CIFAR

A QUANTUM REVOLUTION:
REPORT ON GLOBAL POLICIES FOR QUANTUM TECHNOLOGY

AUTHORS: JOHNNY KUNG, PhD, AND MURIAM FANCY

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ABOUT CIFAR

CIFAR is a Canadian-based global research organization that convenes extraordinary minds to address the most important questions facing science and humanity.

By supporting long-term interdisciplinary collaboration, CIFAR provides researchers with an unparalleled environment of trust, transparency and knowledge sharing. Our time-tested model inspires new directions of inquiry, accelerates discovery and yields breakthroughs across borders and academic disciplines. Through knowledge mobilization, we are catalysts for change in industry, government and society. CIFAR's community of fellows includes 20 Nobel laureates and more than 400 researchers from 20 countries. In 2017, the Government of Canada appointed CIFAR to develop and lead the Pan-Canadian Artificial Intelligence Strategy, the world's first national AI strategy.

CIFAR is supported by the governments of Canada, Alberta, Ontario, and Quebec as well as international partner organizations, individuals, foundations and corporations.

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INTRODUCTION

A century of research into the strange phenomena of the quantum world has given us technologies that are central to modern society: lasers, magnetic resonance imaging, atomic clocks (and thus, GPS), semiconductor electronics (and thus, computers). An increasing ability to control and manipulate quantum systems is fomenting what physicists Jonathan Dowling and Gerard Milburn termed, in a paper in 2003, the "2nd Quantum Revolution".

The tantalizing possibility of technologies such as an unhackable secure network or computers that are billions of times faster than today's supercomputers, and their impact on the economy and society, has driven governments and industry to devote billions of dollars into research and development to try to usher in the new era. Some countries have long focused on providing generous support for research at universities and national institutes, while others have tried to enlist local industry or multinational tech giants; some governments have created national strategies to coordinate a whole-of-government approach to creating a quantum ecosystem, while others have so far divided responsibility (and funding) among government agencies for science, defence and/or telecommunication.

CIFAR has been supporting research in this important scientific field for more than three decades, funding interdisciplinary research programs in Quantum Materials since 1987 and in Quantum Information Science since 2002. The current report will overview the three primary areas of quantum technologies, then highlight the policy measures taken by different countries to support quantum R&D. The intent is not to evaluate the various national approaches or, at this stage, attempt to draw causal links between the policies and the current state of development of quantum technology in the respective country. It is, instead, aimed at providing a snapshot of the rapidly evolving global policy landscape and giving policymakers a reference and a toolkit of potential measures to shape the development of the field in their own countries.

KEY FINDINGS

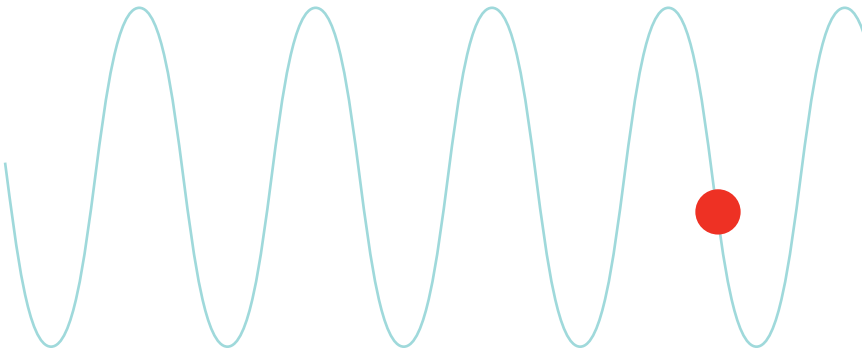
As of January 2021, 17 countries have some form of national initiative or strategy to support quantum technology R&D; 3 have strategies that are in various stages of development. 12 other countries have significant government-funded or -endorsed initiatives. 14 countries in and around Europe that have not developed their own national programs are involved in a number of Europe-wide initiatives.

Many national strategies indicate support for the three primary areas of quantum technology (sensing, communication, computing), but there is clear near-term emphasis on developing quantum communication technologies. Some have also made explicit mid-term goals (by 2030 or before) of building a practical quantum computer and developing use cases that will help create a market for these technologies.

National quantum strategies tend to have two overarching policy goals: convening stakeholders across academia and industry for R&D, and facilitating translation of research into applications. Often there is an additional emphasis on the development of human capital.

