World Economic Forum

State of Quantum Computing: Building a Quantum Economy

INSIGHT REPORT

SEPTEMBER 2022

Images: Getty Images, Unsplash

Contents

Preface 3

Executive summary 4

Introduction 5

1 Quantum computing: a rapidly growing economy 8

1.1 Global initiatives and public financing 10

1.2 Private financing 12

2 What can and will quantum computing do? 17

2.1 A new set of computing possibilities 18

2.2 Key sectors for high-impact applications 20

3 State of technology 26

3.1 Critical components for quantum computer operation 27

3.2 How developed are quantum computers? Are there many? 28

3.3 Which quantum computer is best? 30

3.4 What hardware is needed to run applications 35

4 Unlocking technology potential 36

4.1 Workforce availability and development/training 37

4.2 Policies and regulations 39

4.3 Standardization in developing algorithms and performance measurements 40

Conclusion 42

Contributors 43

Appendix 44

Endnotes 45

Preface

Derek O'Halloran
Head, Shaping the Future of Digital Economy and New Value Creation;
Member, Executive Committee,
World Economic Forum

Quantum computing is seen as a strategic technology by the world's leading economies. This fundamentally new way of computing – it is not just a stronger classical computer – has the potential to dramatically recast our ability to tackle climate change, hunger and disease. For many, its potential to render common cryptographic technologies obsolete, its economic potential and its impact on global digital economy make it geopolitically strategic.

Today, however, the combination of uncertainties that come with an emerging technology and a rapidly moving but fragmented landscape make it difficult for decision-makers across the private and public sectors to maintain awareness, build understanding or know when and how to act.

This report aims to give a holistic and neutral overview of the current state of play in quantum computing – the technology, its applications, the state of the emerging industry and key components of a successful quantum ecosystem. It aims to provide an accessible baseline of information for business executives and policy-makers worldwide, to support informed opinion and fact-based decision-making. The report seeks to avoid both over-excited hype and the downplaying of the potential impact of quantum computing.

Quantum technologies rebuild computing from the 1s and 0s up – replacing the "bit". Knowing the science behind turning on a light switch is not necessary to understand the transformational impact of electricity on societies. At the same time, the basic concepts and language of electricity no longer feel exotic or even scary. This document attempts to demystify quantum computing and build functional literacy among industry and government leaders and influencers.

The insights shared in the paper are brought to light by the World Economic Forum's Global Future Council on Quantum Computing. Thanks to Council's work, quantum computing becomes accessible and enjoyable to read about. Most importantly, it enables everyone to learn new ideas and start considering how quantum computing will impact their walk of life.

Executive summary

Quantum computing is real, and organizations need to take notice now.

Quantum technologies refer to a range of technologies based on our growing ability to see and control reality on a subatomic ("quantum") level to build sensors and an entirely new form of computing and communications. Quantum technologies are rapidly maturing, with an ever-growing number of governments and businesses launching strategic initiatives and collectively investing more than $35.5 billion across multiple continents.[1] Today, the technology is still in the research and development and demonstration phase, making it hard to predict exact time horizons and applications – leading to various beliefs and bets in the market.

This report focuses on the computing aspect, where the unique capabilities of quantum computers open the potential for tackling complex computation problems that, as a result of fundamental limitations in scaling classical computation, would be intractable with classical computing methods and unlocking new possibilities that have not yet been considered. Consequently, many expect that the impact of quantum computing will be as foundationally transformative as the onset of classical computing in the mid-20th century. It also comes with risks, as quantum computers are expected to break the encryption used to secure modern digital communications, blockchain and some cryptocurrencies.

It is important to note that quantum computing is expected to work best across three specific domains of research and industry, with significant economic, environmental and societal opportunities associated with them:

1. Molecular simulation and discovery in materials science and biology

2. Optimization and risk management in complex systems

3. A bi-directional impact on existing technology areas such as AI, security and blockchain.

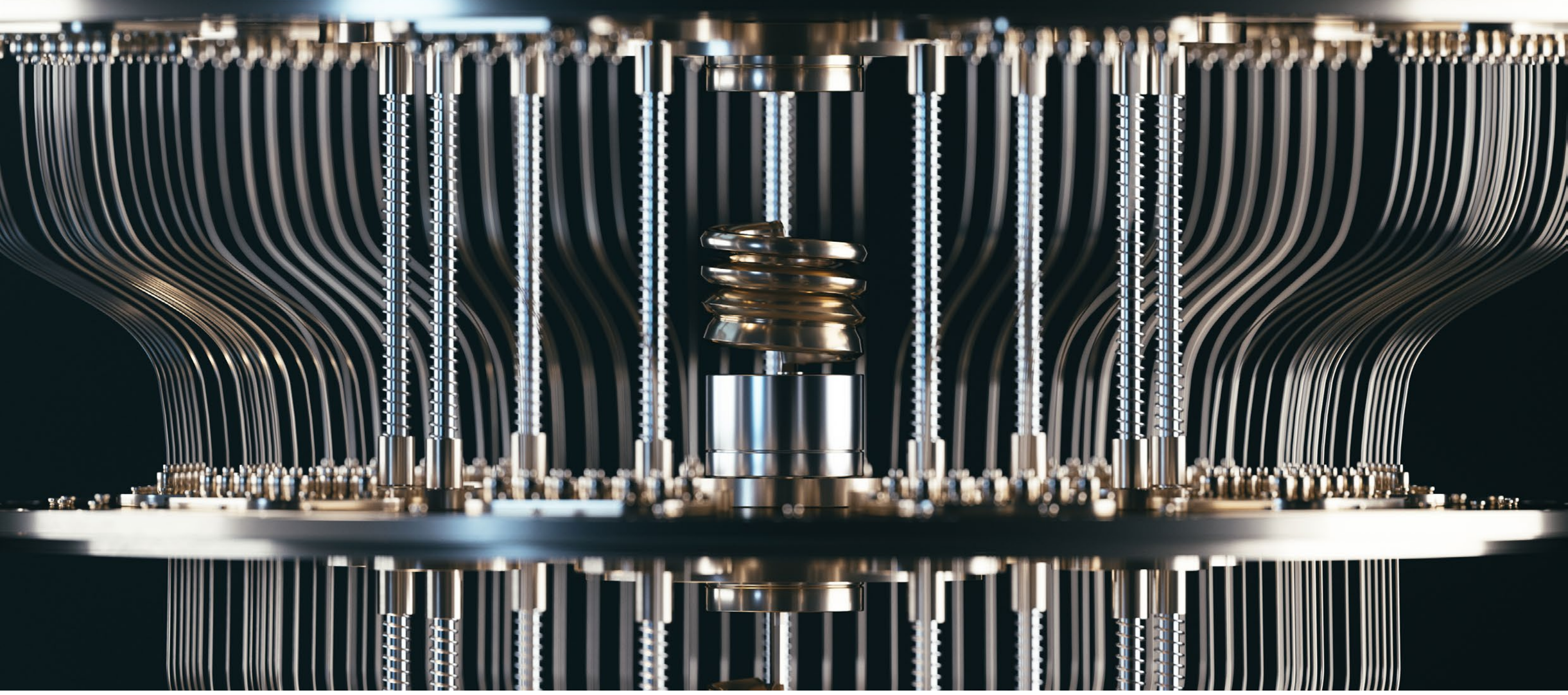
All in all, quantum computing is positioned to complement classical computing and be applied to certain tasks outside the reach of today's supercomputers, carving out its powerful computational niche that didn't exist before, eventually expanding modern research and development and business horizons.

Most quantum applications with provable advantage over classical methods (including breaking encryption) will require a large-scale quantum computer to realize. Different hardware platforms for quantum computing are currently being pursued internationally, at various stages of development and technical achievements. Yet, no platform has reached the required scale, speed and quality of computation to demonstrate an advantage over classical computers in a practical, real-life application. Moreover, it is too early to say which platform will be the first to reach the needed scale, quality or when.

At the same time, today's imperfect quantum computers are suitable to run a subset of applications where a precise answer is not required and seeing trends or a likely direction is more important. This, coupled with cloud access now offered by many quantum computing providers, has allowed many more organizations to start experimenting with quantum applications. Given rapid technological developments, it is only a matter of time before an application that provides a real advantage with the available quantum technology is found. When this occurs, and what application can make best use of the available computational resources is the name of the game.

While these activities receive a lot of attention, the current quantum computing achievements and future development rely on several enablers: workforce readiness, standardization and policy. Workforce availability is the critical bottleneck.

Despite uncertainty over when quantum computers will be ready at scale, governments and businesses must act now, as quantum security risks and business opportunities cannot be ignored. This is a unique moment in modern history where everyone can prepare for the technology as it is being shaped and matured. Governments and academia can further work on scaling quantum workforce programmes and building national ecosystems, incentivizing partnerships. For example, an excellent first step for businesses is to understand quantum computing's impact on business and industry, assess their quantum readiness and formulate a quantum strategy, build internal capabilities, and align with top management and policy-makers on critical focus areas.

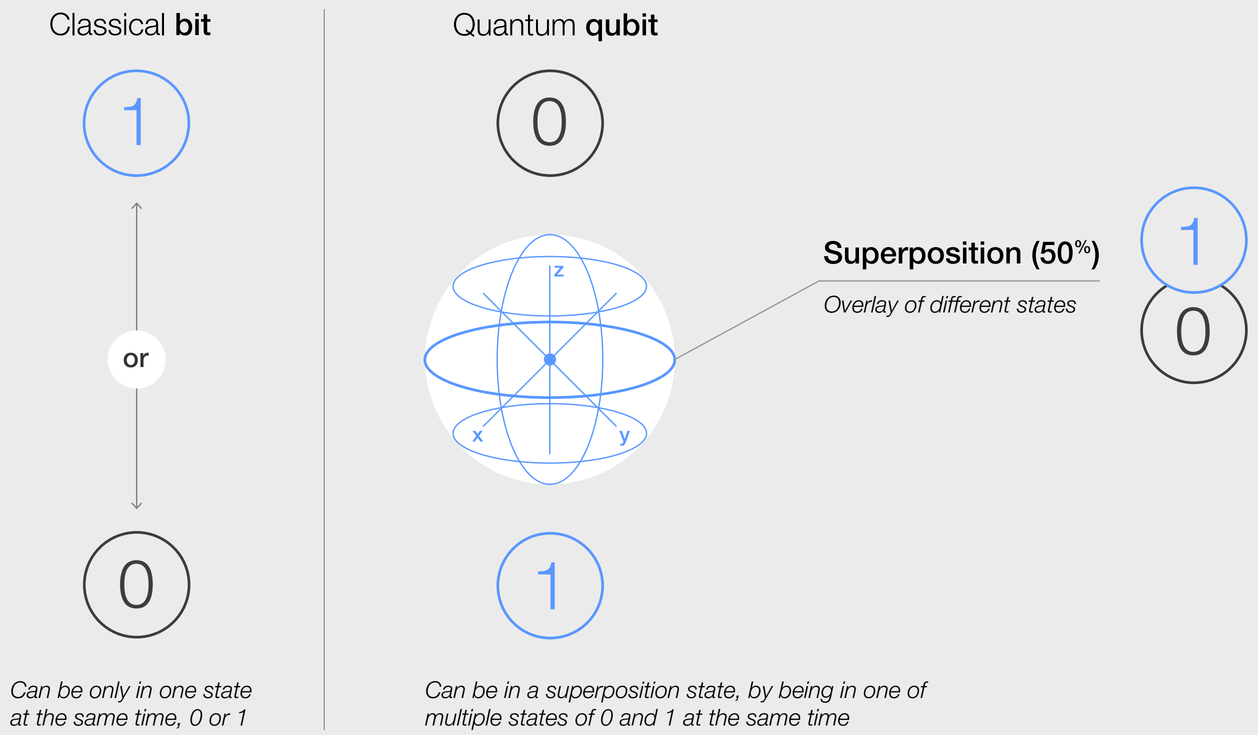


Introduction

Hype around quantum computing has created unrealistic assumptions about the technology, but in reality, it is far from maturity.

Whereas classical computers are built from bits (1s and 0s), the basic unit of information in quantum computing is a quantum bit (or "qubit"). A "bit" is like a gate in an electronic circuit that can be either on or off, whereas a qubit uses the unique properties of quantum mechanics to provide a unit that can be one or zero – or anything in between. The rules from quantum mechanics include operations not found in the classical realm, such as superposition, entanglement and interference. By designing algorithms that take advantage of these effects, there is a path towards the solution of problems that otherwise might require large classical computing resources.

FIGURE 1 **Classical vs quantum computer**



Each chapter of this report offers an understanding of the baseline (current status) of quantum technology, what the targets are and estimates how far from realization they are.

Quantum computers manipulate the quantum properties of qubits to solve problems that are too difficult for classical computers, e.g. factoring large numbers for potentially breaking RSA encryption. The mere mentioning of these possibilities, given their unseen potential, makes the public and media anxious. The complexity of the quantum theory on which quantum computers are built only raises the expectations – and fear. If quantum computers can do things that modern computers can't, they can do anything; from resolving the climate crisis to breaking the internet. With frequent announcements from big companies like Google, IBM or Microsoft reaching quantum advantage or achieving a breakthrough with a new type of qubit,[2] the technology seems to be just around the corner. Yet, it is critical to have a more nuanced view of the excitement.

Each chapter of this report offers an understanding of the baseline (current status) of quantum technology, what the targets are and estimates how far from realization they are. Despite a multitude of technology developments, quantum computing is still in unchartered territory, with many unknowns in the hardware and the applications space, including the critical question: when will the first quantum advantage application be seen? This is when the technology will start having a real impact. Is it achievable with today's imperfect computers, or is it still a long way off?

This report offers guidance in four areas:

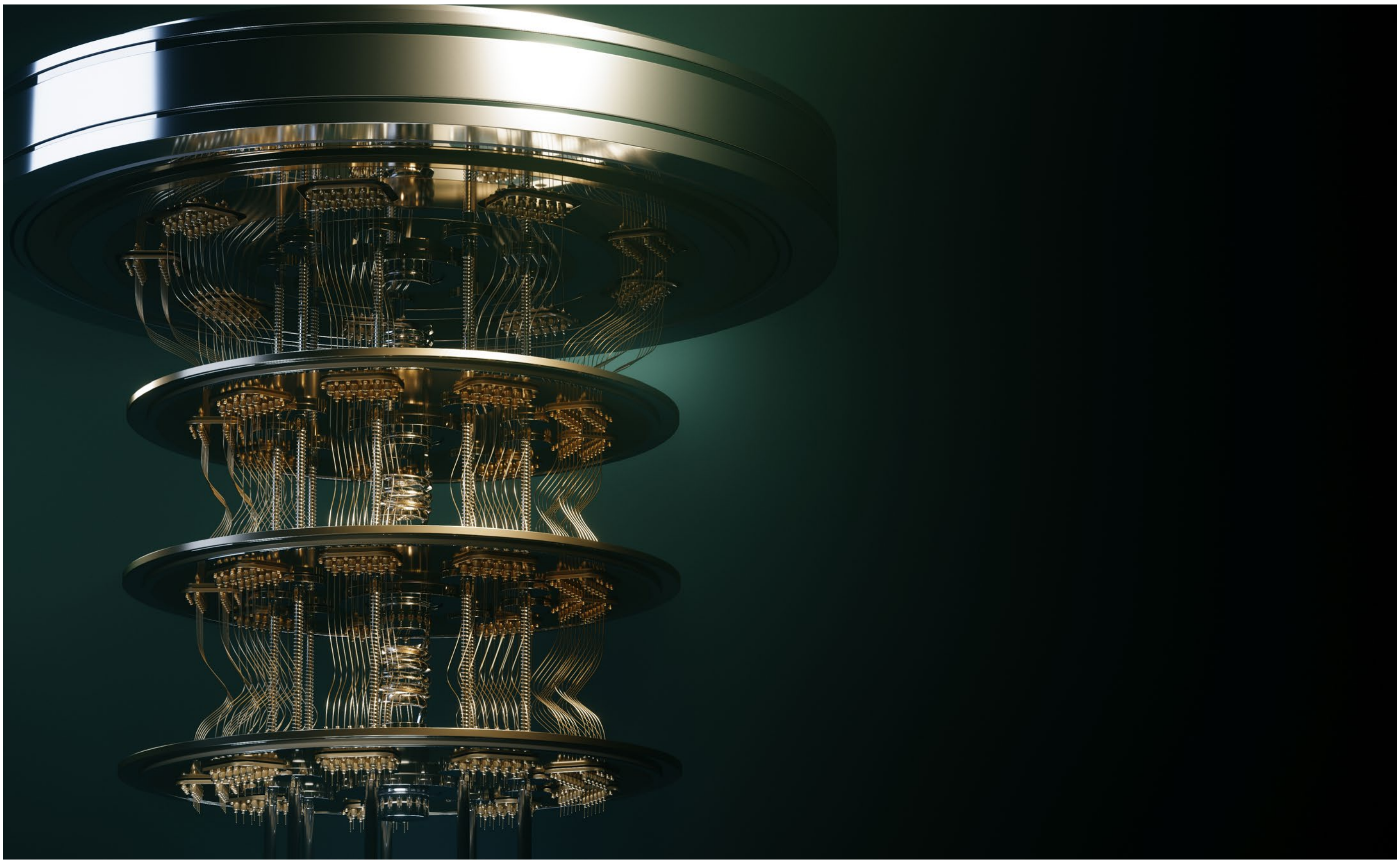
Chapter 1 looks at the current level of funding, industry growth and national interest in quantum technology. Where is money coming from? What are the highest growing areas? Which countries are taking this technology seriously, having developed a quantum strategy?

Chapter 2 examines the potential of quantum computing. What can it do now? What will it be able to do? Although the promise is great, use cases are concentrated within a few industries. The technology is also not a silver bullet for the climate crisis, despite its potential to offer a great deal of help.

Chapter 3 provides an overview of existing approaches to building a quantum computer – against a simple, original model. It sheds light on what it will take for quantum computers to be ready, why they are not there yet, why it is so hard to predict which approach (and organization) will be first to develop a useful quantum computer, and when it will happen. Lastly, the chapter touches on the link between the maturity of quantum computers and their ability to run quantum applications – and break today's encryption.

Chapter 4 examines whether quantum ecosystems have all the necessary enablers to support innovation. What is the limiting factor for any organization that wants to explore quantum computing applications? Why is it so difficult to find the right quantum computing provider to partner with?

The hype around quantum computing is real, and this report is a guiding light to help companies jump-start their quantum journeys.



Do you speak quantum? Top 12 concepts to know

Below are some key terms and definitions that will become familiar over the course of this report.

1. **Quantum technologies**: Any technology that uses the principles of quantum physics, including quantum computing, medical devices, highly-sensitive sensors, secure communications, atomic clocks, etc. Quantum computing is a subset of quantum technologies.

2. **Quantum computing (QC)**: A new approach to computation that exploits the nature of storing and manipulating quantum information.

3. **Qubit**: A quantum bit, a unit of information storage in quantum computing fundamentally different to a classical "bit" that can hold a linear superposition of states, meaning it can be zero and one at the same time, but upon measurement, reveal either zero or one with a defined probability distribution.

4. **Hardware platforms**: Various approaches to building a quantum computer based on different ways to create and control the quantum properties of a qubit. Depending on an underlying physical principle, all hardware platforms will have unique characteristics, affecting their speed, scalability, quality of computation or integration with existing technologies (e.g. silicon chips).

5. **Quantum noise**: Noise in the quantum computation process caused by undesirable external and internal factors that might lead to errors in the computation.

6. **Quantum error correction (QEC)**: A computing technique for dealing with errors in quantum computers that exploits encoding across extra (large) number of qubits to reduce errors rates.

7. **Noisy intermediate-scale quantum (NISQ) devices**: NISQ is a commonly used term to describe today's quantum computers, which are "noisy" (i.e. prone to errors, which can accumulate and lead to incorrect computation) and are of intermediate-scale (i.e. these devices have tens to hundreds of qubits).

8. **Quantum circuit**: A sequence of quantum operations applied on multiple qubits. It is an ordered sequence of quantum gates, measurements and resets, forming the basis of quantum algorithms.

9. **Quantum algorithm:** A collection of quantum circuits to run on a quantum computer to find a solution to a problem. Quantum algorithms are the engines of quantum applications. One algorithm can be the basis of multiple applications in different industries.

10. **Quantum advantage:** A stage when a quantum computer can solve certain problems cheaper, faster and more accurately than classical computing.

