal identifiable data using quantum computers.

Theme 8

Standardization

Goal

Promote standards and road-mapping mechanisms to accelerate the development of the technology.

Opportunities

There is an opportunity to introduce:

- Common standards and benchmarks to ease adoption and acceptance of quantum computing technologies.
- Open standards to accelerate the development of quantum computing technologies and applications that benefit from quantum advantages.
- Shared standards to enable clear descriptions of the performance and behaviours expected of quantum computing technology to a broad audience.
- Common benchmarking methods to enable clear communication of the performances observed from quantum computing technologies by different stakeholders.
- Common languages and architectures to support the development and adoption of quantum technologies by diverse communities.
- Public roadmaps to chart the progress in quantum computing technology and establish a record of demonstrated milestones towards practical applications.
- Coordinated efforts in standardization, benchmarks and roadmaps to integrate diverse communities of stakeholders in defining the development of quantum computing technologies.
- Public standards and roadmaps to enable governments, large corporations and research institutions to prioritize investments in quantum computing technology development.
- Common, open standards and roadmaps to train the next generation of quantum computing workforces.
- Open, shared roadmaps, benchmarks and standards to support growth of the “quantum supply chains” for software and hardware.

Risks

- A lack of common and shared goals, metrics, standards and roadmaps may slow down the development of quantum computing technology.
- Rigid or premature standardization efforts may be self-limiting during a phase of research and exploratory development for quantum computing technology.
- Early benchmarks may not be readily tested or may be biased towards available systems.
- Uncertainties in roadmapping may endorse speculation or bias expectations during a critical exploratory phase of quantum technology.
- Although competing interests among the major stakeholders and technology developers may prevent bias, this could also potentially introduce bias in standardization and roadmap efforts.

Principles

- Common definitions and terminology for different quantum computing technology features, usage and purpose should be promoted.
- The sharing of methods, procedures, uses and purposes of early quantum computing technology to enable growth and awareness should be encouraged.
- Quantitative benchmarks and indicators that measure value, growth and improvement of different quantum computing technologies should be used and defined.
- Stakeholders should continuously improve terminology, definitions and benchmarks as quantum computing technologies develop and new ones arise.

Actions

- Establish standardization efforts that are diversified based on different quantum computing technology readiness levels.
- Establish benchmarks that are clearly motivated and delineated by purpose and limited to well-defined use cases specified in clear and common language.
- Establish roadmaps tied to well-defined metrics that can be tested and evaluated using reliable and reproducible techniques.
- Openly communicate peer-reviewed scientific studies and benchmark results to justify the merits of standards and roadmaps.
- Engage a broad range of disciplines through educational resources, online courses and academic programmes that target STEM, social sciences, ethics and law studies.

Theme 9

Sustainability

Goal

Develop a sustainable future with and for quantum computing technology.

Opportunities

- Quantum computing can potentially help to solve some of the grand challenges of climate change (e.g. carbon capturing, more efficient energy storage or better catalysts).
- Climate modelling could be made more reliable and more efficient using quantum computing.
- Computational efficiency of quantum computing for certain problems could greatly reduce energy consumption (for quantum computing there is no known metric yet to quantify energy consumed per computation).
- More efficient electricity distribution could be achieved together with, for example, renewable energy sources (grid optimization).

Risks

- Resources required to build quantum computers might include rare earth metals.
- There may be a shortage of certain materials needed to build/operate quantum computers (e.g. Helium-3 [^{3}He] for cooling).
- The fabrication/manufacturing of materials/resources and chips for quantum computers might pose certain risks to the environment.
- The energy costs of operating a quantum computer could be higher due to the need for higher cooling, peripheral electronics etc. (for quantum computing there is no known metric yet to quantify energy consumed per computation).

Principles

- The acceleration in the use of quantum computing for new applications in global sustainability should be prioritized (e.g. governments should put preferential funding into these applications immediately).
- The use of quantum computing in environmental monitoring should be enabled.
- Use of scarce materials and resources for the development and operation of quantum computers should be discouraged, especially where it does not hinder development of the technology overall.
- The use and benefits of quantum computing should be aligned with the 17 United Nations SDGs and the Intergovernmental Panel on Climate Change (IPCC).

Actions

- Put preferential funding into research on quantum computing applications, with the aim of tackling problems related to global sustainability or climate change.
- Fund research into quantum computing technologies that do not require scarce materials.
- Fund research into novel methods of material synthesis and chip fabrication.
- Establish an energy consumption metric (in the near future for a known problem) to allow comparison with current energy costs for high-performance computing (HPC).

Conclusion

These guidelines represent the first milestone in this project of establishing governance principles for quantum computing and should be reviewed as the technology and its applications mature.

The development of this technology, and the surrounding discourse, are both in the early stages. Quantum computing has been able to profit from knowledge generated during the discovery of semiconductor technology. Likewise, these principles are also able to benefit from learnings that have stemmed from the implementation of other new technologies, such as AI. Nonetheless, as outlined above, it is crucial to keep the discourse on the governance principles of quantum computing distinct from discussions relating to classical computing technologies. To ensure the effective adoption of this technology, it is strongly recommended that stakeholders commit to adopting these principles as they prepare to participate in the advancement or application of quantum computing technologies. If quantum computing is to have a positive impact on humanity, strong cooperation between industry actors, policy-makers, academics and civil society representatives is required.

The next step in this project is to work with stakeholders to adopt these principles as part of the governance and policy underpinning the development of the technology. The safe, ethical and responsible use of quantum computing should be included in regulatory frameworks, sector-based codes of practice and organization-level policies. Furthermore, the adoption of the principles should also be institutionalized and incentivized by all quantum computing stakeholders.

As part of this effort, the principles formulated in this document will be assessed and particular attention will be paid to their potential in terms of effective adoption, completeness and relevance. Tools and frameworks will be developed to help companies and governments build responsible governance models and create collaborations with businesses, academia, non-profits, governments and individuals to develop and deploy responsible governance approaches. These efforts are geared at establishing communities of practice that promote the safe, ethical and responsible development and use of quantum computing, upholding a culture of common good in the quantum computing community. Furthermore, collaboration with existing international and national governance and regulatory bodies is encouraged on this topic to achieve effective implementation of these principles.

Importantly, the principles are also a call to action. In addition to engaging in critical reflection, discussion and refinement of the principles, it is imperative that they are implemented. We encourage all stakeholders to join us on this journey to ensure that this framework has an impact.

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Endnotes

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