Some governments explicitly acknowledge in their national policies a need to begin paying attention to the ethical, social, legal and economic implications of quantum technologies, including the impact on cybersecurity and the global financial system, potential for monopolization by certain countries or multinationals, and issues of privacy and equity.

Broadly, four policy measures are commonly deployed within national quantum strategies: establishing centres of excellence or innovation hubs; making targeted calls for proposals or competitions; providing direct funding for special projects of national significance; and providing government investment or venture capital for startups.



QUANTUM TECHNOLOGIES AN OVERVIEW

The birth of quantum mechanics at the turn of the 20th century gave us an understanding of the often counterintuitive behaviours of the atomic and subatomic world:

- Light and matter can exist both as waves and particles (*wave-particle duality*)
- There are certain sets of physical properties (such as position and momentum) for which it is not possible to know both with absolute precision (*uncertainty principle*)
- A quantum system can exist as a combination of two or more distinct states until it is measured (or interacts with the environment), when it would then "collapse" into a specific state (*superposition*)
- Two or more particles can interact in such a way that their quantum states become correlated, and remain so no matter how far apart they are, so that measuring one particle to be in a specific state instantaneously determines the state of the other (*entanglement*)
- A particle can pass through an otherwise insurmountable barrier to a different location or energy state (*tunnelling*)

In recent decades, our ability to understand and manipulate these quantum phenomena is leading to the development of a variety of technologies, such as quantum communication systems and quantum computers, that promise to bring significant economic and societal benefits, along with major security implications.

Broadly speaking, there are three areas of technologies of the 2nd quantum revolution that are the focus of research and investment by industry and governments:

QUANTUM SENSING AND METROLOGY

Taking advantage of properties such as superposition and entanglement, and their exquisite sensitivity to the external environment, quantum systems (as small as single atoms) are being developed into new types of sensors for highly sensitive, precise and accurate measurements. Properties that can be sensed or measured by these systems include time (for new, more accurate atomic clocks), gravity (for civil engineering, mining or seismology), acceleration (e.g., for navigation systems resistant to GPS-hacking), and magnetic fields (e.g., for inspecting electronic circuits). An example where quantum sensing technology is being translated into commercial application is the SPLICE project supported by the United Kingdom's National Quantum Technologies Programme (NQTP), where an academic-industrial consortium (including energy giants National Grid and BP) are developing cameras for monitoring leakage of greenhouse gases.

QUANTUM COMMUNICATION

Advances in quantum technology will have a major impact on telecommunications and cybersecurity. Modern-day cryptography is often based on systems that exchange security "keys" for decrypting secure data. Breaking these keys involves the mathematical operation of factorization, and for sufficiently large numbers, such an operation would not be completed by a classical computer in reasonable time. However, the speed-up provided by quantum computers (see below) could defeat today's public key encryption systems. Scientists are already developing *quantum key distribution* (QKD) systems, where the encryption keys are shared in the form of quantum particles. Given the sensitivity of quantum systems, quantum keys cannot be copied or "cloned", and any access or tampering of the quantum keys by potential hackers could be detectable by the parties sharing the secure data. (It is worth noting that some stakeholders, such as the United States National Security Agency, recommend against a focus on QKD and instead for the development of "quantum-resistant" cryptographic algorithms.) Quantum communication can be additionally secured with *quantum teleportation*, which makes use of two entangled particles placed at different locations to transmit information (in this case, the quantum state of a third particle interacting with one of the two entangled particles) without any direct information about this third particle ever traversing between the two locations.

A current limitation to the implementation of quantum communication is the fact that signals travelling via a medium such as fibre-optic cables suffer from losses over long distances. While in classical networks the signal can be boosted by an amplifier, the "no-cloning" property that makes quantum information secure also prevents the use of this method. Devices called "trusted nodes" could be used at various points in the network to receive then re-encode the information, but these introduce potentially insecure points of vulnerability. A scaled-up quantum network will likely require the use of satellites (signals can be transmitted through space with lower losses) as well as breakthroughs in the development of *quantum repeaters* that allow for end-to-end entanglement.

Europe, the US and China, among other jurisdictions, are investing heavily in the development of QKD-secured networks. Since 2017, China has operated a fibre-optics based network between Beijing and Shanghai (connected by trusted nodes) over which bank transactions have been sent, and in that same year, China's Micius satellite was used to transmit

a quantum-secured video call between Beijing and Vienna. In Europe, the Quantum Internet Alliance, one of the projects of the European Union (EU) Quantum Technologies Flagship, is working on developing the hardware, software and use cases for a pan-European quantum network.