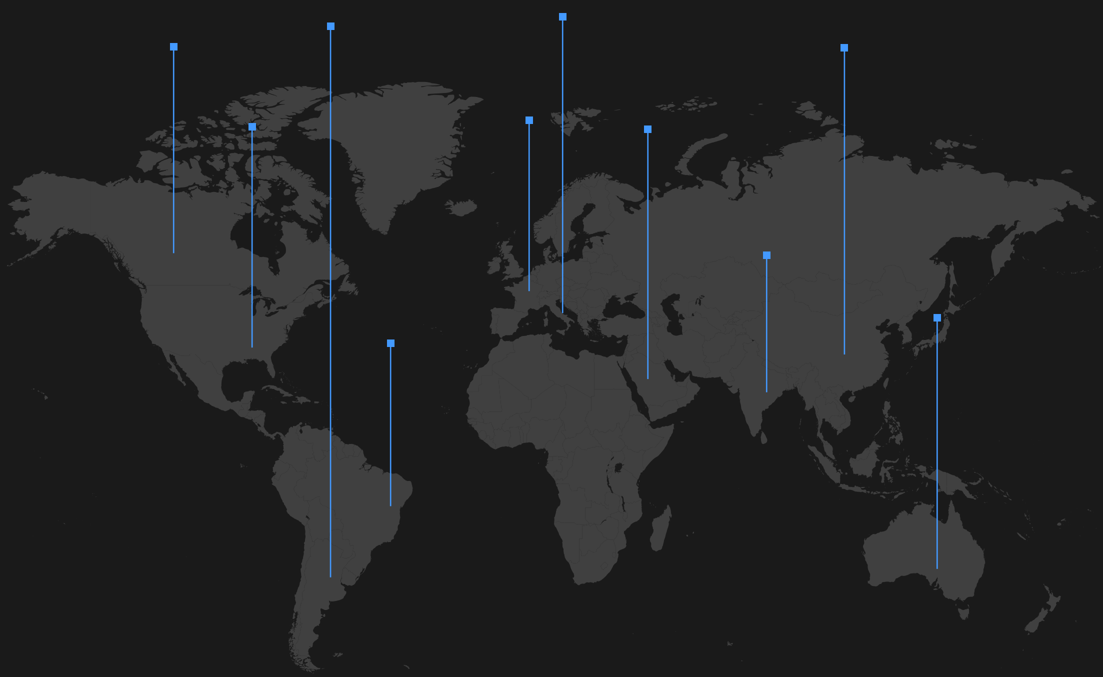
11. **Post-quantum cryptography (PQC)**: Cryptographic algorithms thought to be secure against attacks by quantum computers.

12. **Quantum readiness**: The ability of a business or organization to familiarize and prepare to run applications and gain an advantage when quantum computing hardware is more mature.

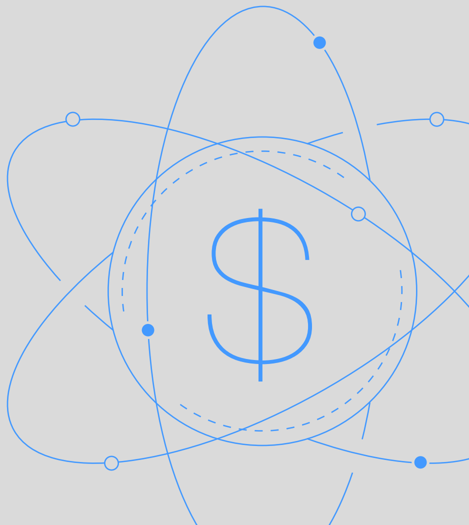
1 Quantum computing: a rapidly growing economy

In light of hefty public and private investments, both established and start-up companies from all over the world see the accelerated momentum with technology development.

Quantum computing activities can be seen in every continent, with major flagship initiatives materializing across most G20 countries.



Private investment is growing rapidly – and shifting from venture capital to initial public offerings marking sector's growing maturity.



$35.5 billion

Public and private investments totalled $35.5 billion by 2022 across a range of quantum technologies.

Countries with leading quantum R&D clusters from around the globe have made strategic investments to capture part of the future quantum computing supply chain.

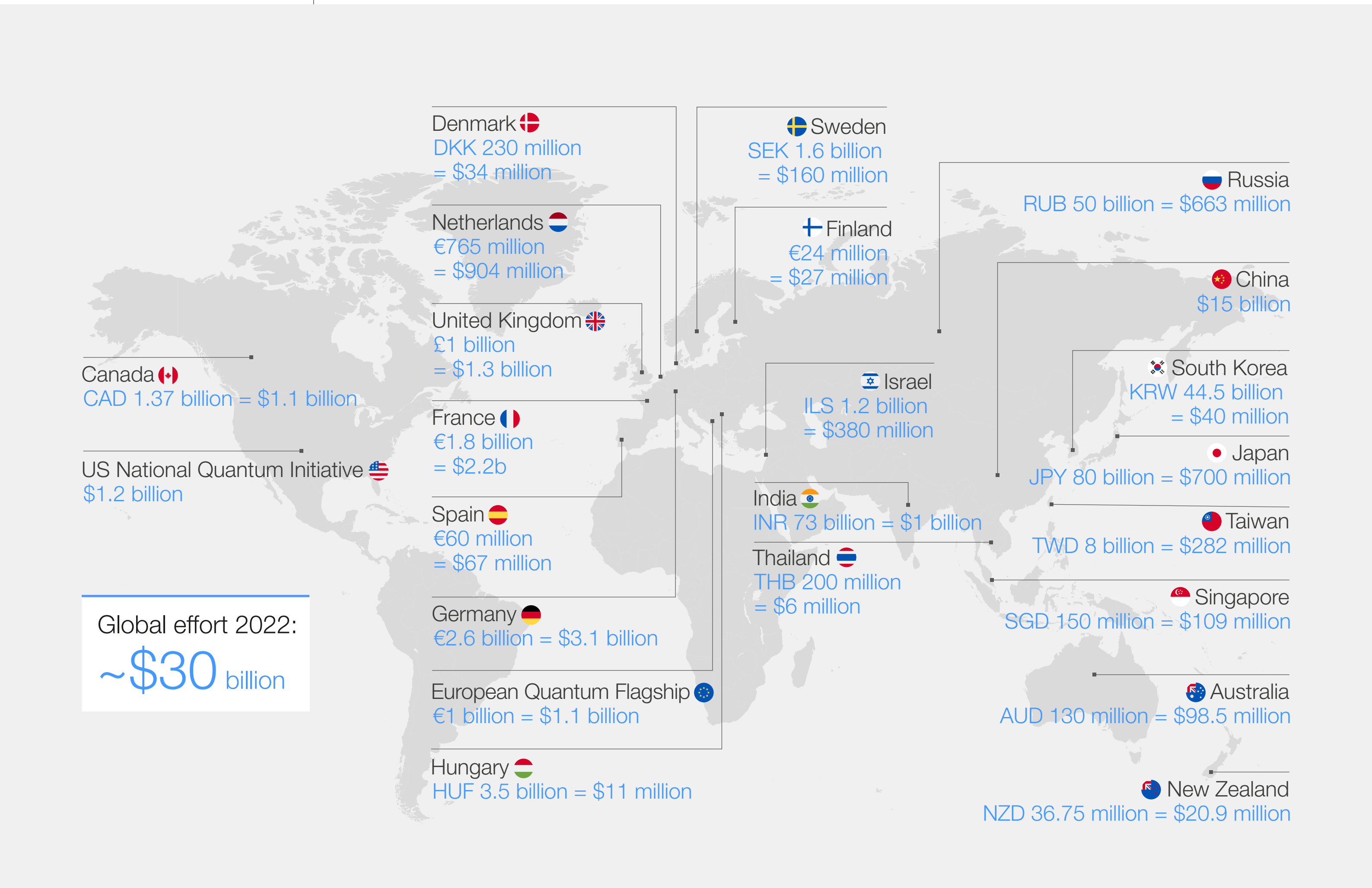
The development of quantum computing technologies today is a global endeavour. All continents are home to companies and governments actively supporting the creation of new, quantum-powered computing solutions. Countries with leading quantum R&D clusters from around the globe have made strategic investments to capture part of the future quantum computing supply chain and create strategic and independent access to future capabilities.

These multi-billion-dollar investments fuel technological advances. According to the latest research, public investments in quantum technologies exceed $30 billion (see Figure 1). Private investments for quantum technologies added $3.2 billion in 2021 alone and over $5.5 billion in the past decade.[3] It is important to note that these numbers are underestimations since not all public investment is captured due to national security concerns and what is tracked and reported in various regions. While some large companies have private and public funds, a few heavily support their quantum efforts from corporate R&D funds. As with public investments, corporate R&D funds are typically not captured by the private investments described above.

The hefty mix of public and private investments has sparked a diverse constellation of companies to develop quantum computers or key building blocks. At the beginning of 2022, 46 companies worldwide were actively developing quantum computing hardware.[4] A growing number of start-ups are entering the scene and attracting funding from investors worldwide. As a result, today's early-stage quantum computers work with a wide variety of hardware platforms in different stages of development. These include superconducting qubits, neutral atoms, trapped ions, photonic qubits and silicon-based qubits.

These different quantum computing flavours reflect a dynamic and rapidly evolving technology sector. Significant milestones have been reported from different corners of the planet: the first quantum processor was made available to everyone through the cloud access in 2016,[5] in 2019 the achievement of quantum supremacy was claimed,[6] whereby the quantum processor realized in a matter of minutes a complex calculation that would take the world's most powerful computer system at the time two days to process. Improvements in the error rates for qubit control and reliable read-out have continued to be a part of the R&D landscape, as well as critical breakthroughs in scaling.

FIGURE 2 **Map of global public investments in quantum technologies**



Source: QURECA, 2022

1.1 Global initiatives and public financing

Asia, North America, Europe and Australia have very different innovation ecosystems. Consequently, national governments follow different pathways in the quantum computing journey. The United States established a national programme in 2019, the National Quantum Initiative Act,[7] to support the development of all quantum technologies. This includes the founding of the Quantum Economic Development Consortium (QED-C) to support the development of a quantum supply chain with the goal and mission to support the future quantum industry. Canada and its provinces continue to work to evolve their national- and provincial-level strategies.

In Europe, national and regional initiatives have been launched to spearhead the development of quantum computing solutions. The UK, the Netherlands, Germany and France have developed national quantum programmes and strategies, with total public support of over $7 billion.[8] The European Commission has also established a separate $1.1 billion research and innovation initiative known as the EU Quantum Flagship, which is dedicated to developing and commercializing quantum technologies in the European Union. Within the EU, quantum computing is prominent and developed in collaboration with European efforts on high-performance computing. There are also initiatives in addition to existing research centres and clusters of excellence in quantum technologies, e.g. Quantum Delta NL in the Netherlands, a dedicated legal entity that governs all related public investments in technology.

In line with these investments, the European industry has also started to coalesce to accelerate the development of commercial quantum solutions. One example is the European Quantum Industry Consortium (QuIC). This pan-European organization brings together start-ups, small and medium enterprises (SMEs), large companies, investors, research and technology organisations, and other associations. At national levels, several other industry associations have also been formed, such as Le Lab Quantique (France), the Danish Quantum Community (Denmark), the Finnish Institute Q and UK Quantum (United Kingdom).

Asia has had a long and growing effort across the quantum landscape. Singapore's focused effort in quantum information dates back to the early 2000s. This was followed by a significant effort in China that initially focused on quantum communications but now includes a large focus on

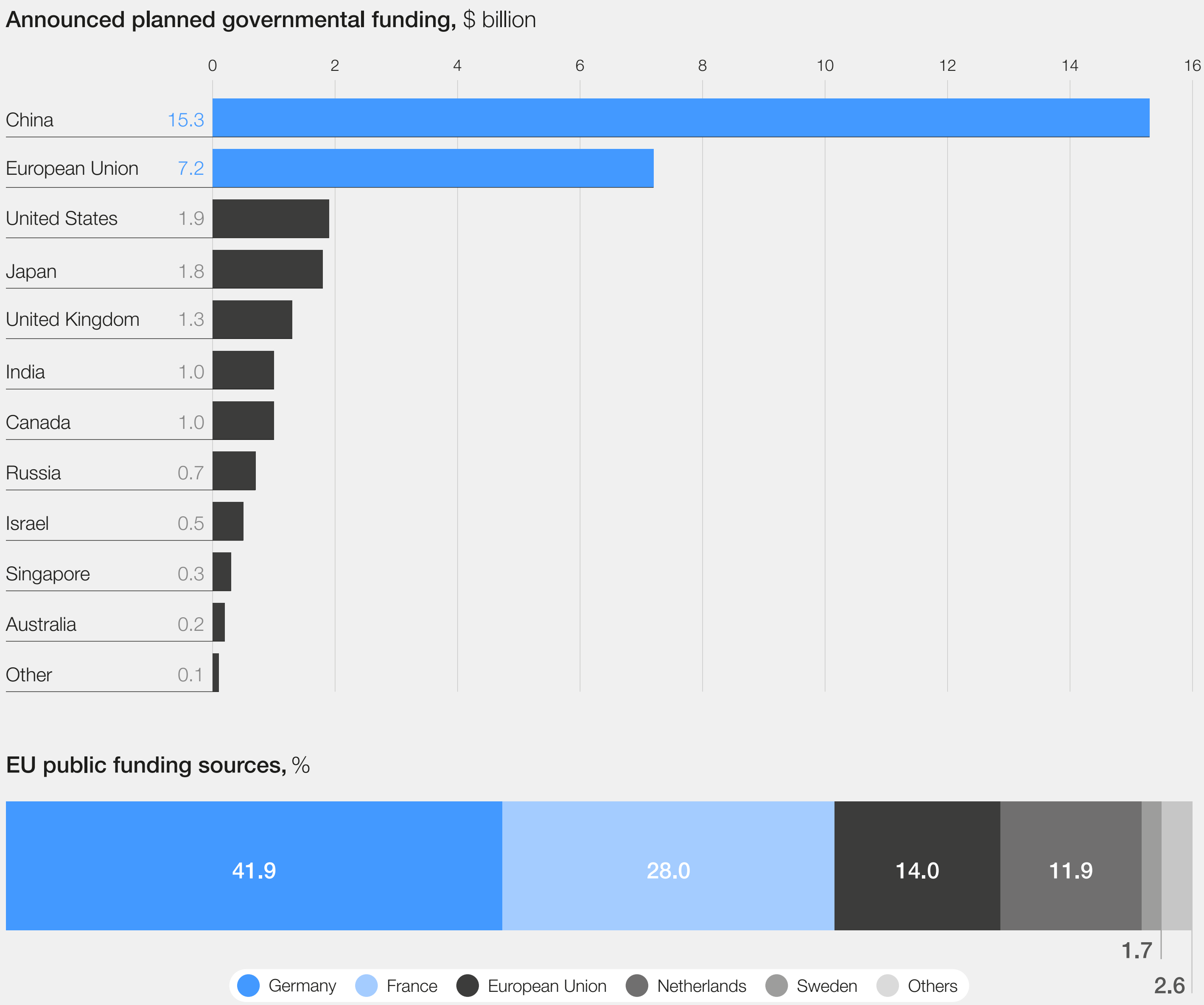
“ National governments follow different pathways in the quantum computing journey.

quantum computation. China's five-year plan was launched in 2016 and put quantum computing as a top priority for national technology sovereignty. During the past ten years, China invested more than $1 billion in quantum technology, with additional investments of $150 million in a start-up fund.[9] Longer-term plans include up to $15 billion of public investments.[10] Efforts in China are believed to be quite large, but no publicly available figure exists. Beginning in 2019, Japan and South Korea created formal quantum strategies; both developed efforts to build quantum computers and access quantum computers through the cloud on hardware created by other companies. Early in 2022, India announced a plan to spend more than $1 billion over the next five years to support the development of quantum technologies, including an effort to build a small prototype quantum computer by 2026.

Australia houses world-class quantum research facilities and expertise established over two decades of sustained research and investment. In 2020, the nation announced its national quantum industry roadmap and, in 2021, a new Quantum Commercialisation Hub to establish strategic partnerships with like-minded countries to commercialize Australia's quantum research. The development of a national quantum strategy to outline Australia's vision for its quantum industry is currently underway.

Numerous activities are underway in other parts of the world, where the quantum ecosystem is lagging in terms of funding and technology. Such initiatives include regional chapters from One Quantum, Quantum Leap Africa, QWorld and events such as Quantum Latino and Quantum Eastern Europe.

FIGURE 3 **China and European Union lead significantly on public funding for quantum computing**



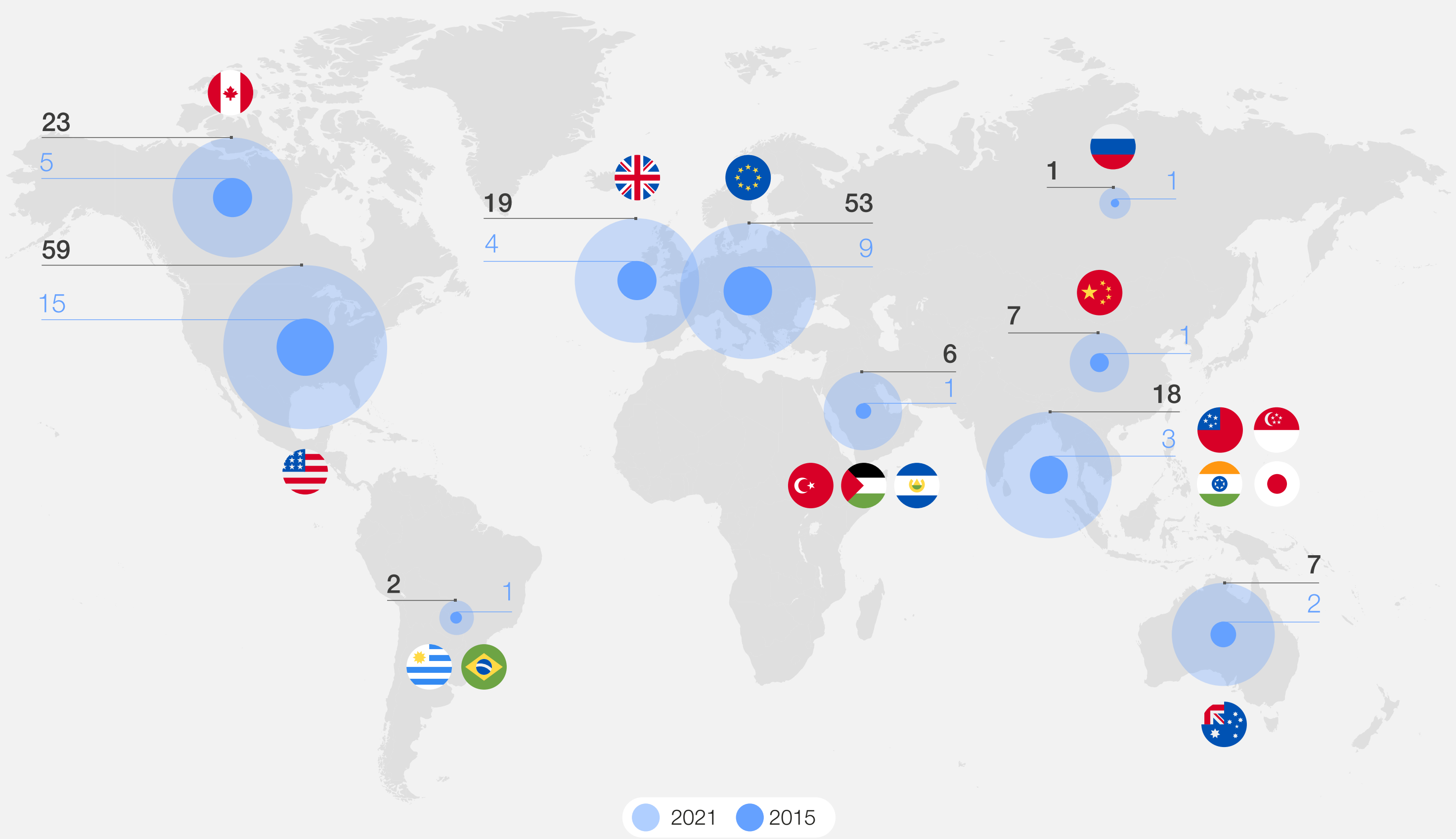
Source: McKinsey & Company, adapted from Johnny Kung and Muriam Fancy, 2021

1.2 Private financing

Private financing has enabled the rise in quantum computing start-ups.

The first commercial special-purpose quantum computing company was founded in 1999, and thirteen years later, the first quantum computing software company was founded.[11] Since then, 196 start-ups globally have been established.[12] Figure 4 shows the rise in quantum computing start-ups globally since 2015. The growth in private companies has been enabled by private financing. Figure 5 shows that the amount of private financing and the number of quantum computing start-ups have grown rapidly in tandem.