QUANTUM COMPUTING

Of the various quantum technologies, the one that has perhaps garnered the greatest attention is the quantum computer. While classical computers operate on electronic signals representing bits of information with a value of either 1 or 0, quantum computers operate with "quantum bits" or *qubits* that can be simultaneously 1 and 0, as a result of quantum superposition. In theory, this allows computations to be performed exponentially more quickly than by classical computers. Computational tasks that may be dramatically speeded up by quantum computers include factorization (with implications for cryptography and cybersecurity, as mentioned above), search, optimization, and simulation.

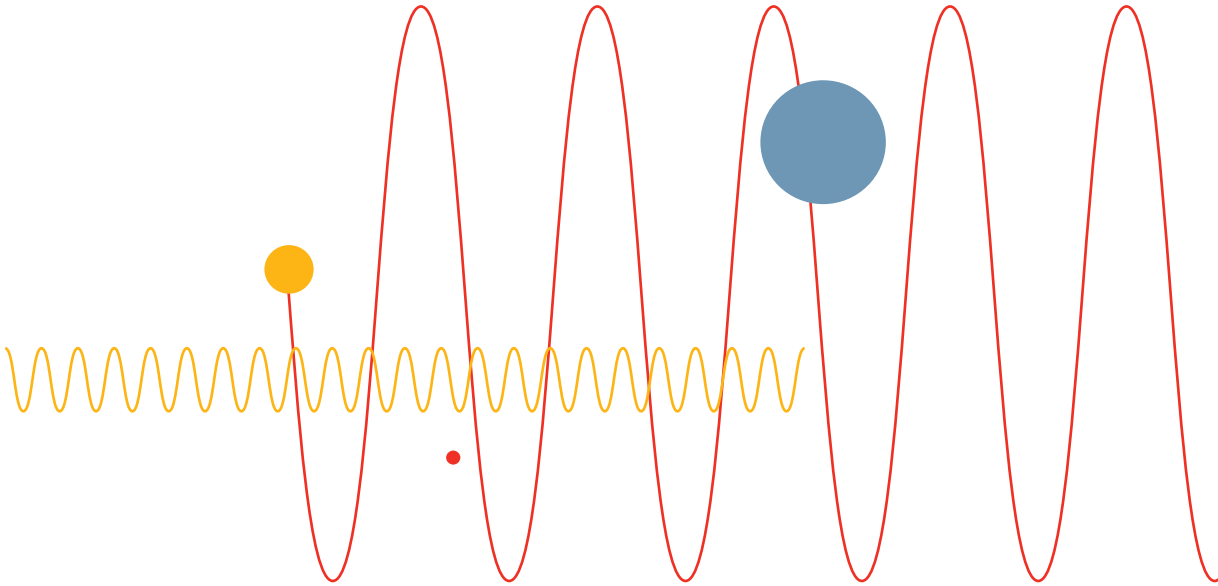
One of the often touted goals in the development of quantum computers is to achieve *quantum supremacy* — when a quantum computer can solve a problem that a classical computer is unable to solve in a reasonable amount of time. In 2019, Google announced that the company had successfully achieved quantum supremacy with a 53-qubit quantum computer, completing in 200 seconds a calculation that, the company suggested, a classical computer would have taken thousands of years. Despite the fact that this particular calculation is very specific and has minimal applicability beyond the experimental setup, and the counterclaim by rival IBM that a classical supercomputer could perform the calculation in days, this development nevertheless brought the possibility of quantum supremacy more firmly into public attention. In December 2020, a team led by the Chinese Academy of Sciences (CAS) Center for Excellence in Quantum Information and Quantum Physics published results for a quantum computer that completed in 200 seconds a calculation that would have taken a supercomputer 2.5 billion years. While many experts in the field consider this demonstration convincing, the computer in question is nonprogrammable — in other words, it can only perform that one task without changes in hardware, rather than just software.

Even without achieving quantum supremacy, however, many researchers and technologists believe that *quantum advantage* (where a quantum computer simply presents a significant speed-up compared to classical computers) could be enough to drive the business case for quantum computers. It is often predicted that, in the next few years, "noisy intermediate-scale quantum" (NISQ) devices (with around a hundred qubits) will be available to begin experimenting with the possibilities provided by quantum computers, and companies including IBM are hoping to roll out 1000-plus qubit machines towards the middle of this decade. But the full potential for quantum computers may likely not be realized until the implementation of *quantum error correction* to counteract the noise and errors caused by the fragility of quantum systems.

There are several different possible technological implementations of qubits, and given that the development of quantum computers is still at a very early stage, it is as yet unclear which one(s) will ultimately prevail. The most mature of the qubit technologies is based on *superconductors*, a type of material in which electric currents flow with no resistance, with each qubit being a small superconducting circuit. Both Google and IBM are focusing their efforts on superconducting qubits, and in September 2020 the UK government announced funding for a £10 million initiative in collaboration with Berkeley-based Rigetti aimed at building the country's first commercially available quantum computer, based on superconducting qubits. Potential shortcomings of superconducting qubits are that they are relatively big, maintain their quantum states for a relatively short time (on the order of ten-thousandths of a second or less) and require refrigeration to near absolute-zero temperature. Other companies, such as Honeywell and Maryland-based IonQ (partly funded by a sovereign investment fund of the United Arab Emirates), are focused on *trapped-ion* systems, where the qubits are electrically-charged atoms (ions) cooled and "trapped" with lasers to maintain superposition. The EU Quantum Flagship is funding the AQTION project to build "an ion-trap quantum computer for Europe".

Yet another approach is to use qubits based on controlling the *spin* (an intrinsic property of particles that, roughly speaking, dictates their magnetic behaviour) of single electrons in silicon, the same element that makes up the circuitry of today's classical computers and which might thus allow for better integration with existing computer chip architecture and manufacturing processes. Intel is investing in silicon spin qubit-based quantum computers (in addition to superconducting qubits), while Silicon Quantum Computing, partly owned by the Australian government, is collaborating with the French Atomic Energy and Alternative Energy Commission to develop a silicon quantum computer. Other technologies include *photonic* quantum computers, which use photons (particles of light) rather than electrons as the information carrier, such as the systems under development by Toronto-based Xanadu and Palo Alto-based PsiQuantum (as well as the Chinese quantum computer by CAS that claimed quantum supremacy); and quantum computers based on an exotic type of superconductors known as *topological materials*, as pursued by Microsoft.

Since the early 2010s, British Columbia-based D-Wave Systems has been commercializing a line of superconductor-based quantum computers with a drastically different mechanism. While the above mentioned systems use logic-gate based circuitry just as in classical computers, the D-Wave computers make use of *quantum annealing*, which essentially simulates computational problems as "energy landscapes" and takes advantage of quantum tunnelling in order to find optimal solutions. It is not universally agreed whether quantum annealers can achieve quantum supremacy for certain calculations, particularly the kind of factorization problems that pose challenges to classical cryptography, but they might still provide useful speed-ups for other applications.



GLOBAL APPROACHES TO SUPPORTING QUANTUM TECHNOLOGY

As with other emerging technologies such as artificial intelligence (AI), quantum technology presents major opportunities for a range of applications, from healthcare, banking, telecommunications, to national security and the military. Countries around the world have recognized the possibilities of quantum technology, and major states such as China, Russia, and the US are racing to develop these technologies.

Part of the reason for this race is economic — one estimate predicts that the emerging market for quantum computers alone would be valued at more than US$800 million by 2024. Similar to the roles played by the digital technology or biotechnology sectors in the late 20th / early 21st centuries, there are strong geopolitical and economic incentives for countries to place their stake in the development of technologies central to this new quantum economy. Another reason driving government interest in this field is the significant security implication of quantum technologies. A fully functioning quantum computer can potentially allow a country or non-state actor to break any public encryption key, enabling them to access and tamper with data secured with current technologies. With quantum technology, information and data security will need to be reimagined.