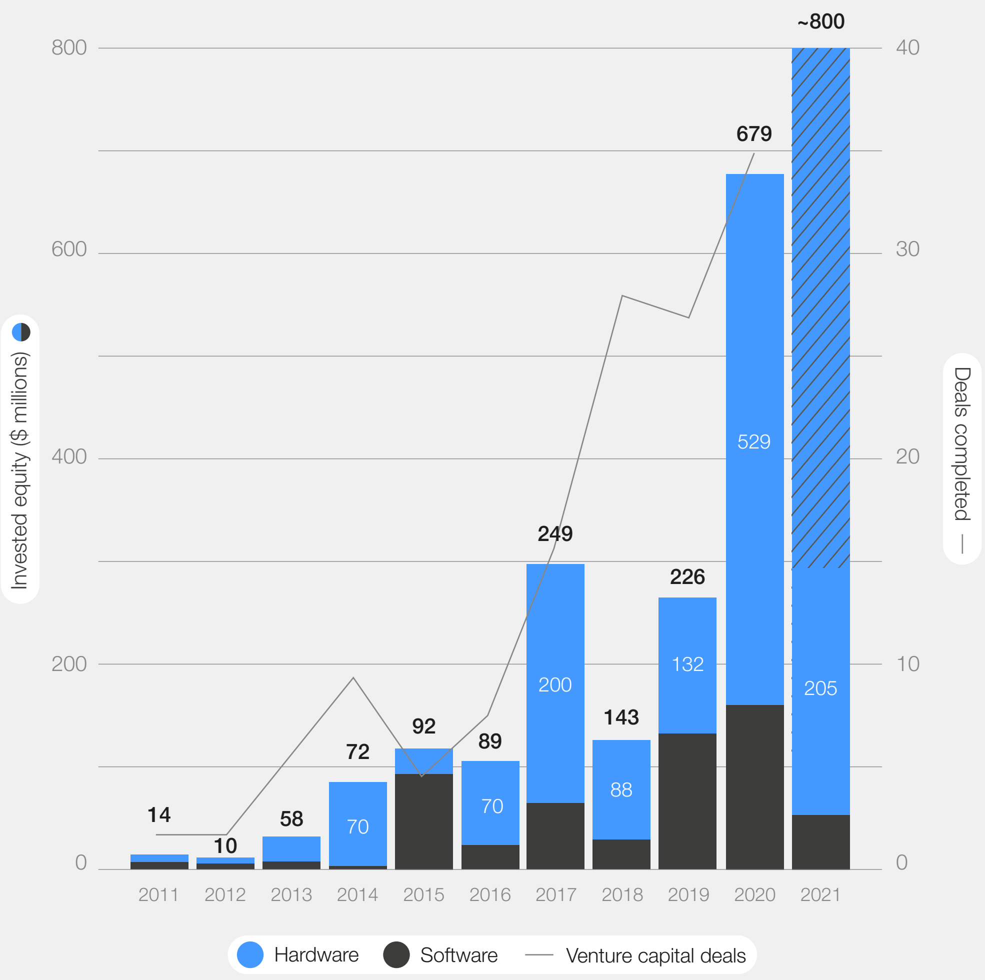
FIGURE 4 **Map of start-ups in quantum computing**



Note: Not exhaustive

Source: McKinsey & Company, adapted from PitchBook, 2021, World Economic Forum analysis

FIGURE 5 **More than two-thirds of equity investments in quantum computing have been made since 2018**



Source: Boston Consulting Group, adapted from PitchBook, 2021

2/3

of all equity investments (~$1.3 billion) have come since 2018

$800 million

Equity investments could have reached a single-year record in 2021 (estimation)

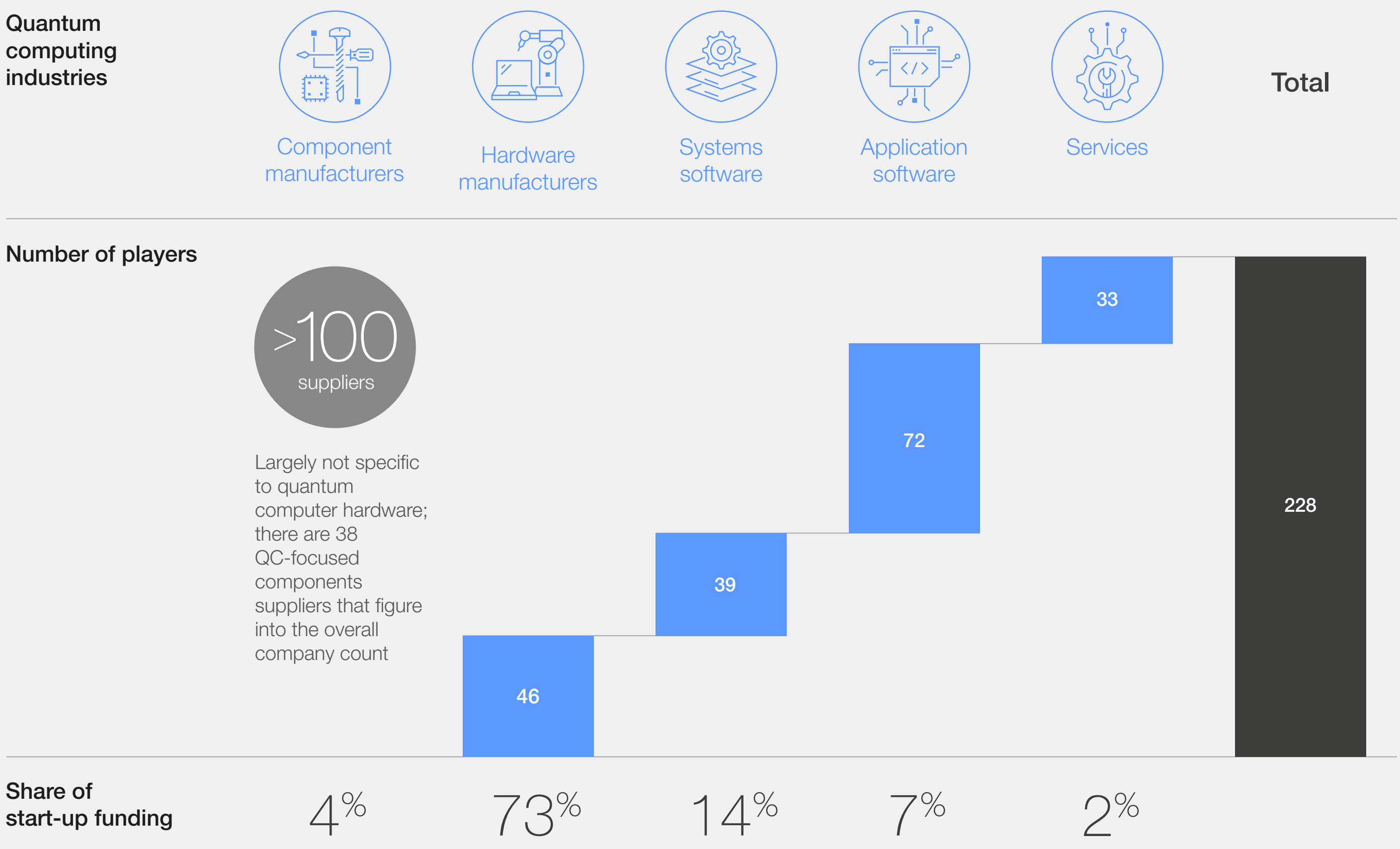
73%

of investments since 2018 have been in hardware

Where the private financing is going

In 2020, more than 90% of this investment went to hardware players. Yet, the number of software and algorithm start-ups is growing faster than hardware start-ups. This can be explained by the massive capital investments needed to develop hardware and the expectation of many that, as in the current ICT economy, there can be a lot of value created in the application domain.

FIGURE 6 | **Share of start-up funding**



Source: McKinsey & Company, adapted from CaptalIQ, Crunchbase, PitchBook, 2022

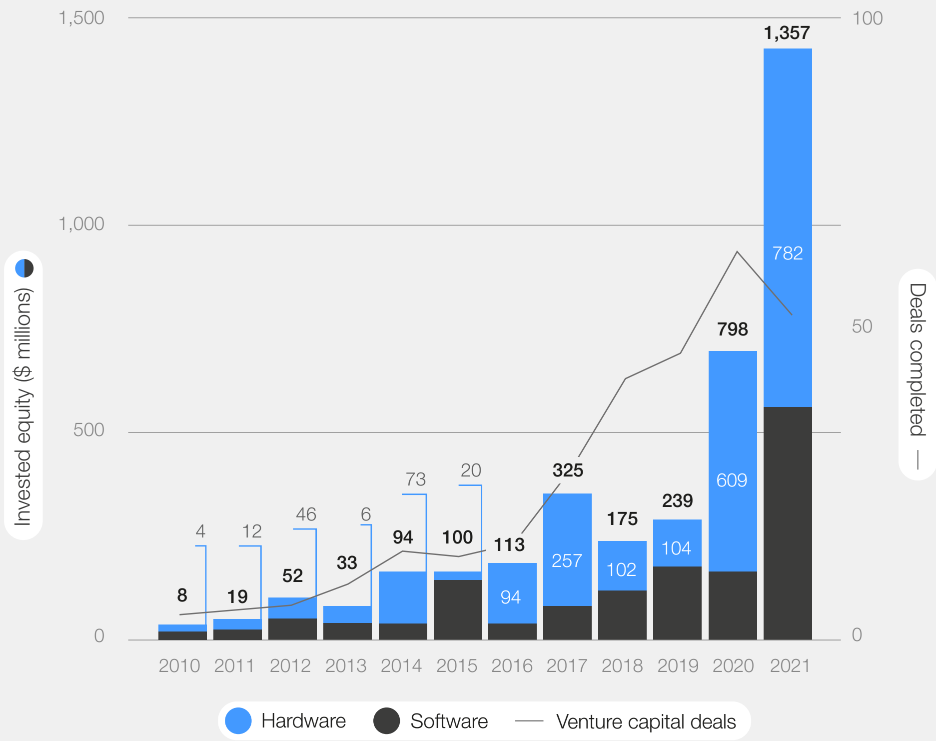
FIGURE 7 | **As capital investment in quantum computing rises, more money is focused on software**

$440 million

invested in software from 2010 to 2019

$764 million

invested in software from 2020 to 2021



Source: Boston Consulting Group, adapted from PitchBook, 2021

TABLE 1 | Notable private financing deals

Company and HQ	Deal date	Deal size ($ millions)	Select investors
Quantum Machines (quantum control) Tel Aviv, Israel	6 September 2021	50	Battery Ventures, Red Dot Capital Partners, Samsung NEXT Ventures, Valor Equity Partners
PsiQuantum (photonic QC) Palo Alto, US	27 July 2021	450	Baillie Gifford, BlackRock, M12, Temasek
Quantinuum (formerly Cambridge Quantum Computing) (quantum software) Cambridge, United Kingdom	8 June 2021*	300	Honeywell
Xanadu (various) Toronto, Canada	25 May 2021	100	Bessemer Venture Partners, Georgian, Tiger Global
Rigetti (superconducting QC) Berkeley, US	4 August 2020	79	Andreessen Horowitz, Battery Ventures, Bessemer Venture Partners, DCVC
IonQ (ion traps QC) College Park, US	16 June 2021	62	Airbus Ventures, Amazon Web Services, Mubadala
IQM Quantum Computers (superconducting QC) Espoo, Finland	22 July 2022	128	World Fund
Oxford Quantum Circuits Reading, United Kingdom	5 July 2022	46	Lansdowne Partners, The University of Tokyo Edge Capital Partners

Note: *Date announced

Source: Temkin, 2021, Honeywell, 2021, World Economic Forum analysis

Companies shifting from private financing to IPOs, mergers and acquisitions, and new start-ups

Several quantum computing companies have completed an initial public offering (IPO) through special purpose acquisition companies (SPACs). SPACs allow these quantum computing companies to circumvent the IPO process, saving them time, money and reducing regulatory oversight (see Table 2).

TABLE 2 **Quantum computing SPAC deals**

Company	Exchange	SPAC	Announcement date	Proceeds
IonQ	New York Stock Exchange	SPAC dMY Technology Group, Inc III	8 March 2021	$636 million
Rigetti[13]	NASDAQ	SPAC Supernova Partners Acquisition Company II	6 October 2021	$261.75 million
Arqit[14]	NASDAQ	Centricus Acquisition Corp	12 May 2021	$70 million
D-Wave[15]	New York Stock Exchange	DPCM Capital	8 February 2022	$9 million (after redemptions)

Source: SEC Filings, World Economic Forum, Global Future Council on Quantum Computing analysis

IonQ was the first quantum computing company to do this, becoming the "first publicly traded, pure-play quantum computing company".[16] They chose were followed shortly by Rigetti, Arqit and D-Wave, although it remains to be seen whether this strategy stays as all four companies are trading below the initial pricing points, with some losing up to 50% value.[17]

Following the Honeywell investment in Cambridge Quantum Computing, in June 2021, Honeywell Quantum Systems merged with Cambridge Quantum Systems to form Quantinuum in late 2021. In an earlier deal, on 25 May 20021 Quantum Benchmark was acquired by Keysight Technologies.[18]

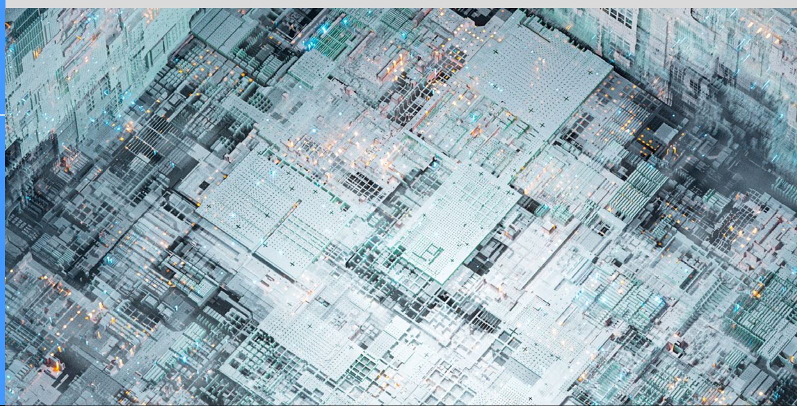
Recent mergers and acquisitions have also been observed in Europe. In 2021 Zurich Instruments was acquired by the German technology group Rohde & Schwarz.[19] In January 2022, the Dutch Qu&Co merged with Pasqal.[20] A few months later, the Danish QDevil became part of Quantum Machines.[21] Additionally, many young start-ups came out of stealth and experienced steep growth trajectories fuelled by venture capital and European Investment Bank investments.

2 What can and will quantum computing do?

Quantum computing is a complementary technology offering transformational impact in materials science, biology, complex systems and affecting security, blockchain and AI.

Quantum computing can tackle new mathematical problems, resembling how nature works at the atomic and subatomic scale.

These problems correspond to game-changing applications across basic science and the industries based on them.



One significant risk to manage is cybersecurity; at scale, quantum computing will break today's encryption methods.

2.1 A new set of computing possibilities

According to popular perception, quantum computers will be faster computers. This is not necessarily true, however, as quantum computing will have strengths and weaknesses compared with digital computing. Given the nature of how computation is consumed, it will naturally co-exist with rather than replace classical computing.

BOX 1 Classical computers will keep most of their tasks

Classical computers are expected to stay alongside quantum ones, to support quantum computing processing workflow (e.g. running quantum circuits) in hybrid data centres, and to continue powering daily tasks for which quantum computers are either not suited (e.g. copying data), or do not provide any meaningful advantage over existing computers (e.g. browsing the internet, reading emails, etc.). In other words, if an application does not require quantum circuits to run, it will likely continue to be run by classical computers.

The rebuild of computing from "bits up" opens the door to tackling new types of problems that are not feasible through classical computing. Quantum computing can tackle certain classes of mathematical problems, which correspond to specific problem statements in the world.

For example, quantum computers have the provable potential to factor large numbers, a mathematical problem so challenging that it is used to encrypt data transfers, exponentially faster than classical computers. The most straightforward corresponding application of this ability is breaking RSA encryption, which is the foundation of the majority of today's secure data-transfer methods.

Key types of mathematical and physical problems that quantum computers are expected to address exceptionally well include **quantum simulation**, **optimization, quantum linear algebra and prime factorization**. The ability to solve these abstract problems (one by one or in combination) opens real-world opportunities in three broad areas (see Table 3):

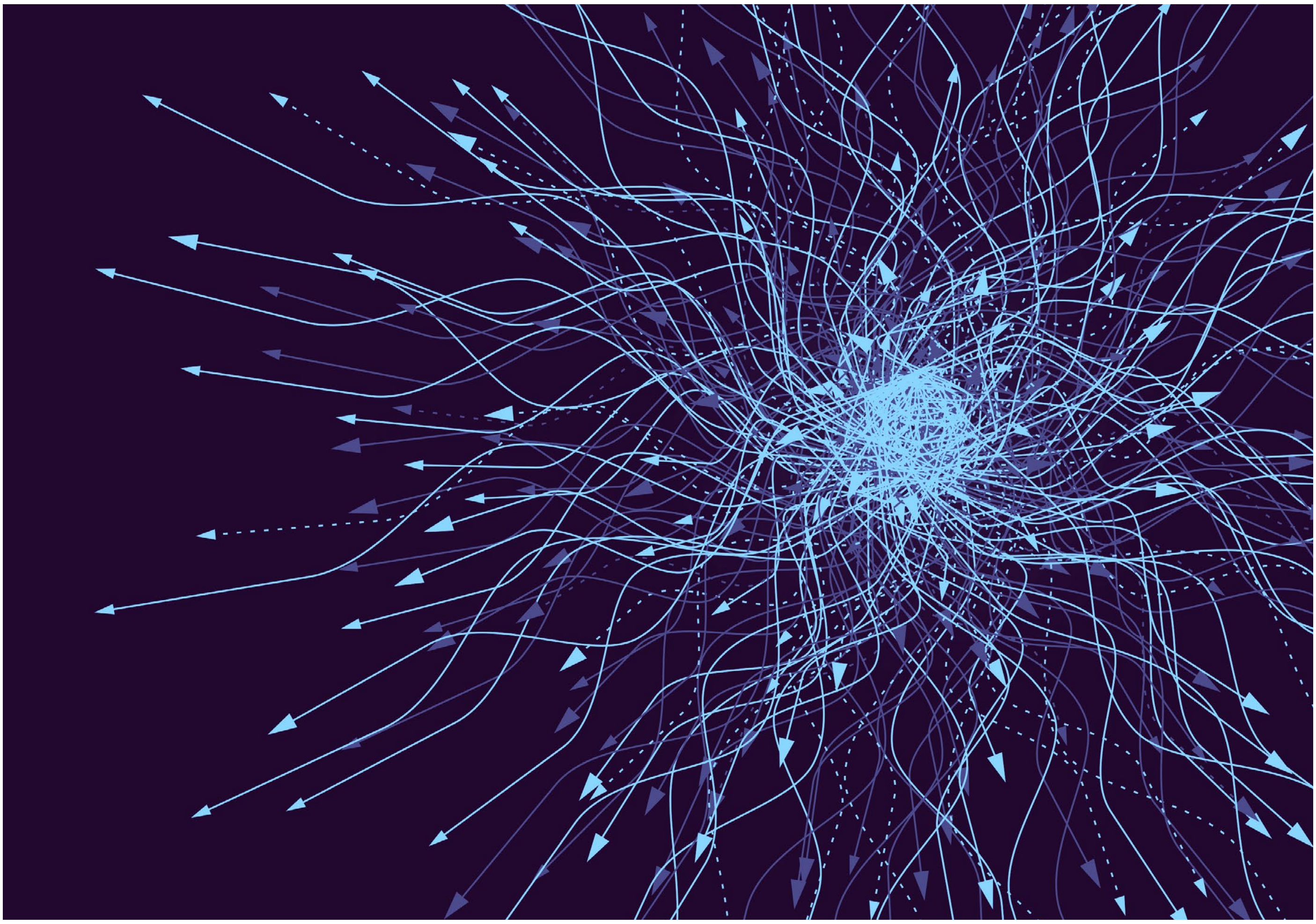


TABLE 3 | **Quantum computing areas of use**

Application domains	Materials science and biology	Complex systems	Existing technology and research
Affected industries	Energy, food and agriculture, manufacturing, chemicals, medicine.	Finance, transport and logistics, industries with complex products (aviation, automotive, etc.).	Industries with intense use of AI, blockchain or high-performance computing (HPC) in general, energy and materials industries, digital communications, defence and security.
Quantum computing use cases	Discovery and design of new molecules and materials, affecting multiple fields: advanced materials development, drug design, crops and fertilizers, green hydrogen catalysts, batteries, chemistry.	Management and optimization of sophisticated systems with a large number of variables or unknowns, from highly complex scheduling, logistical and supply chain challenges to modelling financial portfolios and risk profiles to assessing national defence strategies.	Impact on existing technologies such as AI, blockchain, as well as our scientific capabilities.
Social and environmental impacts	Reduced energy consumption, carbon capture, efficient materials and processes, more robust and nature-friendly crop variety, accelerated disease and response discovery, personalized medicine.	Reduced energy consumption and emissions across global networks, circular business models.	Breaks current cryptography, potential stronger cryptography with increased privacy and security. Accelerates exploration and discovery in fundamental science research. Alleviates peak computational load in combination with HPC.
Illustrative examples	Molecules with the right attributes to sequester carbon at scale. More naturally resilient grains to improve food production while avoiding monocultures.	Optimizing empty shipping container space yielding both environmental and economic gains. Improving real-time customer credit scoring.	The ability to accelerate training of machine learning algorithms. Breaking RSA and cryptocurrencies encryption. Contributing to our fundamental understanding of the quantum behaviour of nature.
Underlying quantum problems	Quantum simulation, optimization, quantum linear algebra and prime factorization.		

Source: World Economic Forum, Global Future Council on Quantum Computing

Quantum computing is based on the ability to 1) **create** and 2) **control** quantum circuits. To be effective in real-world deployment, this needs to happen 3) **at scale and with high quality and speed**. While different quantum computing development paths are at various stages of maturity, reaching appropriate scale, quality and speed to demonstrate impactful quantum advantage has yet to be realized. The current status is reviewed in further depth in the "State of Technology" section. As such, the applications in section 2.2 are based on a shared understanding of where this technology is naturally suited to have a major impact – based on the nature of the problem and the natural capabilities of quantum computing.

2.2 Key sectors for high-impact applications

Materials science – entering a new age of discovery

> [Quantum computers] could transform the way the climate, food and energy security, and health are managed.

Given the ability of quantum computers to simulate quantum interactions at the atomic and molecular level, problems well outside the scope of current computers have the potential to be solved, launching a new chapter of scientific discovery (in new materials, medicine, energy, biology) that could transform the way the climate, food and energy security, and health are managed.

Systems or processes, such as molecules, chemical reactions, nuclei or electrons in solids, are quantum mechanical. Understanding the behaviour and properties of these processes is the central challenge in physics, chemistry and biology, and is the basis of advancement in pharmaceuticals, energy, agriculture and materials science.

Traditional experimental methods advance slowly. The exponentially large number of possible combinations of molecules that could produce the desired outcome – like an efficient and clean catalytic process for energy production – mean that the probability of finding new solutions in any given experiment is low, making the overall endeavour both slow and expensive.

The inability of conventional computers to precisely mimic quantum systems with more than just a few particles means computing has had constrained impact on these fields. Even the most advanced supercomputers would take centuries to model any of these problem statements.

The properties of atoms and molecules and their interactions are determined by quantum mechanics, making quantum computers naturally suited to model and dramatically accelerate discovery in these fields.

Advanced materials
New quantum computing capabilities open up the possibility of quantum-mechanical modelling systems, such as molecules, polymers and solids, at a different level of precision.

– For chemical-based industries, it becomes possible to identify the most effective molecular designs or structures to accomplish specific tasks and achieve required effects – before synthesizing a single molecule in the lab[22] – from new catalysts to new batteries (see below).

– For manufacturing and construction industries, extending the knowledge from molecules and compounds to materials will allow new alloys, fabrics and coatings to be designed with the desired characteristics of weight, durability and flexibility at a faster rate. This would pave the way to conscious industrial and customer products adhering to energy efficiency, safety, allergies or other constraints (e.g. zero-carbon cement clinker).

TotalEnergies and Quantinuum are using quantum computing algorithms to develop and deploy new carbon capture materials by simulating the behaviour of metal-organic frameworks, a task too difficult for modern supercomputers.[23]

Energy generation, storage and efficiency
The most direct application of materials science to the energy industry lies with the components of the energy system, allowing for the generation and storage of electricity, as well as with energy processes modelling and research. Additionally, some of the use cases promising significant improvements

[Quantum computers] could contribute to ongoing climate change efforts across industries.

in energy efficiency – all of which could contribute to ongoing climate change efforts across industries.

- Simulate perovskites to create **more efficient solar cells** that convert more solar energy into electricity. This can involve mimicking and learning from the natural photosynthesis process[24] occurring in plants that can be simulated with quantum computers.

- Design **novel batteries and energy storage systems**, accelerating quantum simulation of electrolyte, anode and cathode materials, and choosing the best options through optimization.

- Discover better catalysts – special chemical compounds accelerating chemical reactions that serve a defined purpose. Catalysts are key to:

  - Decreasing energy costs and speed of **green hydrogen** production

  - The viability and efficiency of **carbon sequestration** – a chemical reaction of extracting carbon dioxide out of the air (aka carbon capture).

- Model gas phase processes (thermal cracking, pyrolysis, combustion), leading to **more efficient generation and use of energy** in various processes and products.

Mercedes-Benz and PsiQuantum have recently shared research findings about the impact of quantum computing on the design of the batteries for electric vehicles, including lithium-ion batteries (most common), which suggests an order of magnitude speedup in computational runtime.[25]

Food production

Extending the logic of materials science to agriculture, everything has molecular structures, which makes quantum computing an essential tool for speeding up existing processes and solving some previously intractable (chemical) problems.

- Improve the **energy efficiency of fertilizer (ammonia) production**, which accounts for 1-2% of worldwide carbon dioxide emissions.[26] Due to its complexity, the molecule of ammonia cannot be modelled by any existing supercomputers. The only industrial process able to perform nitrogen fixation was developed in the 1900s, and it is still being used to produce ammonia despite its vast energy footprint. Similar to the carbon capture case, nitrogen fixation (ammonia production) can be modelled by future quantum computers. In doing so, researchers can also use quantum computers to mimic processes inside two existing bacteria that can carry out nitrogen fixation with low energy requirements – a task outside of the modelling capabilities of current computers.

- Novel **crop-protection chemicals** with the desired characteristics are more likely to be designed using quantum simulation and optimization tools, with a less significant carbon footprint and reduced side effects on plant growth.

The applicability of quantum computers to model the nitrogen fixation process has been explored in theoretical proof-of-concept by ETH Zurich and Microsoft.[27]

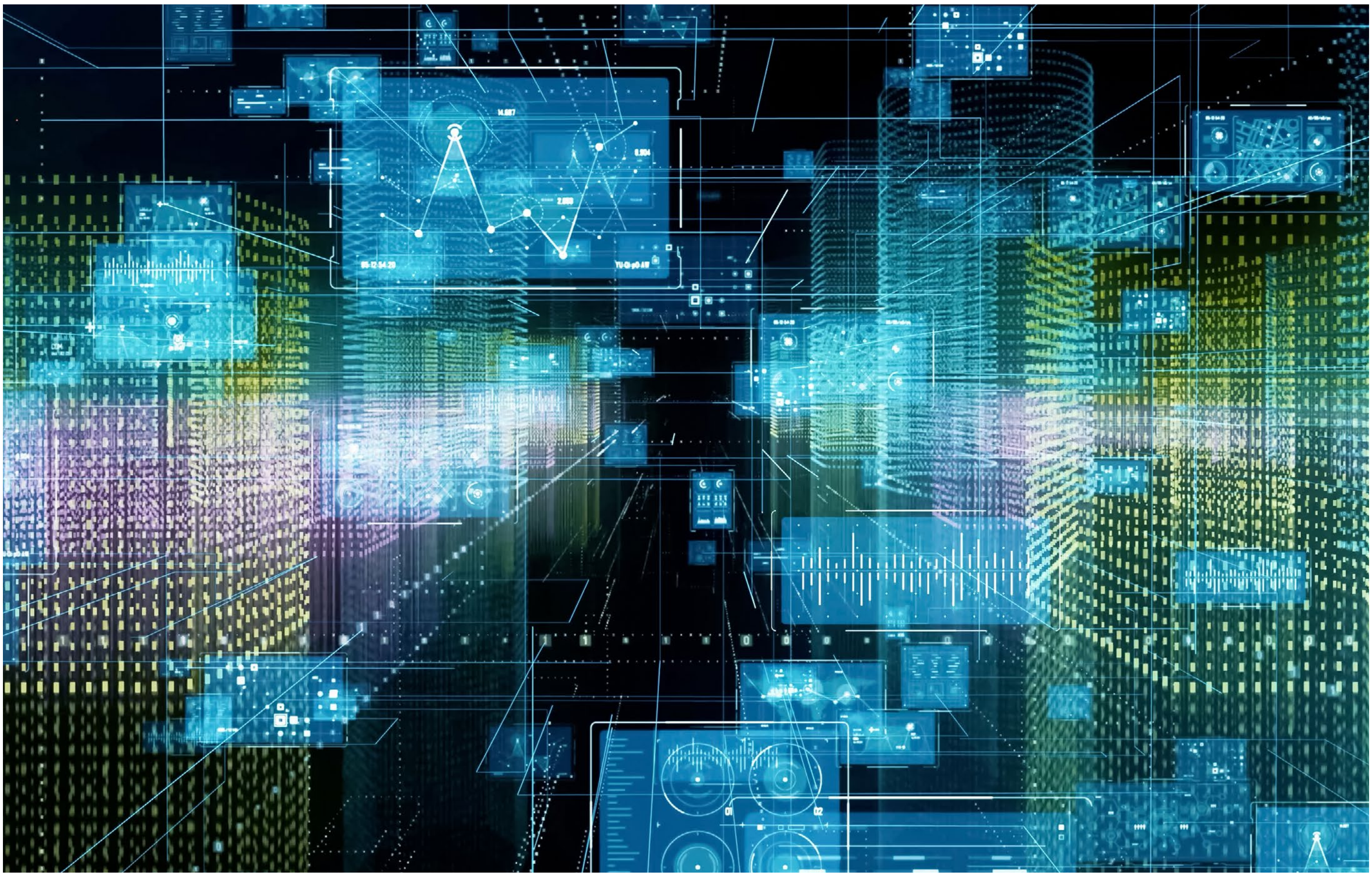
Healthcare

As part of nature, the human body is also made of molecules. Understanding and treating it better is one of the fundamental opportunities offered by quantum computing.

- **More efficient drug design** will significantly reduce the computational barrier to assessing and comparing new compounds and their characteristics "in vitro", without the need to synthesize them. The same approach applies to specific areas of modelling protein folding[28] and peptides design.[29]

- **Genome sequencing** will be done in a fraction of the time, paving the way to the next step in drug design, personalized medicine, addressing specific patient biological markers and situations, theoretically increasing treatment efficiency.

Seventeen companies have recognized the promise of quantum computing and formed QuPharma,[30] a consortium for pre-competitive collaboration, in 2020. At the same time, leading pharmaceuticals companies (Biogen, Boehringer Ingelheim, Roche, Pfizer, Merck, Janssen) have already started[31] their own partnerships and study of the quantum or quantum-inspired applications for small molecule discovery, molecular dynamics simulation, quantum-level chemical molecules simulation and more.



Modelling complex systems – enabling (better) real-time decisions

Quantum computers that can run quantum circuits are naturally positioned to work with complex systems where data has inherent structure[32] and many variables. Structure that is pervasive across a large dataspace is extremely costly to determine with classical computers and solving many of today's hard computational problems with this structure comes down to finding the balance between the time spent finding the answer and its usefulness for the end user.

With many industry sectors relying increasingly on data for planning and operations, quantum computers will allow industries to potentially augment their optimization and machine learning processes to find new insights and make better and more precise decisions.

Financial, investment and insurance products
One of the most straightforward applications of the aforementioned concepts is in the financial industry. Banks, credit unions and trading companies are all dealing with a massive amount of data, probabilities and assumptions in their decision-making.

– Crunch billions and trillions of financial transactions and associated data on location, time of day, merchant history, payment habits and more to identify unusual activity and flag potential fraud. Quantum computers can improve pattern recognition in structured and unstructured data sets, improving the quality and speed of **fraud detection**.

– Similarly, **credit scoring** at the point of sale, which considers more diverse and uncommon sources, such as social media behaviour or other patterns, can become a reality due to the increased speed and complexity of scoring models. Such an approach could increase profitability of credit offers and allow to reach unbanked population.

– **Better securities and derivatives valuation**, incorporating more market factors to price risk in close to real-time. The ultimate extension of this is **portfolio risk assessment, analysis and optimization**, allowing for future behaviour to be modelled and for portfolios to be optimized according to given parameters – by comparing various combinations in a much more efficient way. One notable example is better performing sustainable investment portfolios, taking into account more ESG-related information, scoring and emissions disclosures. Lastly, quantum computers are also more efficient in running Monte Carlo (probability) simulations.

Some of the largest financial institutions have already carried out inquiries to investigate the most promising use cases for industry preparation (BBVA[33]), or are working on their quantum applications with clear timelines to be the first to get a competitive advantage once quantum computers are more developed (Goldman Sachs[34]).

> Quantum computers can process highly complex design tasks [...] both simulating the behaviour of [...] an advanced system and optimizing product [...] options.

Transport, logistics and supply chains

From the complexity of transport routes to that of global supply chains, the sheer number of start and end points and types of transport leads to an incredible number of route options that need to be optimized according to given criteria.

- **Route and traffic optimization** for public transport can adjust to real-time road and demand conditions, including more transport modalities (trains, bicycles, taxis, etc.).
- **Optimizing international shipping and delivery** routes increases anticipation and service disruptions management.
- **Management and coordination of global supply chains** with thousands of business partners, national and macro risks affecting their delivery performance.

Deutsche Bahn started its work on exploring the potential of existing quantum computers to be used regularly in real-world train scheduling (stage 1) and increasing the network capacity and use while minimizing costs (stage 2).[35]

New product design

Quantum computers can process highly complex design tasks with numerous variables, both simulating the behaviour of the material or an advanced system and optimizing product components by comparing options.

- Whether in **aerospace or aviation**, engineering requires an incredible number of design choices in materials, structure, weight distribution, flexibility and cost to work in perfect harmony for the end product to function. New models take years to decades to develop. Quantum computing is expected to overhaul the process with dramatic speed and quality improvements.
- A similar logic applies to almost any manufacturable industrial or consumer product. Improving **the product design and characteristics** of an end product in every area will lead to an overall increase in the quality of new products, faster development and a decrease in the time-to-market – forcing companies to rethink how they compete.

In 2019, in response to inevitable computing limitations, Airbus launched its Quantum Computing Challenge,[36] asking competing teams around the world to address five critical design problems for developing a new aircraft using quantum computing methods. The winning team developed a quantum algorithm that proved quantum computing could optimize an aircraft's payload capability to maximize revenue, optimize fuel burn and lower overall operating costs.[37]

Impact on existing technologies, digital infrastructure and research

The types of problems that quantum computing is expected to be best at solving (quantum simulation, optimization, quantum linear algebra and prime factorization) underpin the inner workings of many existing technologies. On the one hand, it is expected to accelerate machine learning algorithms and provide pathways for unprecedented opportunities in fundamental science, from physics to chemistry to biology and advanced materials. On the other hand, it carries a disruptive potential for the security of today's digital communications and, by extension, national security. Blockchain solutions, including cryptocurrencies, are also under threat, although good news exists for these areas.

Cybersecurity

Modern digital systems, products and services rely on a set of mathematical problems to secure data collection, storage and exchange. These problems are beyond the reach of classical computers, but quantum computing can solve them much faster – up to a matter of minutes and days[38] – making encryption breaking both feasible and worthwhile.

- Shor's algorithm, developed in 1994, spearheaded the field of quantum computing as it was a tangible quantum algorithm that could have serious implications for society. If used on a general-purpose scalable quantum computer (that does not exist yet), it would break the encryption of today's digital communications, compromising existing public-key cryptographic algorithms.

There's a lot at stake when it comes to digital encryption:

- Data breaches, especially sensitive health or financial data
- Private and business digital communication, including objects of critical infrastructure like power grids
- The integrity of digital documents
- Breaking blockchain and cryptocurrencies, which are also used in digital identity, financial transactions and trading, among other areas.

> There's a lot at stake when it comes to digital encryption.

The good news is that there are actionable approaches for businesses to implement to start preparing or enabling a full-scale transition to the security infrastructure capable of withstanding attacks from quantum computers:

- The first is **post-quantum cryptography**, a set of new encryption algorithms that quantum computers cannot break. The US National Institute of Standards and Technology (NIST) only recently announced the results of a six-year-long competition to develop quantum-resistant algorithms. Four of these have formed a basis of an upcoming post-quantum cryptography standard.[39]
- The second approach is to use **quantum random number generators** (QRNGs) to secure communications instead of pseudo-random numbers generated with today's techniques. Several quantum computing start-ups are offering QRNG devices.
- Lastly, the **quantum key distribution** technique (QKD) exchanges encryption keys using quantum communications. These experiments have been successful for networks of limited geographical size, and development continues.

None of the three methods is a silver bullet able to provide guaranteed protection from break-ins in the new quantum computing era. Malicious actors constantly adapt, but using at least one of the stated approaches – or a combination of them – will reduce the risk to a manageable level.

More details about quantum threats, as well as available solutions and what firms can do to protect themselves today, are covered in the newest white paper on Quantum Security.

Artificial intelligence

A primary application of quantum computing is solving machine learning algorithms more efficiently, thus turbocharging existing and new artificial intelligence (AI) applications, e.g. quantum-assisted models for generating data to enhance weather forecasting.[40] In some applications, such as quantum neural networks, the entire learning technique is transplanted into the quantum domain.

Machine learning problems are relevant in multiple industries, including, for example, autonomous driving, automated trading, speech and image recognition, and predictive maintenance.

By accelerating machine learning training routines, with many groundbreaking models requiring a significant amount of computational capacity (e.g. GPT-3 allegedly took 355 years in effective computing time[41]), quantum computing has an opportunity to be a part of an overall shift towards democratizing AI and opening doors for smaller firms to train complex models theoretically at a fraction of the time and cost and without access to modern hyperscale data centres. At the same time, with faster training, businesses can transition to AI applications capable of processing real-time data flows and constantly improving or adjusting to circumstances, which would trigger new use cases and business model pivots.

> [Quantum] simulation, optimization and machine learning can contribute to our fundamental understanding in scientific fields.

Defence and security

Governments worldwide are pouring money into quantum computer research to increase national security. Quantum computers could be used for various defence applications, including developing better materials for military machinery and weaponry, accessing opponents' secure communication lines and running combat simulations. The critical use case remains the ability of quantum computers to break RSA encryption. On 4 May 2022, the Office of the President of the United States released a memorandum[42] demanding the transition of vulnerable national systems to quantum-resistant cryptography, marking it as the first country to have taken security action against a potential quantum computing threat at a national level.

Realizing the potential of the technology, NATO has launched the world's first $1 billion multi-country emerging technology innovation fund[43] to support investments in early-stage ventures with dual-use technologies, including quantum computing.

China, a world leader in quantum technologies, is succinct in disclosing information about the state of quantum computing development. Yet, China's People's Liberation Army is known to fund quantum research through a network of military science academies[44] and collaborating academic institutions.

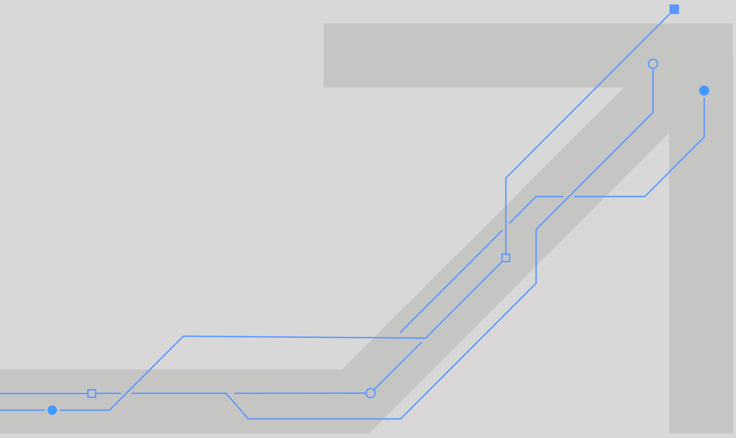
Scientific breakthroughs

Simulation, optimization and machine learning can contribute to our fundamental understanding in scientific fields such as nuclear, particle, condensed matter, fluid and astrophysics, plasma science, chemistry, materials and biology. For many scientists, this is the deeper motivation to work on quantum computers. Whether it's the physical, chemical and biological processes previously mentioned, finding patterns in large amounts of data coming from space observatories, the unravelling of the behaviour of quarks and gluons that clump together inside the nuclei of atoms,[45] or the explanation of dark matter in our universe, or emerging phenomena from trillions of trillions of interacting electrons in a solid, the limitations of classical computing hamper scientific fields.

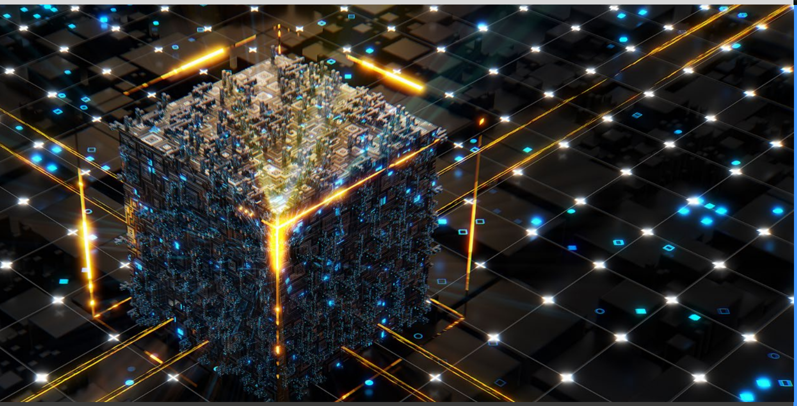
3 State of technology

Although quantum computers have yet to demonstrate their advantage, the hardware development is steadily progressing to the point when organizations can experiment with it through the cloud.

With multiple technology pathways developing in parallel, an exciting period of steady technology advances is beginning with tangible roadmaps to track progress and align industry uptake.

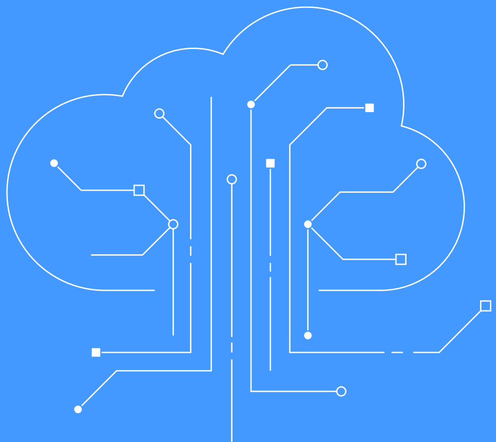


Two approaches to build a quantum computer – superconducting qubits and trapped ions – have currently reached a more advanced level of development than others, though it is likely that multiple hardware platforms will be able to either catch up or otherwise play a role in the future.