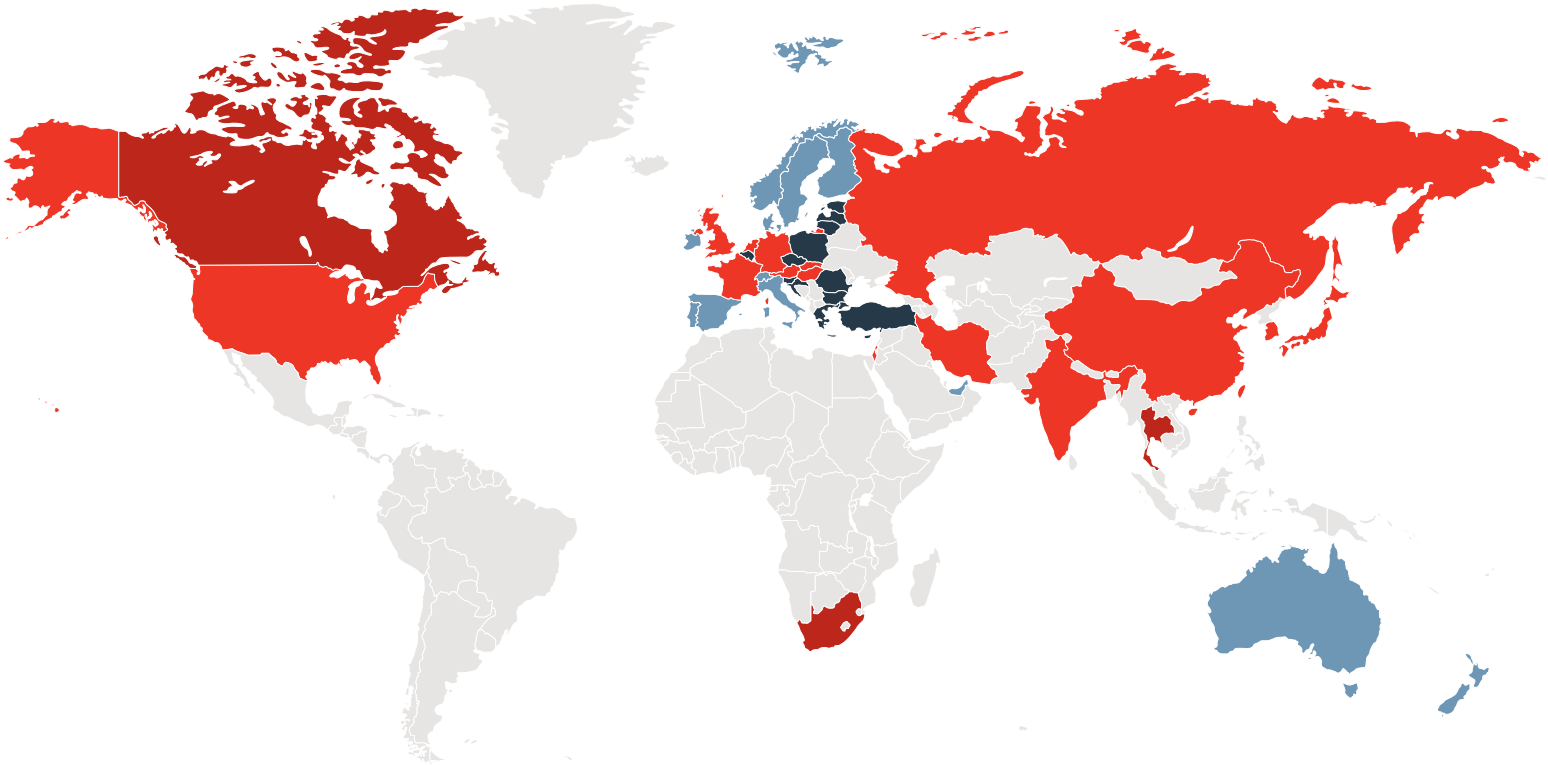
In this section, we provide an overview of the various aspects of national policies or strategies to support quantum technology research and development, including funding types and policy measures.

STRATEGY TYPES

Globally, national approaches to quantum technology R&D can be broadly classified into three categories: countries with a coordinated national strategy (including those with strategies in development); countries that do not have a coordinated strategy but do have significant government funding or programs; and countries that are involved primarily through participation in international partnerships. (See Tables 1-2, Figures 1-2, and Appendix)

FIGURE 1

Global landscape of quantum technology R&D policies.



- Countries with coordinated national quantum strategy
- Quantum strategy in development
- Countries without national strategy, but with significant government or government-endorsed initiatives
- Countries without significant initiatives but are participants in international quantum partnerships

TABLE 1

List of countries categorized by approach to quantum technology R&D.

COUNTRIES WITH COORDINATED NATIONAL QUANTUM STRATEGY

- Austria
- China
- France
- Germany
- Hungary
- India
- Iran
- Israel
- Japan
- Netherlands
- Russia
- Singapore
- Slovakia
- South Korea
- Taiwan
- United Kingdom
- United States