Given the high physical infrastructural requirements to create environments in which quantum computers operate, most users will get access to the technology via the cloud, and likely paired with other traditional cloud computing services.

Even though today's imperfect quantum computers have not yet demonstrated a quantum advantage and cannot run many promising industry applications, they can already be accessed for research, pilots and business use case assessments.



3.1 Critical components for quantum computer operation

To fully exploit the potential of quantum applications, real quantum computers with real hardware to run quantum circuits are required. Although it is possible to use classical computation to simulate qubits and quantum interactions, this can only be done up to a certain size, after which there isn't enough computational power.

So what is needed for a quantum computer to work?
Quantum computing relies on a hierarchy, or "stack", of components to ensure ease of use, interoperability, scalability and reproducibility. Together, this stack of interrelated technologies – physical hardware, control electronics, programming languages and algorithms to name a few – allows instructions that form quantum circuits to reach a quantum processor and perform necessary actions on qubits to produce a computational result. Quantum computers can operate independently or in tandem with classical computers, either in parallel or in sequence. For instance, a quantum computer takes up part of the computation, where it can provide advantage in calculation speed or quality, while the rest of the problem is being addressed by a classical computer.

While all components of a quantum computing stack are important and can influence the quality and the speed of the calculation, the underlying hardware and quantum circuits to be run are arguably the most critical components that must be figured out.

– Quantum hardware (e.g. the qubit processing unit, or QPU) is where the actual quantum circuits are run.

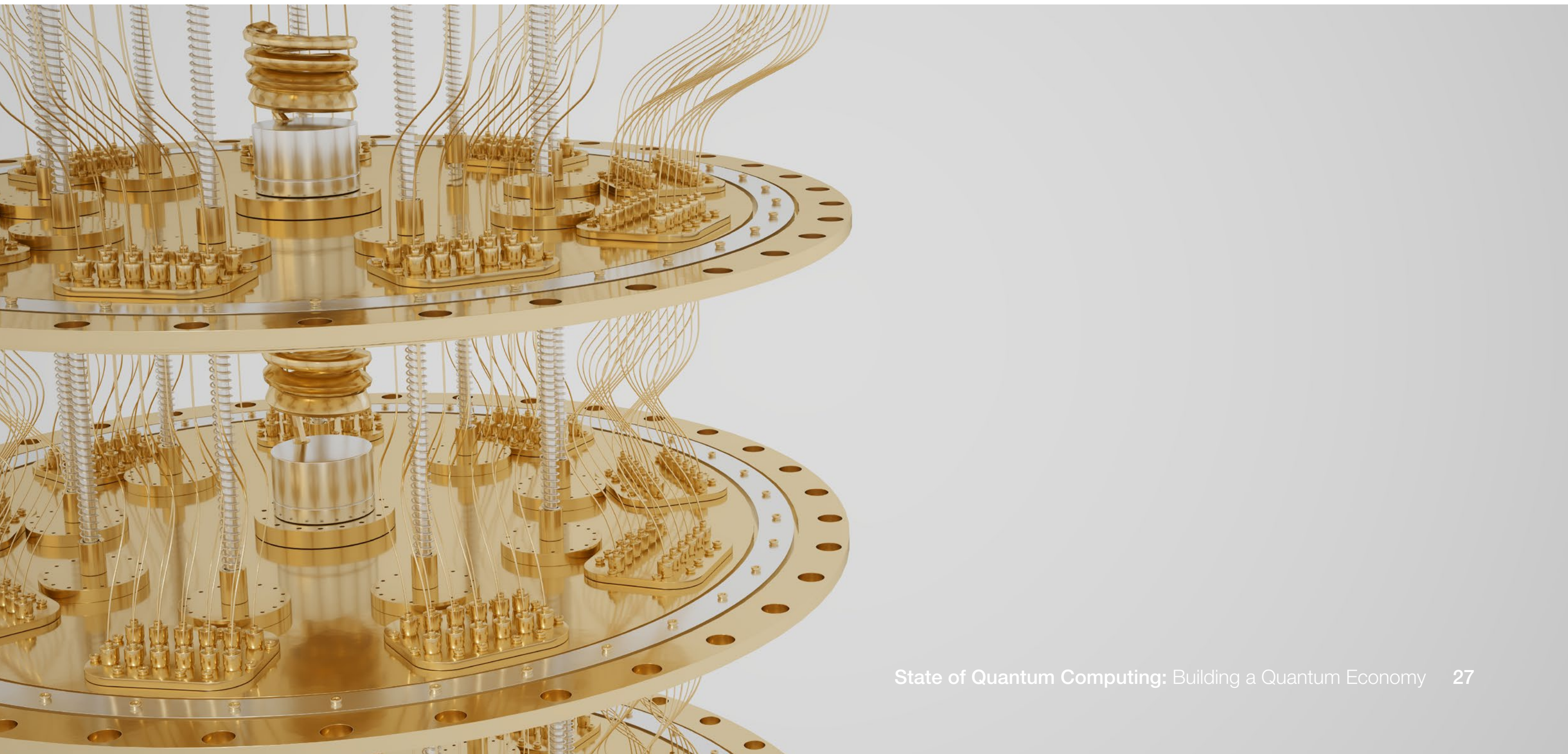
– A quantum circuit is a sequence of quantum operations applied on multiple qubits. Combinations of the results of quantum circuits advance a program to solve a computation.

Many quantum computing hardware platforms require specialized environments to operate within, including cryogenic cooling, ultra-high vacuum and magnetic shielding.

BOX 2 Cloud access to quantum computers as a game changer

High hardware requirements mean that most commercial systems are offered "as-a-service", often in collaboration with leading cloud providers. This means that organizations will likely be buying computing time, not quantum computers.

Still, it is a good idea to create clarity over "what's in the box" or the cloud and whether it is the right option for an organization. Knowing the state of development and quantum hardware types is essential from a quantum application perspective. Only parts of quantum algorithms (and hence applications) can be run on today's imperfect quantum machines; the most promising applications of quantum with provable advantage (e.g. Shor's) will need much more developed and scalable quantum hardware to operate.



3.2 How developed are quantum computers? Are there many?

> In 2022, there continue to be technological improvements across multiple hardware platforms with technological development roadmaps to help forecast paths.

Competing quantum computing systems under development today rely on various quantum physical interactions to define qubits – electrical, optical and magnetic. The hardware and conditions needed to create and control qubits differ according to the quantum activity being controlled, e.g. a photon of light or the spin of an electron. Each approach has different trade-offs in terms of investment and benefits. Again, there are parallels to classical computing, which evolved over multiple modes of physical infrastructure – from vacuum tubes to magnetic tape to silicon circuits on chips.

In 2022, there continue to be technological improvements across multiple hardware platforms with technological development roadmaps to help forecast paths.

Despite the differences in approaches, the basic milestones in the development of a quantum computing system are the same:

1. The system must be able to create well-characterized[46] qubits.

2. The system must allow for the qubits to be initialized, universally controlled and measurable for calculations.

3. The system must be able to correct errors inherent in the physical hardware realization of the qubits.

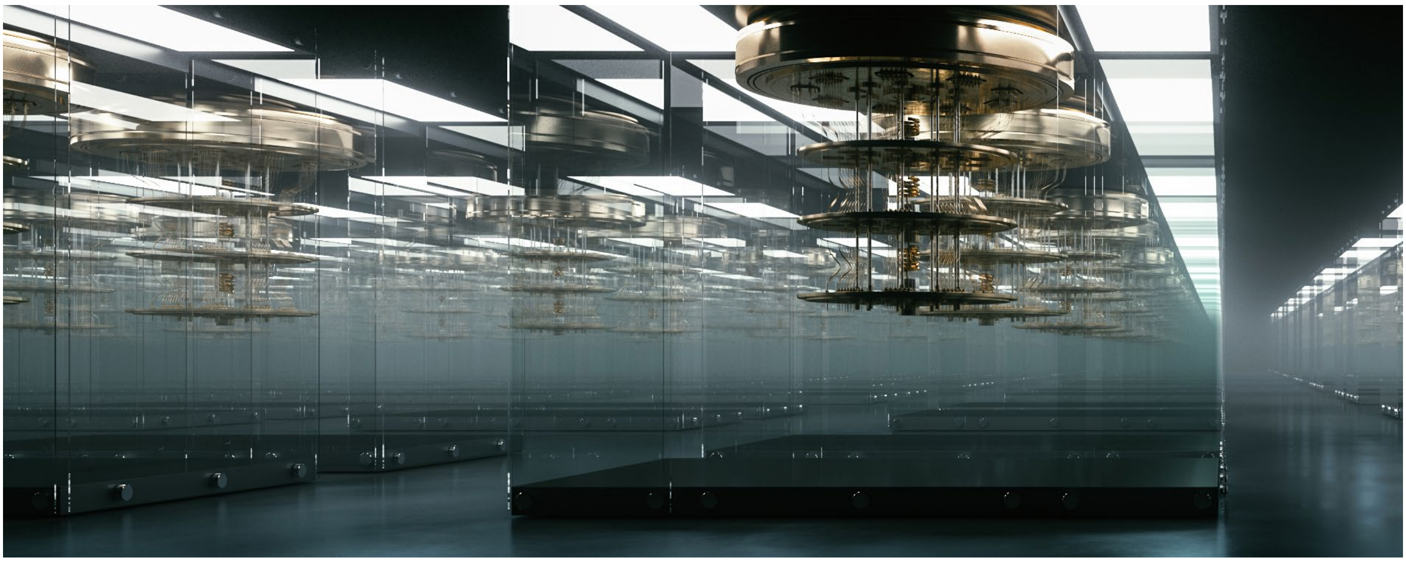
4. The system must be able to do all of the above at scale.

Based on the above, all hardware platforms can be classified according to the milestones achieved by mid-2022 (see Table 4, where level 1 is in its early stages, level 3 is the most technically advanced and higher-level systems satisfy all lower-level requirements).

While two hardware platforms are ahead on the development path – superconducting qubits and trapped ions – other platforms and approaches could still be able to catch up at a later stage. In the long term, it is likely that multiple hardware approaches will co-exist and find their niche in a new quantum computation ecosystem, based on their inherent advantages.

Important to note that no system has reached the fourth milestone (level 4) today and cannot operate at scale. Roughly speaking, "at scale" could be understood as the ability to control 1 million qubits in a computation, theoretically allowing for the creation of a sufficient number of error-corrected qubits to demonstrate quantum advantage in a real-life application. Today, our best-performing platforms have demonstrated capabilities in the low hundreds.

Building systems that follow the four steps of development require universal control and are capable of running quantum circuits. These "quantum circuit-model platforms" all have a universal gate set, which is a set of gates that allow any arbitrary quantum circuit to be run, and combinations of quantum circuits with classical computations drive algorithms to fuel application development. These are critical pre-requisites for building a general-purpose quantum computer that can be integrated as part of a computational workflow. As mentioned prior, quantum computers will not exist on their own in vacuum but must be architected into the appropriate classical computer infrastructure for ease of use and flexibility for the end user.



One existing approach outside the realm of universal quantum computing is quantum annealing, which will never produce general-purpose quantum computers but is tailored to solve certain optimization problems. It is somewhat easier to build and scale, hence it was one of the first commercially available platforms, currently counting a few thousand qubits. It is unclear if it can demonstrate computational advantage over classical computers (speedups) since the problem space is hard to make rigorous.

Some useful applications and benefits could be realized at less than full maturity or scale – for both circuit-based and non universal approaches.

TABLE 4 **Quantum computing hardware platforms according to their level of development towards the universal quantum computer**

Maturity	Level 1	Level 2	Level 3	Level 4
Milestone/ threshold	Platforms demonstrating coherence properties (creating qubits).	Platforms demonstrating a universal gate set (controlling qubits).	Platforms demonstrating quantum error correction and/or error mitigation.	Platforms demonstrating level 1-3 properties at scale.
Hardware platforms (non-exhaustive)	**T-cells** Advantages: potential for on-chip integration, expected to be scalable.	**Neutral atoms** Advantages: qubit stability (long coherence times) and low error rates, modularity (optical interconnects or shuttling on chip), identical qubits. **Photonic simulators** Advantages: all-to-all connectivity, horizontal scalability, has the potential to be seamlessly integrated in the existing chip (silicon) architectures, qubits resistant to interference (noise). **Spin systems** Advantages: potential for on-chip integration, leading to easier scalability and manufacturing, operating speed, stability (long coherence times). **Nitrogen-vacancy (NV) centres** Advantages: potential for on-chip integration, stability (long coherence times), modularity (optical interconnects).	**Superconducting qubits** Advantages: operation speed, integrability via semiconductor scaling and packaging techniques, relatively easy to manufacture. **Trapped ions** Advantages: all-to-all connectivity (this can allow for building shorter (faster) quantum circuits, and use a wider range of quantum error correction methods), modularity (optical interconnects or shuttling on chip), identical qubits.	**None (yet)**

Source: World Economic Forum, Global Future Council on Quantum Computing

What can hardware platforms do at each level?

Level 1: Platforms demonstrating coherence properties. Approaches at this level have demonstrated that they can create qubits but cannot necessarily reliably control them. The absence of universal control (done with universal gate sets implementation) does not yet allow these platforms to run universal quantum algorithms. It is critical that qubits demonstrated here show the potential to achieve scale, quality and speed to realize effective quantum circuit operations. Some approaches, such as Majorana qubits, that hold promise as intrinsically noise-resilient qubits, are quite close to but haven't yet reached criteria for a Level 1 platform. All non gate-based technical approaches can be considered Level 1.[47]

Level 2: Platforms demonstrating a universal gate set. All approaches at this level have proven they would be able to run an arbitrary quantum application – if or when they reach necessary scale

“There are defined (although constantly updated) roadmaps for several platforms, meaning that it is only a matter of time as to when quantum computers will get [to level 4].

and computational quality required by quantum algorithms. This was achieved by demonstrating the capability to run general quantum circuits with a universal gate set. A typical universal gate set consists of a reset operation that initializes the qubits, a set of single qubit operations and an entangling two-qubit operation, and a measurement operation.

Level 2 hardware, however, often operates without error correction, referred to as “noisy intermediate-scale quantum devices” or NISQ devices. Errors occurring at this level can be suppressed using error-mitigation techniques but not removed entirely, thus potentially affecting the quality of the calculation and its usability in real-life scenarios.

Level 3: Platforms demonstrating quantum error correction and/or error mitigation. The technical demands for handling errors in quantum systems are a challenge for all physical hardware systems. Achieving scalable fault-tolerant quantum error correction (QEC) is widely considered the ultimate goal for general capability for quantum computing systems. If the quality of the qubit is sufficiently high, such that the execution of an error correcting algorithm resolves more errors than it generates, then scaling to larger number of qubits reduces the error rates. In other words, the key to scalable fault-tolerant QEC will be many high-quality qubits in scalable system architecture. This is an ongoing area of research where initial demonstrations of QEC concepts on a few hardware platforms have been achieved.

Other avenues of exploration include error mitigation and suppression techniques, which entails methods to either learn the physical noise through running a larger set of quantum circuits, or to alter the quantum circuits to minimize the effects of certain forms of noise. These techniques extend what is possible on noisy intermediate scale quantum systems but potentially at the cost of overall circuit runtime and system stability.

Level 4: Platforms demonstrating coherence properties, speed and quality at scale. No hardware platform has reached this level yet, as it would signify demonstrating a quantum advantage on a real-world application. However, there are defined (although constantly updated) roadmaps for several platforms, meaning that it is only a matter of time as to when quantum computers will get there.

3.3 Which quantum computer is best?

Comparing different approaches in terms of performance is not as straightforward as one may think. Similar to choosing a new PC, one may favour speed over memory, calculation reliability over special features or power consumption over footprint. More fundamentally, different hardware platforms may legitimately track particular metrics of progress or performance based on the architecture goals being pursued.

As of 2022, three main challenges need to be addressed to build a computer demonstrating quantum advantage with real-world applications: scale, quality and speed, corresponding to the areas against which systems could be evaluated. The performance metrics can thus be roughly grouped into an analysis of individual components and benchmarks that offer a holistic analysis of the entire system.

FIGURE 8 **Areas for quantum computers’ evaluation**

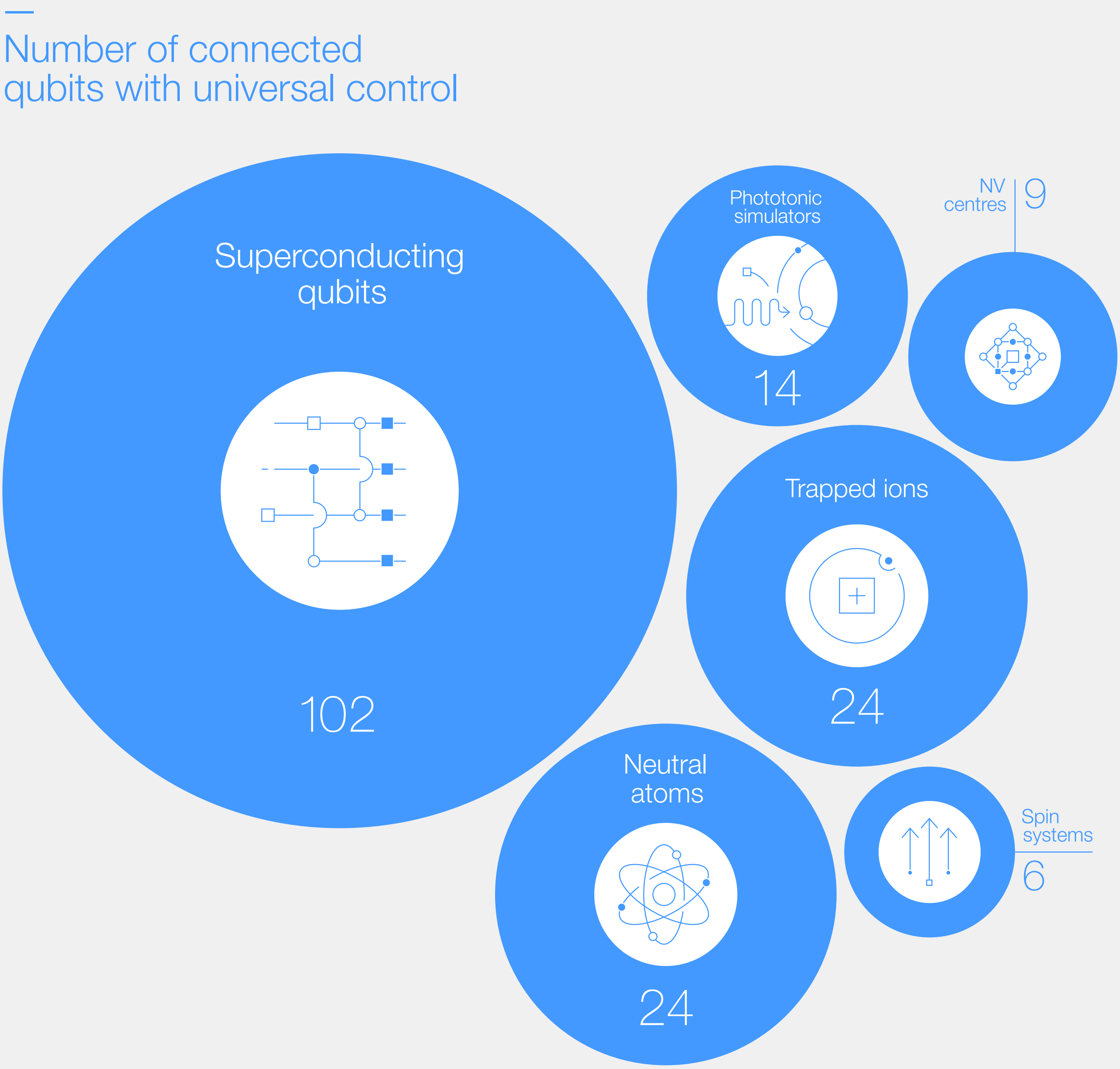
Source: World Economic Forum, Global Future Council on Quantum Computing

Scale

News articles often present the number of qubits as a metric to evaluate new achievements in quantum hardware. The number of qubits explains how scalable the hardware is, but it doesn't explain anything about the quality or speed of the qubits and quantum operations. Numbers may fluctuate significantly depending on which qubits are taken into account. For instance, neutral atoms platform has demostrated 289 coherent qubits, the largest achievement so far; however, not all of them are entagled or even fully connected (here the number drops to 24 qubits), and thus their use may be limited.

One of the balanced ways to look at the pure scale of the platforms (see Figure 9) is to count the largest number of connected qubits with universal control (to prepare a non-trivial quantum state). Again, every metric will have its caveats, and should not be used as a standalone measure for platform evaluation.

FIGURE 9 **Quantum computing platforms scale comparison: the largest number of connected qubits with universal control (to prepare a non-trivial quantum state)**



Source: World Economic Forum, Global Future Council on Quantum Computing

Speed

For quantum computers, computation speed is measured in the number of circuits (or algorithms) executed in a given time. Therefore, "calculations per second" for QC cannot be compared to classical computers' similarly sounding benchmark. Figure 10 shows a general order of magnitude in the rate of execution for trapped ions, superconducting and neutral atom systems, for which data is available. The larger the calculations per second, the better. For actual computations, there is likely the need to run a large number of circuits to improve accuracy. IBM has proposed circuit layer operations per second (CLOPS)[48] as a potentially more stringent metric for benchmarking speed. So far, CLOPS has only been measured for multiple superconducting qubit platforms.

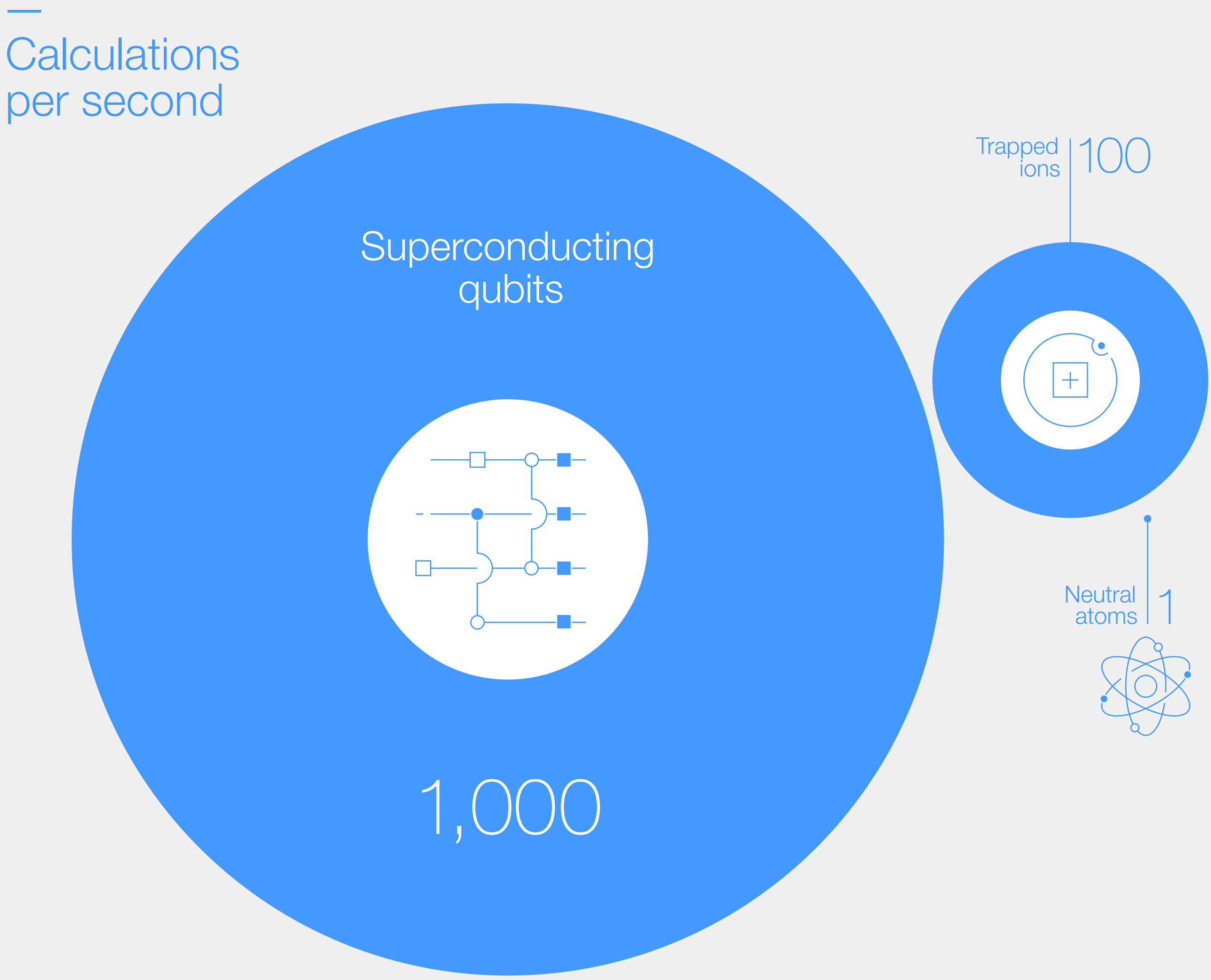
BOX 3

There is a common speed bottleneck for most approaches

When looking at the quantum computer as a whole, a full stack, classical control electronics is a speed limiting factor for most approaches in the current state. It creates a bottleneck with a qubit measurement time, slowing the error-correction cycle. Until control electronics improves, circuit speeds, demonstrated by different platforms, does not translate into application speeds and can be misleading.

FIGURE 10

Quantum computing platforms speed comparison: number of circuits executed in a given time



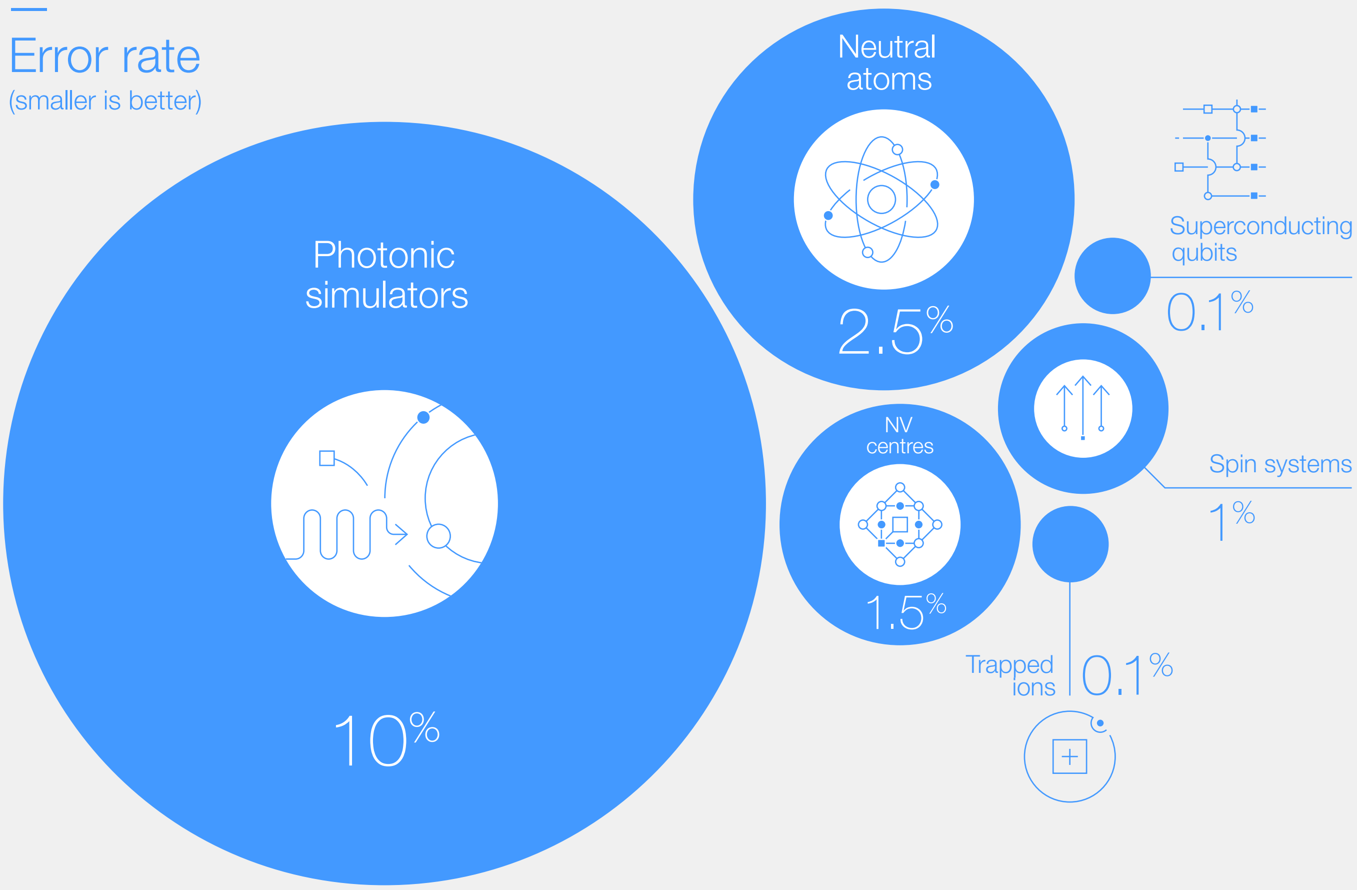
Source: World Economic Forum, Global Future Council on Quantum Computing

Quality

The quality of quantum computation is measured by the accuracy of the results for running quantum circuits – looking at the error rates. Different quantum circuits of different complexity will obviously have varying error performance (see Figure 11). Note that for general performance measures, there is the **quantum volume** (QV),[49] which gives a single number based off of the performance of the system across a set of randomized circuits.

FIGURE 11

Quantum computing platforms quality comparison: two-qubit gate error rates



Source: World Economic Forum, Global Future Council on Quantum Computing

Such a holistic measure attempts to throw out hardware bias, and considers several features of the underlying hardware, from gate and measurement errors, connectivity, crosstalk and other unintended noise to give an overall better idea of the usefulness of a quantum computer.

BOX 4

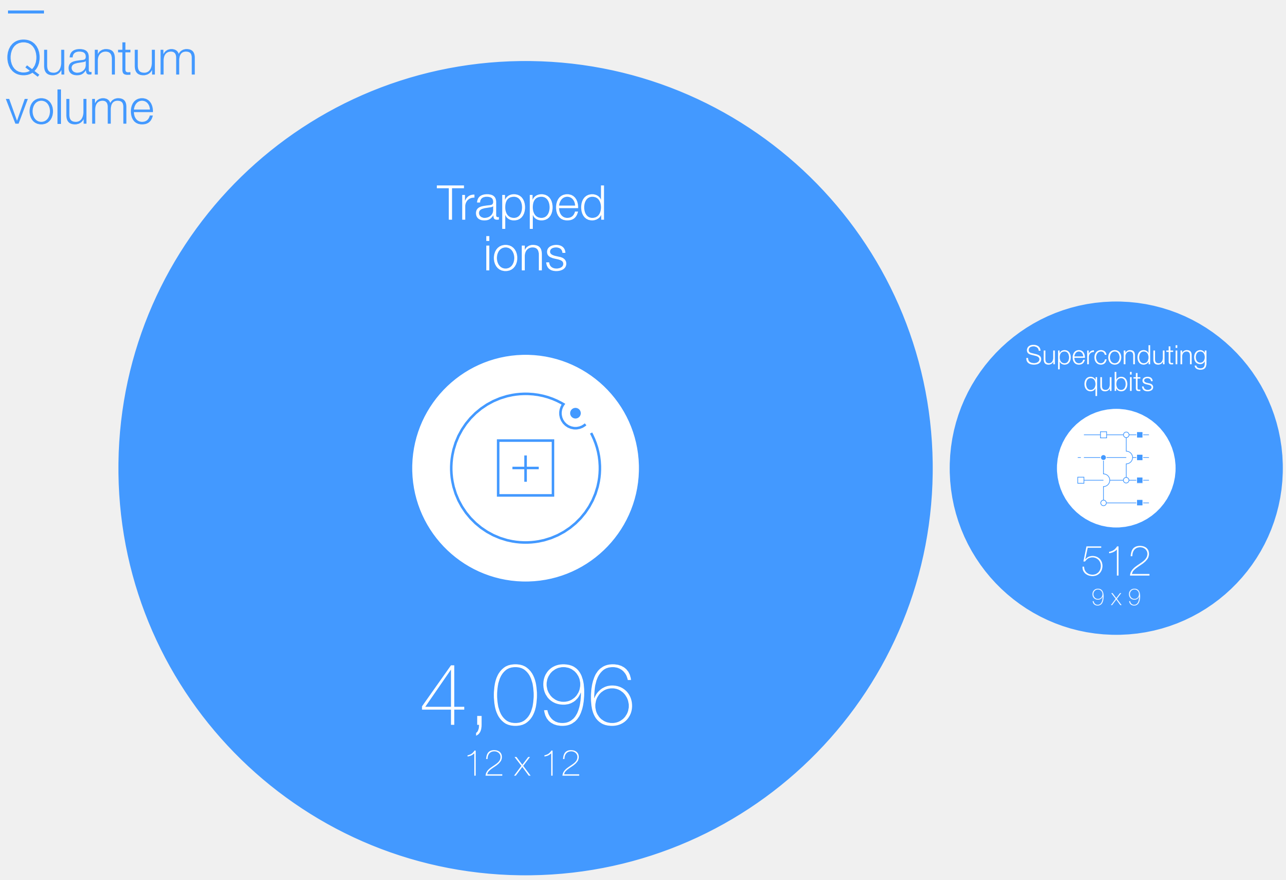
Necessary literacy to better understand QC quality challenges

Crosstalk: Occurs when an operation on one qubit affects other qubits unintentionally. Crosstalk is a major source of noise in NISQ systems and is a fundamental challenge for hardware design.

Connectivity: Describes the connections between qubits in the quantum architecture. These connections enable entanglement between different qubits.

Figure 12 shows the QV metric for trapped ions and superconducting systems. The larger the QV, the better. Other hardware approaches have not yet been benchmarked with quantum volume.

FIGURE 12 **Quantum computing platforms holistic comparison: quantum volume**



Source: World Economic Forum, Global Future Council on Quantum Computing

Other ways of benchmarking the performance of a system is an "application-driven" approach: A combination of speed and quality, looking at performing a specific algorithm to track progress towards useful quantum advantage. QED-C has developed a benchmark suite[50] that can measure the progress towards the performance of quantum computing on four specific algorithms and use cases. As new algorithms are developed they can be added to the suite.

3.4 What hardware is needed to run applications?

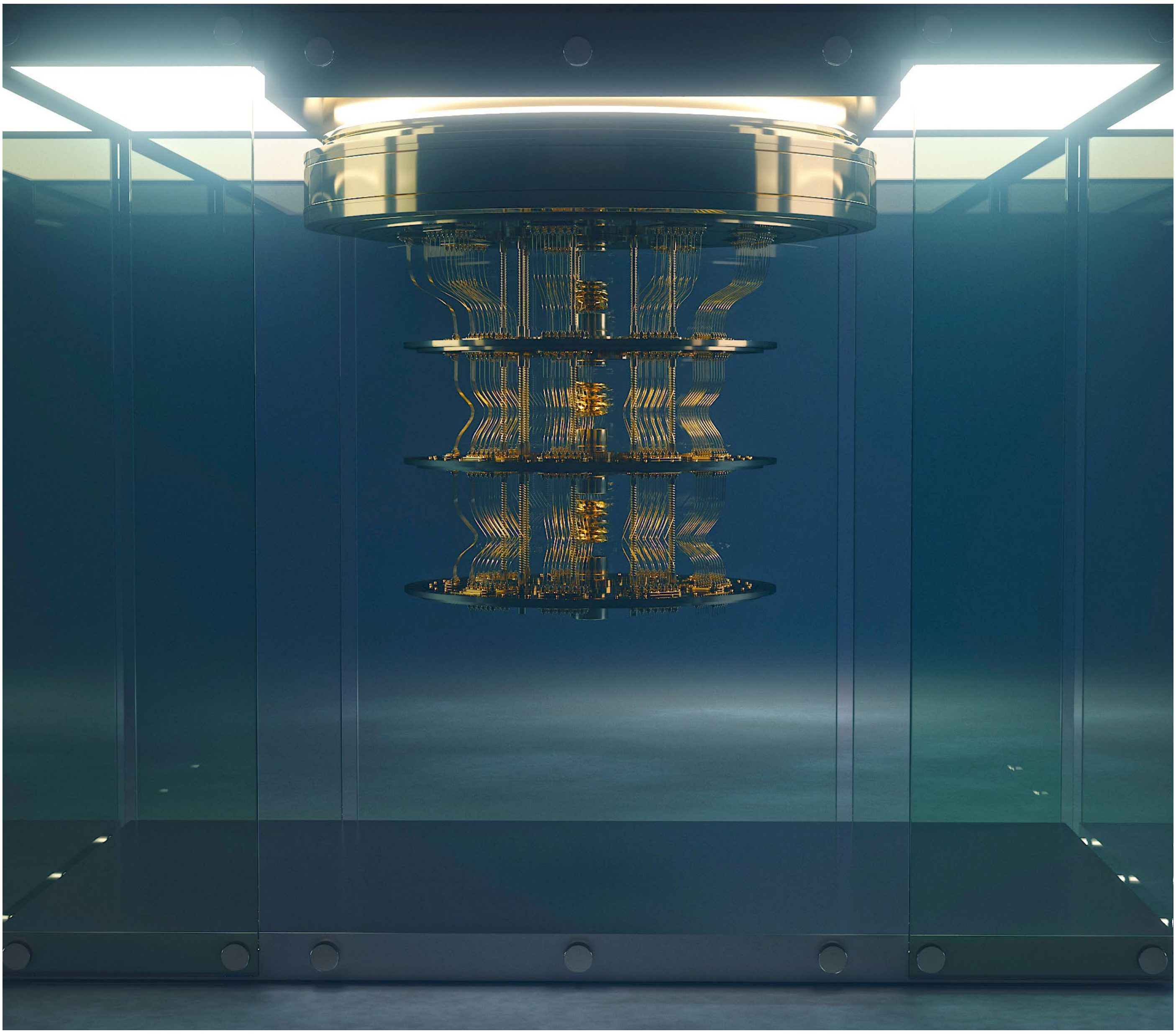
Today all quantum applications can be divided into two types depending on the quantum computing hardware requirements: fault-tolerant (requiring hardware above level 3) and near-term applications (can be run on level 2 and 3 hardware).

1. **Fault-tolerant**: Applications with provable advantage over existing computational methods that will likely require a more developed quantum computer capable of quantum error correction.

2. **Near-term**: Applications that could be run on today's noisy quantum computers, although it is not yet clear if or when these applications will provide any advantage over similar applications run by classical computers. Bridging these from what is likely achievable in the near term with what is proven on large error-corrected quantum computers is the subject of intense study and exploration throughout the industry.

As of today, quantum applications in use have yet to demonstrate their advantage in a real-life scenario, and are not yet being used on a day-to-day basis to power end user solutions at scale. Researchers and businesses are, however, already experimenting with near-term quantum applications to evaluate the potential of the technology – for their industry and to inform further research efforts into new algorithms and applications.

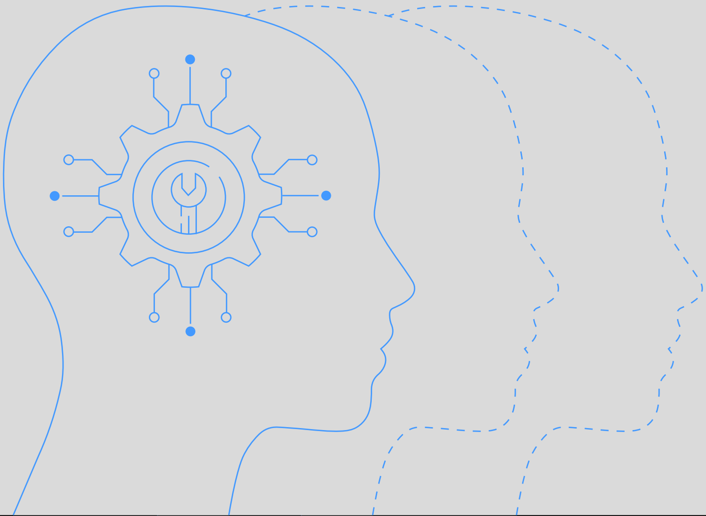
In summary, the jury is out as to whether a quantum advantage can be reached on a non fault-tolerant quantum computer. What is certain is that error mitigation techniques with current noisy quantum computers allow the running of a handful of applications, good enough for organizations to start their inquiries and get prepared instead of waiting for general purpose (level 4) quantum hardware to be fully developed.

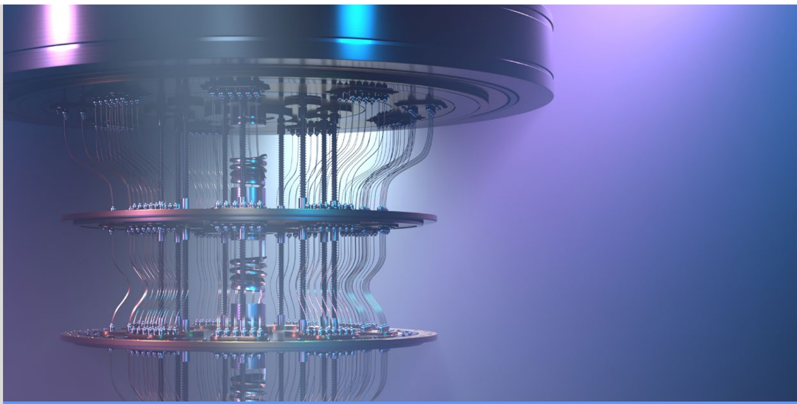


4 Unlocking technology potential

Realizing the benefits of quantum computing will depend on key enablers: workforce readiness, standardization and policy.