QUANTUM STRATEGY IN DEVELOPMENT

- Canada
- South Africa
- Thailand

COUNTRIES WITHOUT NATIONAL STRATEGY, BUT WITH SIGNIFICANT GOVERNMENT-LED OR -ENDORSED INITIATIVES

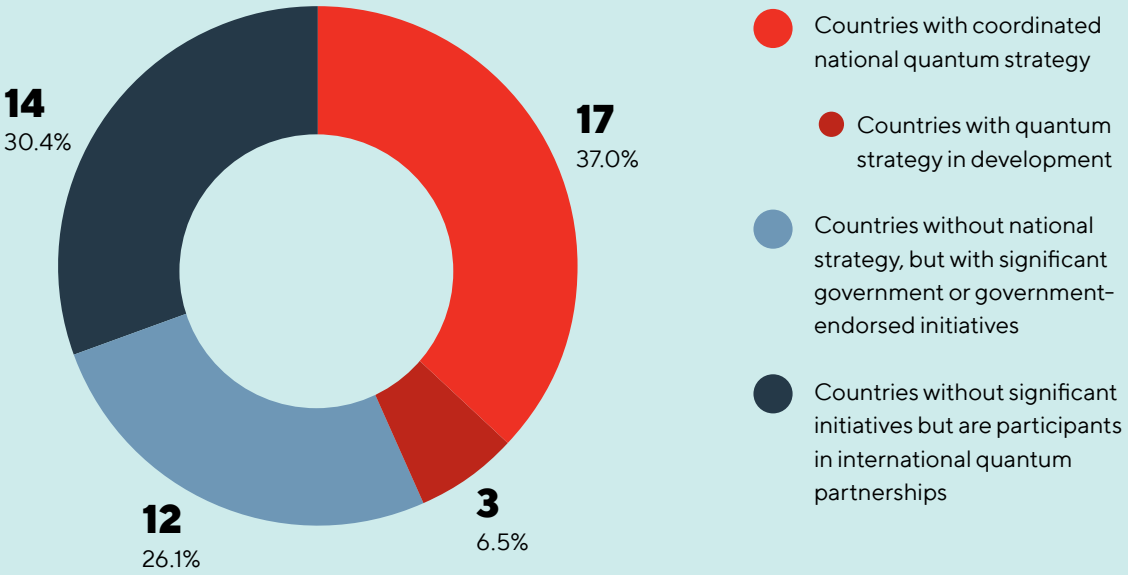
- Australia
- Denmark
- Finland
- Ireland
- Italy
- New Zealand
- Norway
- Portugal
- Spain
- Sweden
- Switzerland
- United Arab Emirates

COUNTRIES WITHOUT SIGNIFICANT INITIATIVES BUT ARE PARTICIPANTS IN INTERNATIONAL PARTNERSHIPS

- Belgium
- Bulgaria
- Croatia
- Cyprus
- Czech Republic
- Estonia
- Greece
- Latvia
- Lithuania
- Malta
- Poland
- Romania
- Slovenia
- Turkey

FIGURE 2

Proportion of countries by type of quantum technology R&D policies.



As of January 2021, 17 countries, including the US, China, Russia, and the UK, have some form of national initiative or strategy to support quantum technology R&D. A further three, including Canada, have strategies that are in various stages of development. In 12 other countries such as Denmark, Spain, and the United Arab Emirates (as well as Canada), the government and/or non-profit foundations have devoted significant resources into quantum-related research or technology development. While these are not coordinated, fully fleshed-out national strategies, they are still often nationally focused, e.g., through supporting research efforts in universities across the country. In two of these countries (Australia and Switzerland), national scientific bodies have given advice to their governments in 2020 on the need to develop a national quantum strategy.

Countries within and around Europe, including 14 that have not developed their own national quantum strategies or significant national programs, are involved in a number of Europe-wide initiatives related to quantum. The most significant of these is the €1 billion EU Quantum Flagship, currently the largest international funding framework for quantum technology, which brings together stakeholders in government, academia and industry from 32 countries within the EU and beyond. The EU's ongoing research funding framework additionally supports other quantum-related projects, including QuantERA (a consortium of research funding agencies across 27 countries that coordinate international, interdisciplinary funding) and OpenQKD (a consortium of industry, university and national institutes from 13 countries working to advance quantum key distribution technology).

TABLE 2

Quantum technology R&D strategies and initiatives in a selection of countries with comprehensive policy measures.

SEE APPENDIX FOR FULL LIST AND DETAILS (P. 24)

COUNTRY (*INCLUDING THE EUROPEAN UNION)	NATIONAL STRATEGY	MAJOR QUANTUM R&D INITIATIVES OR POLICY MEASURES (SINCE 2015 UNLESS OTHERWISE NOTED; US DOLLAR AMOUNTS AT JAN 2021 CONVERSION RATES)
Australia	N/A	• 4 Australian Research Council Centres of Excellence focused on quantum research (AU$130.8M (US$98.6M) for 2017-24) • Department of Defence Next Generation Technologies Fund call-for-proposal on quantum technology (AU$6M (US$4.5M)) • Federal and state governments part-ownership of Silicon Quantum Computing • Sydney Quantum Academy • May 2020 CSIRO roadmap "Growing Australia's Quantum Technology Industry"
Canada	N/A (Quantum Canada strategy in development since 2016)	• Government funding for quantum research centres (C$191.3M (US$149.7M) from federal government in 2015-18 for 4 centres) • Canadian Space Agency Quantum Encryption and Science Satellite (QEYSSat) mission • National Research Council of Canada's Security and Disruptive Technologies Research Centre: Quantum Sensors Challenge program • Natural Sciences and Engineering Research Council / UK Research and Innovation joint call for industry-academia consortia for quantum technology development (C$4.4M (US$3.4M) from Canada) • Venture investments in quantum startups
China	Quantum technology R&D as strategic industry in Five Year Plans and "Made in China 2025"	• Chinese Academy of Sciences Center for Excellence in Quantum Information and Quantum Physics • Quantum Experiments at Space Scale (QUESS) project (Micius satellite) • Beijing-Shanghai Quantum Secure Communication Backbone • National Quantum Laboratory (¥100B (US$15.3B) over five years)

European Union*	Quantum Technologies Flagship (2018)
	
	EuroQCI Declaration
		• Quantum Flagship: ten-year, billion euro program, €152M (US$181M) allocated for 2018-21
		  ◦ 21 technical projects across five areas (communications, simulation, sensing and metrology, computing, basic science) plus 3 horizontal activities
		  ◦ QTEdu
		  ◦ Quantum Industry Consortium
		• QuantERA: €39.8M (US$48.8M) coordinated international research funding partnership
		• OpenQKD: industry-academic consortium for QKD development
		• European Quantum Communication Infrastructure (EuroQCI): towards a secure Europe-wide quantum internet

COUNTRY (*INCLUDING THE EUROPEAN UNION)	NATIONAL STRATEGY	MAJOR QUANTUM R&D INITIATIVES OR POLICY MEASURES (SINCE 2015 UNLESS OTHERWISE NOTED; US DOLLAR AMOUNTS AT JAN 2021 CONVERSION RATES)
France	National Strategy for Quantum Technologies (2021)	• €1.8B (US$2.2B) plan, including €1B (US$1.2B) from government • Key elements of quantum plan: ◦ Call for projects focused on 4 technological areas ◦ Grand Challenge on first-generation NISQ quantum accelerators ◦ Industrial Development Program to support near-market public-private collaborative R&D on enabling technologies ◦ Technology Maturation Program for medium term public-private R&D ◦ Matching fund for startups ◦ Funding for hundreds of new doctoral students, postdocs and young researchers per year ◦ Quantum training for technical diploma, undergraduate and master's students
Germany	Quantum Technologies — From Basic Research to Market (2018)	• €2B (US$2.4B) to support quantum technology research in COVID recovery • Proposed in quantum framework: ◦ Centre of Excellence for Quantum Technologies ◦ Calls for proposals for academic-industry collaborative projects ◦ "Junior research groups" to train future executives in quantum technology ◦ Grand Challenge competition in quantum communication ◦ Up to three Clusters of Excellence in quantum computing • 7 current German Research Foundation Clusters of Excellence with a quantum focus; Quantum Alliance of research centres • QuNET: central platform for secure quantum communication • Fraunhofer-Gesellschaft - IBM collaboration to build Europe's first quantum computer by 2021
India	National Mission on Quantum Technologies & Applications (2020)	• Five-year (2020-24), ₹80B (US$1.08B) budget, with focus on fundamental science, translational research, technology development, and entrepreneurship in four areas: computing, materials, communications, sensing/metrology • Establish 4 research parks and 21 quantum hubs
Israel	National Program for Quantum Science and Technology (2019)	• ₪1.25B (US$380M) over 6 years, including ₪190M (US$58M) in new funding • Program recommendations: establish new research labs; build national quantum computing hardware infrastructure; establish applied R&D centre; speed up application projects in industry and defence • Quantum Technologies Consortium, co-funded by Israel Innovation Authority and Administration for the Development of Weapons and Technological Infrastructure