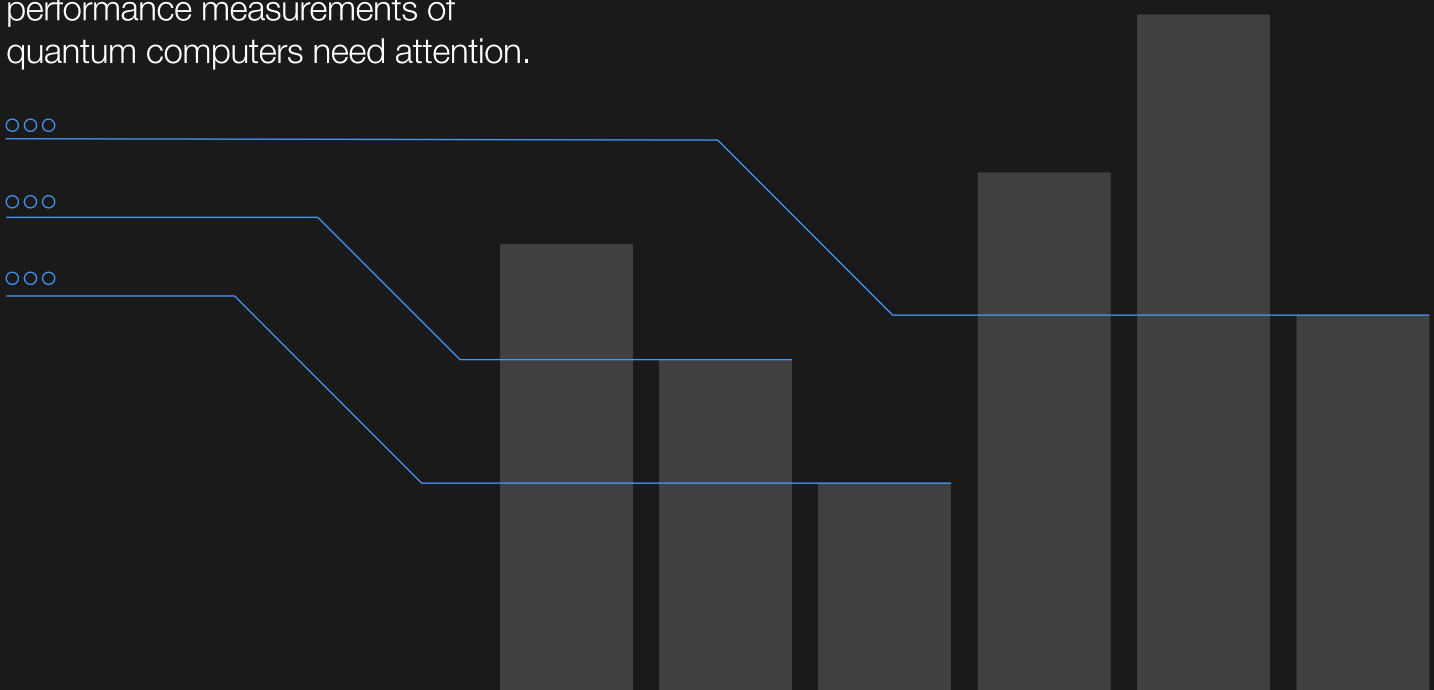
Quantum skills shortage is a key constraint at the moment.





Standards have been developed for cybersecurity in the policy area but lack energy efficiency and responsible technology development.

Standards on interoperability and performance measurements of quantum computers need attention.



Progress in several “enabling” areas is needed for quantum computing technology to be applied to real-world problems: 1) workforce availability and development, 2) policies and regulations, and 3) standardization.

Workforce availability and development: The current state of the quantum workforce includes jobs in academia, government, and public and private companies. In addition to the existing workforce, it is important to note the state of the enabling content for the future workforce, which includes university degrees, high school courses and other educational content, such as books, talks and online courses. Furthermore, the state of collaboration between industry, government and academia must be considered. Without a current workforce, the progress of the technology would be stagnant, and without a potential workforce, future progress would halt. Therefore, workforce availability and development are crucial for quantum technology to develop and be applied.

Policies and regulations: Policies inform the workforce and other stakeholders on how to develop and apply the technology. The current state of policies and regulations must be considered concerning access to quantum hardware, the ethics of the technology and international collaborations. With the stated strategic importance, a wide range of policy interventions is evolving in various parts of the world, including export controls, investment screening and strategic partnerships.

Standardization: Standardization enables better collaboration and communication across the quantum industry. Standardization can be implemented across different aspects of the quantum industry, including standards within quantum hardware, tools, software and algorithms. Standards within the technology development enable faster development and better benchmarking for researchers and engineers. Standardizing terminology in the quantum industry would lead to a common language that could allow better communication within the industry and with external stakeholders. Note also that, standardization should be handled with exquisite care, as, if wielded improperly, it can significantly hinder technology development.

4.1 Workforce availability and development/training

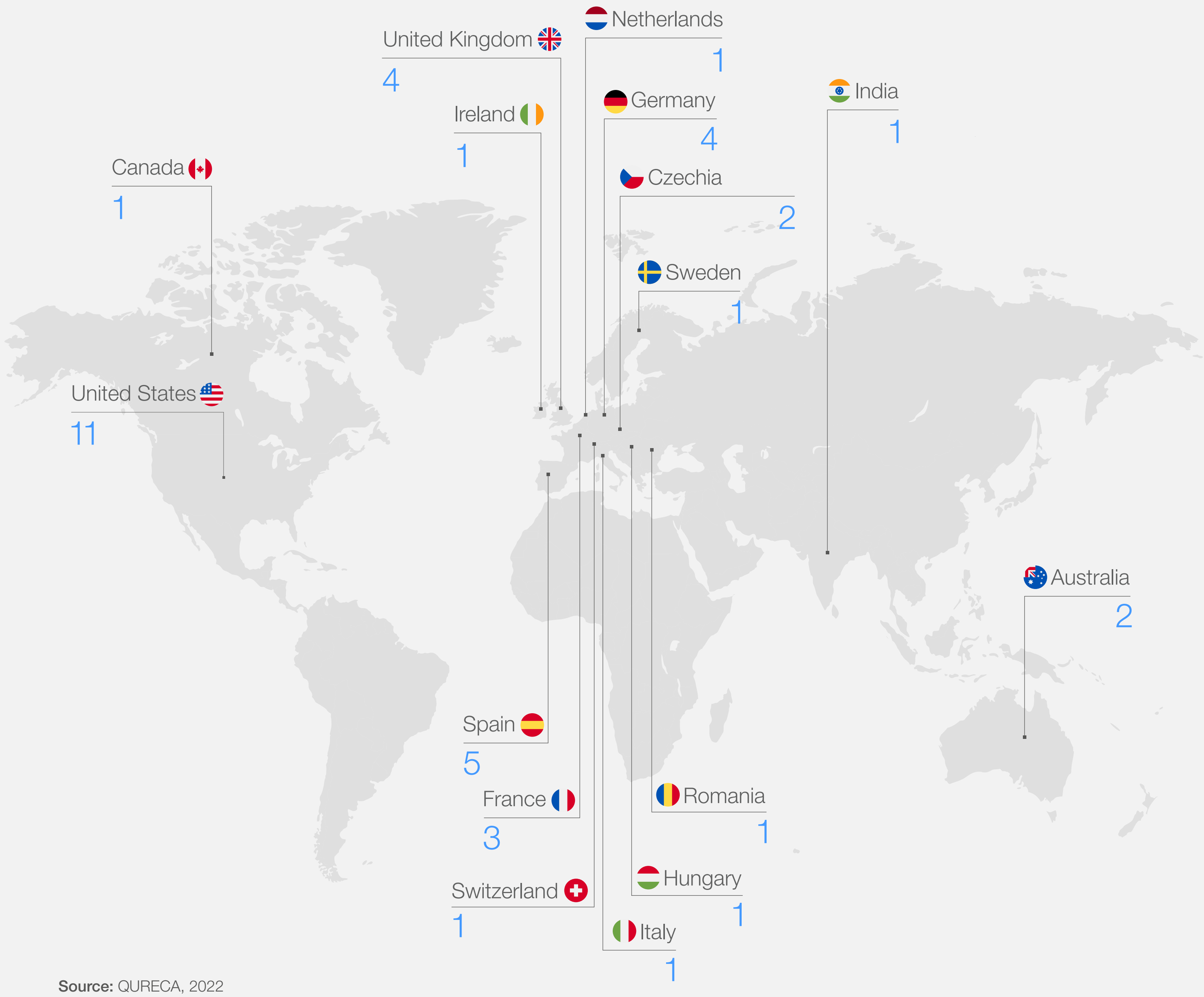
From a global perspective, every continent already has start-ups in quantum technologies, and this number continues to grow. This business boom would require an exponential growth of jobs in quantum technologies over the next two decades.[51]

There is a need for skilled labour in the field of quantum technologies. More than half of quantum companies are currently hiring. These companies struggle to find people with the right skills for new positions in the emerging quantum job market. Some have referred to this as the “quantum skills shortage”. The fact that quantum technologies are still in their infancy means that most current jobs are highly technical, especially with academic specializations and PhDs. In the past year, however, more diverse profiles, such as marketing and sales roles requiring prior work experience, have begun to appear, showing that the market is maturing. Simultaneously, the only people trained in the field of quantum technologies are highly academic, that is, at the doctoral level. Finding qualified individuals with previous work experience in the world of business or engineering in an already scarce talent pool is proving increasingly difficult.

“ An effort must be made to ensure that there are enough people with the right skills to fill this explosion of jobs in the next twenty years..

More importantly, an effort must be made to ensure that there are enough people with the right skills to fill this explosion of jobs in the next twenty years. The only way to educate the workforce of the future is by introducing quantum concepts at the primary and secondary education levels and creating more opportunities and programmes specifically for quantum engineering. Educating the future workforce is a long process, but there are already several higher education programmes worldwide focusing on quantum engineering[52] (see Figure 13). The quantum workforce includes a wide range of skilled labourers, such as quantum physicists, computer scientists, engineers, technicians and people with business, sales and policy backgrounds.

FIGURE 13 | **Master's programmes around the world with a focus on quantum technologies**



Source: QURECA, 2022

Globally, many individuals, both students and professionals, are looking for additional resources to help them build their careers in the field of quantum technologies. New companies specialized in quantum careers focus on supporting people seeking employment in quantum technologies, providing them with professional guidance and placing them as ideal candidates in quantum companies. Opportunities to build and sustain a quantum-ready workforce are abundant, including public-private partnerships, industry-academia collaboration, development of national quantum education programmes and addressing diversity issues.[53]

There is also the dilemma of bringing quantum technologies closer to potential end users and specific business sectors that are not yet part of the quantum ecosystem. Fortunately, there is a very promising scenario in terms of educational resources for both individuals and businesses at different levels of specialization. Numerous global education initiatives include games, online courses and events.

4.2 Policies and regulations

❝ It is never too early to consider and address any socioeconomic issues posed by a new technology.

Now, in 2022, is an ideal time to create policies regarding quantum computing, as the technology itself is approaching the sweet spot when it is increasingly clear what technology will be able to do, and what impact can be expected on different sectors of economy, while the actual applications are currently limited, so any regulation will still be proactive but informed.[54] The lessons learned from AI demonstrate that it is never too early to consider and address any socioeconomic issues posed by a new technology. The World Economic Forum published a *Quantum Computing Governance Principles* report[55] to help policy-makers and governments develop policies and regulations on quantum computing.

The types of policies and regulations needed in quantum computing include those pertaining to common good, accountability, inclusiveness, equitability, non-maleficence, accessibility and transparency.[56] The threat of quantum computing to cybersecurity also requires policies to mitigate this risk. Moreover, in a quickly progressing NISQ era, security takes on a new and unique role as an enabler. In January in the US, an executive order was passed that brought high-profile attention to the quantum cybersecurity ecosystem, presenting a roadmap to transition all federal agencies to post-quantum cryptography in 2035. This order was shortly followed by a presidential memorandum regarding quantum security and quantum ecosystem development.[57]

Many countries, including those in Europe, North America, Asia and Australia, are increasingly developing regulations around emerging and critical technologies; many include quantum technologies.

These policies include issues around export control that will likely be defined in a handful of national initiatives, and hopefully aligned through international agreements. Risk may lie in individual countries acting to control specific hardware items relevant to building a quantum computer for both economic and national security reasons. Given the potential value of quantum computing to social good and economic competitiveness, it can be said that broad international agreements are the most ethical and fair process in moving forward. Moreover, the supply chain for building a quantum computer is likely to be global, as it is for most high-technology industries. Although, given the current geopolitical situation, political incentives will likely localize supply chains and aim for strategic tech sovereignty via measures like foregin direct investment (FDI) screening.

There are currently no policies regarding quantum computing and its energy usage. Introducing such policies should be considered to ensure future scalable technology that isn't at the expense of enormous energy costs.[58] Lessons can be learnt from classical computing, which is currently struggling to decarbonize and is responsible for roughly 4% of global electricity consumption, and 1.4% of global carbon emissions. There should be no delay in promoting green quantum computing if technological choices are to be made during its development.

4.3 Standardization in developing algorithms and performance measurements

> Some level of standardization across several aspects of [quantum computing] development could help enable better communication, benchmarking and compatibility.

As quantum computing continues to mature, some level of standardization across several aspects of its development could help enable better communication, benchmarking and compatibility across various products – while mitigating risks of hindering technology development. For example, standards and ecosystem agreement could be effective in the following areas:

– Terminology for better communication

– Benchmarks and metrics for evaluating quantum algorithms and quantum hardware

– Standards for developing quantum software, algorithms and languages

– Guidelines and best practices

– Certification and test protocols.

Multiple international standards organizations have become engaged and have begun to discuss the path forward for future standards. These include ITU Telecommunication Standardization Sector (ITU-T), Institute of Electrical and Electronics Engineers (IEEE), European Committee for Electrotechnical Standardization (CEN-CENELEC), International Organization for Standardization (ISO), Corporation for Education Network Initiatives in California (CENIC), among others.

Right now, the most valuable activities are not so much around formal standards but the accumulation of benchmarks for characterizing the hardware's overall performance and creating a set of standards that can be the basis for comparing various quantum hardware.

Standards play a foundational role in market development, especially for emerging technologies such as quantum computing. By defining common terminology, hand-offs between companies, interfaces between devices, and best practices and benchmarks, standards are the glue that holds a supply chain together.

Nevertheless, the areas for standardization should be chosen carefully. Due to the proliferation and evolution of multiple hardware platforms for quantum computing, it is too early to develop standards for many aspects of this technology. For example, photonic quantum computing will need optical interconnect standards to connect photon sources to photonic processing chips to photon detectors. Since there are many different schemes under development using different wavelengths of light and different ways to encode information, custom connections needed for one company's system will not necessarily be relevant for other technical approaches. This problem is not limited to photonic computing, since different ion species are at the heart of different trapped ion computing platforms, the components they connect to will need to work at different wavelengths, making standards premature.

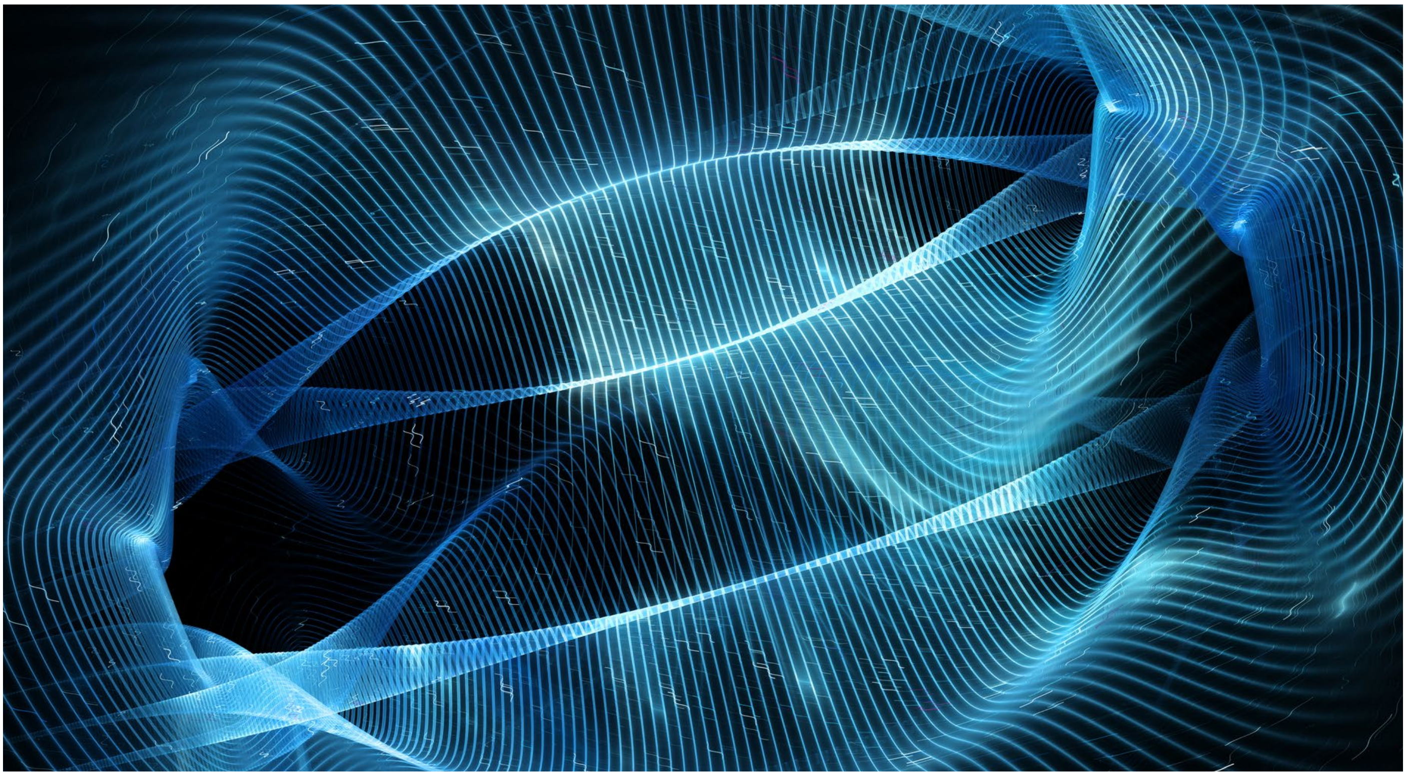


TABLE 5 | **Areas of standardization activity**

Type of standard/ pre-standard	Organization/document	Description
Terminology for quantum computing	ISO/International Electrotechnical Commission (IEC) JTC1 WG14/4879	This joint ISO/IEC committee is developing a standard specifically for terminology and vocabulary for quantum computing. As of March 2022, it was in the committee draft stage.
Terminology for quantum technologies	IEEE P7130	The IEEE quantum computing nomenclature working group has an active and approved project authorization request to develop a standard for terminology specific for quantum technologies.[59]
Terminology for single photon sources and detectors	Under development by NIST	A small team of experts is drafting proposed standard terminology for single photon sources and detectors, expected to be submitted to a standards development organization in late 2022.
Practical Intermediate Representation for Quantum (PIRQ) 2022[60]	Under development by the QED-C	The QED-C is actively exploring architectural concepts for an "intermediate representation" to facilitate running programs in a variety of languages on different quantum computing back-ends. The Standards and Performance Metrics Technical Advisory Committee held a workshop on the topic in July 2021 and published resulting recommendations.
Application-Oriented Performance Benchmarks for Quantum Computing[61]	Publication by the QED-C	This publication, dated 3 January 2022, introduces an open-source suite of quantum application-oriented performance benchmarks (available at https://github.com/SRI-International/QC-App-Oriented-Benchmarks) that is designed to measure the effectiveness of quantum computing hardware at executing quantum applications. The benchmarks probe a quantum computer's performance on various quantum computing algorithms and small applications, as a candidate method for comparing performance across platforms.
Programming language for quantum instructions	Open Quantum Assembly Language (OpenQASM) released by IBM	The language was first described in a paper published in July 2017, and a code implementation was released as part of IBM's software development kit Qiskit. Several quantum computing software development kits, including Google's Cirq, Xanadu's Pennylane, and IBM's Qiskit enable using OpenQASM for defining quantum instructions. This allows researchers and developers to use a common language and use it for different quantum platforms.
Standardization roadmap for quantum technologies	CEN-CENELEC Focus Group on Quantum Technolgies (FGQT)	Motivation to start developing European quantum technology standards in the pillars: quantum computation, quantum communication, and quantum metrology, sensing and imaging.
Use case for quantum technologies	CEN-CENELEC FGQT	Use case for quantum technologies, complementary to the roadmap.

Source: World Economic Forum, Global Future Council on Quantum Computing

A key area that deserves focus is the development of application and performance benchmarks that enable the comparison and evaluation of different technological implications of quantum computing, differences in underlying performance, changes in connectivity and eventual changes in error correcting codes.

Conclusion

Governments, businesses and research organizations have the potential to accelerate technology development for common good – if they work together.

Much progress has been made during the pandemic, particularly in the past year, both in technology development and its accessibility through the cloud, which drove early real-world application trials by businesses.

While the jury is out on what technological approach or approaches to building a quantum computers at scale will prevail, and when quantum computers will be ready, there's no doubt that they will come. In addition to public funding, private investment has tipped the scales, marking the transition of quantum technology from the lab to the real world.

A number of powerful forces are sparking governments and businesses to move:
Firstly, when quantum computers reach the level at which they can provide an advantage over classical computers, they will likely be in short supply. Given the groundbreaking potential of quantum applications in certain industries, no one wants to find themselves in a situation where their competitor is suddenly able to synthesize new compounds for potential drugs in days rather than years. Investing in or partnering with a company developing quantum computers is essentially buying priority access to the technology when it's ready – or the right to sell priority access, if you are an investor.

Secondly, quantum computing developers need business partners to guide technology evolution. They are experts in quantum physics but not in modern industries. This is where companies are coming in, getting early access and having an opportunity to quantify the potential impact of the technology on their industry, find the most efficient use cases and help accelerate technology understanding and development simultaneously. With cloud access to quantum computers, technology providers can look for partners well outside their geographical location.

Thirdly, if the promise of the technology does not convince organizations or they are from the industry sectors that might be less affected and not explicitly mentioned in the "Key sectors for high-impact applications" section, they would still be subject to cybersecurity concerns. Understanding the level of exposure to the potential quantum computing attack and identifying the necessary steps to secure their organization is absolutely doable in 2022. More information on what companies need to know regarding cyber risks posed by quantum computers and detailed actions are covered in the *Transitioning to a Quantum-Secure Economy* white paper.[62]

Further action is needed by governments and businesses to keep the momentum going:
More public-private and pre-competitive collaboration is needed to scale existing workforce development and research programmes and find consensus on common language and performance standards, combined with new policies and regulations to secure an ethical and reliable development and use of technology. More details on the recommended actions for stakeholders to foster the responsible development of the technology are covered in the *Quantum Computing Governance Principles* paper.[63]

More businesses need to understand the implications of quantum computing on their industry and formulate a quantum computing strategy. According to research carried out in March 2022,[64] only 24% of companies in the UK – the host country of one of the most vibrant quantum ecosystems – have put together a team to explore the potential of quantum computing. Yet, 44% are planning to do this in the near term, meaning that understanding the impact of quantum computing on organizations is becoming a staple in technology and business strategy.

In the end, this report will have achieved the desired impact if, upon finishing it, readers feel intrigued to learn about how quantum computers work and how they will benefit them in daily life – and perhaps, join the Forum's Quantum Computing Network. This instinct can prove invaluable, helping to ease apprehension and begin making educated choices in partnerships, technology development and use cases. With more people applying their creativity and collaborating on quantum technology, humanity can get into its golden age of innovation, growth and prosperity much sooner – as well as stand a chance of fighting climate change with quantum-powered decarbonization and other solutions. What else can one wish for?

Contributors

Lead authors

Jerry Chow
Fellow and Director of Quantum Infrastructure, IBM Quantum T. J. Watson Research Center

Eliška Greplová
Assistant Professor, Delft University of Technology

Freeke Heijman
Co-founder and Director, Ecosystem Development, Quantum Delta NL

Carlos Kuchkovsky
Co-founder, QCentroid

Derek O'Halloran
Head, Shaping the Future of Digital Economy and New Value Creation; Member, Executive Committee, World Economic Forum

Jessica Pointing
Quantum Computing Researcher, Oxford University

Grigory Shutko
Platform Curator, IT Industry, World Economic Forum

Carl J Williams
President and Founder, CJW Quantum Consulting

Acknowledgements

Achyut Chandra
Lead, Open Innovations, HCL Technologies

Antonio Córcoles
Research Staff Member, IBM Thomas J. Watson Research Center

Jan Ole Ernst
PhD Candidate, University of Oxford

Mrityunjay Ghosh
Quantum Computing Principal, HCL Technologies

Koen Groenland
Quantum Innovation Officer, QuSoft

Stacey Jeffery
Senior Researcher, QuSoft

Karen Hallberg
Principal Researcher and Associate Professor, Balseiro Institute and Bariloche Atomic Center

Emily Haworth
Research Scientist, Cambridge Quantum

Travis Humble
Deputy Director, Quantum Science Center, Institute of Electrical and Electronics Engineers

Naveen Kumar Malik
Director, Accelerator (Exploration and Incubation); Chief of Staff at CTO Office, HCL Technologies

Justine Lacey
Research Director, Commonwealth Scientific and Industrial Research Organisation

Ulrich Mans
Strategic Partnerships Lead, Quantum Delta NL, Netherlands

Thomas Monz
CEO and Founder, Alpine Quantum Technologies GmbH

Sarah Mostame
Research Staff Member, IBM Thomas J. Watson Research Center

Ana Predojevic
Assistant Professor, Stockholm University

Araceli Venegas-Gomez
CEO and Founder, QURECA

Appendix

The World Economic Forum would like to express its gratitude to the members of the Council, who, through their work and fierce discussions, have been an inspiration and guided many of the concepts presented in the paper.

Members of the Global Future Council on Quantum Computing 2022

Jaya Baloo
Chief Information Security Officer, Avast Software

Thierry Botter
Executive Director, European Quantum Industry Consortium

Fernando Brandão
Head of Quantum Algorithms, Amazon Web Services

Jerry Chow
Fellow and Director of Quantum Infrastructure, IBM Quantum T. J. Watson Research Center

Andrew Fursman
Chief Executive Officer, 1QB Information Technologies

Eliška Greplová
Assistant Professor, Delft University of Technology

Karen Hallberg
Principal Researcher and Associate Professor, Balseiro Institute and Bariloche Atomic Center

Freeke Heijman
Co-founder and Director, Ecosystem Development, Quantum Delta NL

Travis Humble
Deputy Director, Quantum Science Center, Institute of Electrical and Electronics Engineers

Stacey Jeffery
Senior Researcher, QuSoft

Rebecca Krauthamer
Co-founder, Quantum Thought, QuSecure

Carlos Kuchkovsky
Co-founder, QCentroid

B Kalyan Kumar
Global Chief Technology Officer and Head Ecosystems, HCL Technologies

Justine Lacey
Research Director, Commonwealth Scientific and Industrial Research Organisation

Julie Love
Partner Director of Program Management, Quantum Computing, Microsoft

Thomas Monz
CEO and Founder, Alpine Quantum Technologies GmbH

Jessica Pointing
Quantum Computing Researcher, Oxford University

Ana Predojevic
Assistant Professor, Stockholm University

Michelle Simmons
Founder and Chief Executive Officer, Silicon Quantum Computing

Araceli Venegas-Gomez
CEO and Founder, QURECA

Christian Weedbrook
Founder and Chief Executive Officer, Xanadu Quantum Technologies

Carl J Williams
President and Founder, CJW Quantum Consulting

Ilana Wisby
Chief Executive Officer, Oxford Quantum Circuits

Endnotes

1. Swayne, Matt, "TQI Annual Report Looks Back at 2021 in Quantum." *The Quantum Insider*, 6 January 2022, https://thequantuminsider.com/2022/01/06/tqi-annual-report-looks-back-on-3-2-billion-in-investments-steady-stream-of-scientific-advances-of-2021/.
2. Langston, Jennifer, "In a historic milestone, Azure Quantum demonstrates formerly elusive physics needed to build scalable topological qubits", *Microsoft*, 14 March 2022, https://news.microsoft.com/innovation-stories/azure-quantum-majorana-topological-qubit/#:~:text=Microsoft%20believes%20creating%20a%20more,quantum%20physics%20to%20produce%20them.
3. McKinsey & Company, *The Quantum Technology Monitor*, 2022, https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/quantum%20computing%20funding%20remains%20strong%20but%20talent%20gap%20raises%20concern/quantum-technology-monitor.pdf.
4. Ibid.
5. IBM, *IBM Makes Quantum Computing Available on IBM Cloud to Accelerate Innovation* [Press release], 4 May 2016, https://uk.newsroom.ibm.com/2016-May-04-IBM-Makes-Quantum-Computing-Available-on-IBM-Cloud-to-Accelerate-Innovation.
6. Gibney, Elizabeth, "Hello quantum world! Google publishes landmark quantum supremacy claim", *Nature*, 23 October 2019, https://www.nature.com/articles/d41586-019-03213-z.
7. "National Quantum Initiative Act", *US Congress*, 26 June 2018, https://www.congress.gov/bill/115th-congress/house-bill/6227/text.
8. McKinsey & Company, *The Quantum Technology Monitor*, 2022, https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/quantum%20computing%20funding%20remains%20strong%20but%20talent%20gap%20raises%20concern/quantum-technology-monitor.pdf.
9. Qiang Zhang, Feihu Xu, Li Li, Nai-Le Liu and Jian-Wei Pan, "Quantum Information Research in China", *Quantum Science and Technology*, vol. 4, no. 4, 8 November 2019, https://iopscience.iop.org/article/10.1088/2058-9565/ab4bea.
10. "Preliminary trial of quantum computing industrialization China prepares to build 100-billlion level national laboratory", *First Financial*, 6 September 2018, https://www.sciping.com/18028.html.
11. McKinsey & Company, *The Quantum Technology Monitor*, 2022, https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/quantum%20computing%20funding%20remains%20strong%20but%20talent%20gap%20raises%20concern/quantum-technology-monitor.pdf.
12. "The Rise of Quantum Computing" *McKinsey*, 14 December 2021, https://www.mckinsey.com/featured-insights/the-rise-of-quantum-computing.
13. "Rigetti Announces SPAC Deal", *Rigetti Computing*, 6 October 2021, https://www.rigetti.com/merger-announcement.
14. Lefebvre, Manfredi, "Centricus Acquisition Corp. to Combine With Arqit Limited, a Leader in Quantum Encryption technology", *PR Newswire*, 12 May 2021, https://www.prnewswire.com/news-releases/centricus-acquisition-corp-to-combine-with-arqit-limited-a-leader-in-quantum-encryption-technology-301289698.html.
15. Yasmin, Mehnaz, et al., "Quantum computing company D-Wave to go public via $1.6 bln SPAC deal", *Reuters*, 8 February 2022, https://www.reuters.com/technology/quantum-computing-company-d-wave-go-public-via-16-bln-spac-deal-2022-02-08/.
16. "IonQ Becomes First Publicly Traded, Pure-Play Quantum Computing Company; Closes Business Combination with dMY Technology Group III" *IonQ*, 1 October 2021, https://ionq.com/news/october-01-2021-ionq-listed-on-nyse.
17. Sullivan, Mark, "Why quantum computing companies like D-Wave are using SPACs to IPO", *FastCompany*, 13 August 2022, https://www.fastcompany.com/90778231/why-quantum-computing-companies-like-d-wave-are-using-spacs-to-ipo.
18. Keysight Technologies, *Keysight Technologies Acquires Quantum Benchmark* [Press release], 25 May 2021, https://www.keysight.com/us/en/about/newsroom/news-releases/2021/0525-nr21083-keysight-technologies-acquires-quantum-benchmark.html.
19. Zurich Instruments, *Zurich Instruments is now a Rohde & Schwarz Company* [Press release], 5 July 2021, https://www.zhinst.com/ch/en/news/zurich-instruments-now-rohde-schwarz-company.
20. Pasqal, *Quantum Startups Pasqal and Qu&Co Announce Merger to Leverage Complementary Solutions for Global Market* [Press release], 11 January 2022, https://pasqal.io/2022/01/11/quantum-startups-pasqal-and-quco-announce-merger-to-leverage-complementary-solutions-for-global-market/.
21. Lardinois, Frederic, "Quantum Machines Acquires QDevil to Build Out its Full-Stack Quantum Orchestration Platform", *TechCrunch*, 30 March 2022, https://techcrunch.com/2022/03/30/quantum-machines-acquires-qdevil-to-build-out-its-full-stack-quantum-orchestration-platform/.
22. Budde, Florian and Daniel Volz, "The next big thing? Quantum computing's potential impact on chemicals", *McKinsey & Company*, 12 July 2019, https://www.mckinsey.com/industries/chemicals/our-insights/the-next-big-thing-quantum-computings-potential-impact-on-chemicals.

23. Swayne, Matt, “Quantinuum and TotalEnergies Investigate Using Quantum Computers to Study Carbon Capture”, *The Quantum Insider*, 11 April 2022, https://thequantuminsider.com/2022/04/11/quantinuum-and-totalenergies-investigate-using-quantum-computers-to-study-carbon-capture/.
24. Katwala, Amit, “Quantum computers are already detangling nature’s mysteries”, *Wired*, 17 June 2021, https://www.wired.co.uk/article/quantum-computing.
25. Kim, Isaac H., Ye-Hua Liu, Sam Pallister, William Pol, Sam Roberts and Eunseok Lee, “Fault-tolerant resource estimate for quantum chemical simulations: Case study on Li-ion battery electrolyte molecules”, *Physical Review Research*, 7 April 2022, https://journals.aps.org/prresearch/abstract/10.1103/PhysRevResearch.4.023019.
26. Massachusetts Institute of Technology, “Fertilizer and Climate Change”, *Climate Portal*, n.d., https://climate.mit.edu/explainers/fertilizer-and-climate-change.
27. Reiher, Markus, Nathan Wiebe, Krysta M. Svore, and Matthias Troyer, “Elucidating reaction mechanisms on quantum computers”, *Proceedings of the National Academy of Sciences of the United States of America*, 24 May 2017, https://www.pnas.org/doi/10.1073/pnas.1619152114.
28. Maguire, Jack B. Daniele Grattarola, Vikram Khipple Mulligan, Eugene Klyshko and Hans Melo, “XENet: Using a new graph convolution to accelerate the timeline for protein design on quantum computers”, *PLoS, Computation Biology,* e1009037, 27 September 2021, https://journals.plos.org/ploscompbiol/article?id=10.1371/journal.pcbi.1009037.
29. Mulligan, Vikram Khipple, et al., “Designing Peptides on a Quantum Computer”, *bioRxiv*, 11 March 2020, https://www.biorxiv.org/content/biorxiv/early/2020/03/11/752485.full.pdf.
30. Hua, Kefeng, “QuPharm – Pharmaceutical Companies Form Alliance to Share the Risks and Rewards of Quantum Computing”, *LinkedIn*, 14 May 2020, https://www.linkedin.com/pulse/qupharm-pharmaceutical-companies-form-alliance-share-risks-hua/.
31. “Quantum Computing will Transform Drug Discovery Development, Manufacturing, and Supply Chain Management”, *Pharma’s Almanac*, 24 June 2022, https://www.pharmasalmanac.com/articles/quantum-computing-will-transform-drug-discovery-development-manufacturing-and-supply-chain-management.
32. Liu, Yunchao, Srinivasan Arunachalam and Kristan Temme, “A rigorous and robust quantum speed-up in supervised machine learning”, *Nature Physics*, vol. 17, no. 1013-1017, 12 July 2021, https://doi.org/10.1038/s41567-021-01287-z.
33. Banco Bilbao Vizcaya Argentaria, *BBVA pursues the financial sector’s ‘quantum advantage’* [Press release], 17 July 2020, https://www.bbva.com/en/bbva-pursues-the-financial-sectors-quantum-advantage/.
34. “Investing at Quantum Speed”, Goldman Sachs, n.d., https://www.goldmansachs.com/careers/possibilities/quantum-computing/.
35. Cambridge Quantum, *Cambridge Quantum and Deutsche Bahn Netz AG Partner* [Press release], 11 November 2021, https://cambridgequantum.com/cambridge-quantum-deutsche-bahn-partnership/.
36. “Airbus Quantum Computing Challenge – Bringing flight physics into the Quantum Era”, *Airbus*, n.d., https://www.airbus.com/en/innovation/disruptive-concepts/quantum-technologies/airbus-quantum-computing-challenge.
37. Airbus, *Airbus quantum computing challenge helps advance sustainable flight* [Press release], 10 December 2020, https://www.airbus.com/en/newsroom/press-releases/2020-12-airbus-quantum-computing-challenge-helps-advance-sustainable-flight.
38. Gidney, Craig and Martin Ekera, “How to factor 2048 bit RSA integers in 8 hours using 20 million qubits”, *Quantum*, vol. 5, p. 433, 15 April 2021, https://doi.org/10.22331/q-2021-04-15-433.
39. National Institute of Standards and Technology, *NIST Announces First Four Quantum-Resistant Cryptographic Algorithms* [Press release], 5 July 2022, https://www.nist.gov/news-events/news/2022/07/nist-announces-first-four-quantum-resistant-cryptographic-algorithms.
40. Enos, Graham R., et al., “Synthetic weather radar using hybrid quantum-classical machine learning”, *arXiv*, 30 November 2021, http://arxiv.org/abs/2111.15605.
41. Li, Chuan, “OpenAI’s GPT-3 Language Model: A Technical Overview”, *Lambda*, 3 June 2020, https://lambdalabs.com/blog/demystifying-gpt-3/.
42. National Security Agency/Central Security Service, *President Biden Signs Memo to Combat Quantum Computing Threat* [Press release], 4 May 2022, https://www.nsa.gov/Press-Room/News-Highlights/Article/Article/3020175/president-biden-signs-memo-to-combat-quantum-computing-threat/.
43. North Atlantic Treaty Organization, *NATO launches Innovation Fund* [Press release], 30 June 2022, https://www.nato.int/cps/en/natohq/news_197494.htm.
44. Kania, Elsa B., “China’s quest for quantum advantage – Strategic and defence innovation at a new frontier”, *Journal of Strategic Studies*, vol. 44, no. 6, pp. 922-952, 27 December 2021, https://www.tandfonline.com/doi/abs/10.1080/01402390.2021.1973658.
45. “DOE Explains… Quantum Computing”, *Office of Science*, n.d., https://www.energy.gov/science/doe-explainsquantum-computing.
46. “DiVincenzo’s Criteria”, *University of California, Davis*, 2022, https://qc-at-davis.github.io/QCC/How-Quantum-Computing-Works/DiVincenzo’s-Criteria/DiVincenzo’s-Criteria.html.
47. Zhong, Han-Sen, et al., “Quantum computational advantage using photons,” *Science*, vol. 370, no. 6523, pp. 1460-1463, 3 December 2020, https://www.science.org/doi/10.1126/science.abe8770?cookieSet=1.

48. Wack, Andrew, et al., “Quality, Speed, and Scale: three key attributes to measure the performance of near-term quantum computers”, *arXiv,* 28 October 2021, https://arxiv.org/abs/2110.14108.

49. “Measuring Quantum Volume”, *IBM*, 17 June 2021, https://qiskit.org/textbook/ch-quantum-hardware/measuring-quantum-volume.html.

50. Lubinski, Thomas, et al., *Application-Oriented Performance Benchmarks for Quantum Computing*, QED-C, 3 January 2022, https://arxiv.org/pdf/2110.03137.pdf.

51. Venegas-Gomez, Araceli, “The Quantum Ecosystem and Its Future Workforce”, *Phonotics Views*, vol. 17, no. 6, pp. 34-38, January 2021, https://onlinelibrary.wiley.com/doi/10.1002/phvs.202000044.

52. Kaur, Maninder and Araceli Venegas-Gomez, “Defining the quantum workforce landscape: a review of global quantum education initiatives”, *Quantum Resources and Careers*, 2022, https://arxiv.org/pdf/2202.08940v1.pdf.

53. World Economic Forum, *Quantum Computing Governance Principles*, 19 January 2022, https://www.weforum.org/reports/quantum-computing-governance-principles/.

54. Ibid

55. Ibid.

56. Ibid.

57. National Security Agency/Central Security Service, *President Biden Signs Memo to Combat Quantum Computing Threat* [Press release], 4 May 2022, https://www.nsa.gov/Press-Room/News-Highlights/Article/Article/3020175/president-biden-signs-memo-to-combat-quantum-computing-threat/.

58. Auffèves, Alexia, “Quantum technologies need a Quantum Energy Initiative”, *arXiv*, 6 April 2022, http://arxiv.org/abs/2111.09241.

59. “Standard for Quantum Technologies Definitions”, *IEEE SA,* n.d., https://standards.ieee.org/ieee/7130/10680/

60. *Practical Intermediate Representation for Quantum (PIRQ) 2022,* QED-C, 2022, https://quantumconsortium.org/pirq22/

61. Lubinski, Thomas, et al., *Application-Oriented Performance Benchmarks for Quantum Computing*, QED-C, 3 January 2022, https://arxiv.org/pdf/2110.03137.pdf.

62. World Economic Forum, *Transitioning to a Quantum-Secure Economy*, 13 September 2022, https://www.weforum.org/reports/transitioning-to-a-quantum-secure-economy.

63. World Economic Forum, *Quantum Computing Governance Principles*, 19 January 2022, https://www.weforum.org/reports/quantum-computing-governance-principles/.

64. Ernst & Young, *Quantum Readiness Survey 2022*, June 2022, https://assets.ey.com/content/dam/ey-sites/ey-com/en_uk/topics/emerging-technology/quantum/ey-quantum-readiness-survey-2022.pdf.

COMMITTED TO
IMPROVING THE STATE
OF THE WORLD

The World Economic Forum, committed to improving the state of the world, is the International Organization for Public-Private Cooperation.

The Forum engages the foremost political, business and other leaders of society to shape global, regional and industry agendas.

World Economic Forum
91–93 route de la Capite
CH-1223 Cologny/Geneva
Switzerland

Tel.: +41 (0) 22 869 1212
Fax: +41 (0) 22 786 2744
contact@weforum.org
www.weforum.org