COUNTRY (*INCLUDING THE EUROPEAN UNION)	NATIONAL STRATEGY	MAJOR QUANTUM R&D INITIATIVES OR POLICY MEASURES (SINCE 2015 UNLESS OTHERWISE NOTED; US DOLLAR AMOUNTS AT JAN 2021 CONVERSION RATES)

Japan	Quantum Technology Innovation Strategy (2020)	• ¥21.5B (US$206M) allocated in FY2020 budget
		• Principles and strategies for next 10-20 years:
		  ◦ Roadmaps for 4 priority technological areas and 3 integrated innovation areas (AI, biotechnology, security)
		  ◦ 5+ quantum innovation centres
		  ◦ 10+ venture companies supported via government investments, procurement, etc
		• Quantum Leap Flagship Program (3 flagship projects and supporting basic research)
		• Project for Innovative AI Chip and Next-Generation Computing Technology Development (R&D stream on quantum annealer and software)
		• Cross-ministerial Strategic Innovation Promotion Program (Photonics and Quantum Technology stream)
		• Goal 6 of the Moonshot Research and Development Program — practical 100-qubit NISQ computer and effective quantum error correction by 2030; large-scale, fault-tolerant quantum computers by 2050

Netherlands	National Agenda for Quantum Technology: Quantum Delta NL (2019)	• Proposed 7-year investment of €700M (US$850M); €23.5M (US$30.0M) over 5 years committed in 2020
		• 3 catalyst programs:
		  1. Build the first European quantum computing platform
		  2. Create National Quantum Network
		  3. Develop quantum sensing applications
		• 5 Innovation Hubs
		• Field labs, expanded national cleanroom facilities, technology transfer program with support for startups
		• Expanded educational programs, industry internships, courses for those currently in industry
		• National ELSA (ethical, legal and social aspects) committee

Russia	Quantum Technologies Roadmap (2019)	• 5-year budget of ₽51.1B (US$691 million) • Responsibility shared by 3 state-owned organizations: Rosatom for quantum computing, RZD (Russian Railways) for quantum communications, Rostec for quantum sensing and metrology • Proposal to build 30-100 qubit computer by 2024 and 1000 qubit computer by 2030 • National Quantum Laboratory with shared infrastructure and startup support • RZD pilot quantum internet in 2021; venture investment funds in partnership with Russian Venture Company

COUNTRY (*INCLUDING THE EUROPEAN UNION)	NATIONAL STRATEGY	MAJOR QUANTUM R&D INITIATIVES OR POLICY MEASURES (SINCE 2015 UNLESS OTHERWISE NOTED; US DOLLAR AMOUNTS AT JAN 2021 CONVERSION RATES)

Singapore	Quantum Engineering Program (2018)	• SG$121.6M (US$90.9M) (2018-25) national program to fund research and ecosystem-building
		• Centre for Quantum Technologies, research centre of excellence supported by National Research Foundation (SG$100M (US$74.8M) core funding for 2017-22)
		  ◦ Commercialization collaboration with SGInnovate
		  ◦ QKD technology for Singtel's fibre network
		  ◦ QKD Qubesat (partnership with UK's RAL Space)

South Korea	Quantum Computing Technology Development Project (2019)	• ₩44.5B (US$40.9M) over 5 years • Goals include developing core hardware for quantum computers and simulators (practical 5-qubit machine with 90% reliability by 2023, use cases demonstration for quantum simulators), and software for quantum computers • Pilot nationwide QKD network in post-COVID "Digital New Deal"
United Kingdom	National Quantum Technologies Programme (2013)	• £400M (US$540M) for first phase (2014-19), at least £350M (US$473M) for second phase • 4 quantum technology hubs • National Quantum Computing Centre to develop use cases with industry and promote formation of UK-based quantum supply chain • Centres for Doctoral Training; Training and Skills Hubs in Quantum Systems Engineering • Rigetti-led consortium to build UK's first quantum computer by 2023 • Industrial Strategy Challenge Fund for projects by academic-industry consortia to bring technology to market • Investment in quantum startups
United States	National Quantum Initiative (2018)	• Up to US$1.275B in spending • National Quantum Coordination Office within White House Office of Science and Technology Policy • National Science Foundation: 3 Quantum Leap Challenges Institutes; Quantum Foundry; Center for Quantum Networks • Department of Energy: 5 Quantum Information Science Centers; blueprint for nationwide quantum internet • Quantum Economic Development Consortium (QED-C) of industry, academic and government stakeholders to build ecosystem and supply chains • National Q-12 Education Partnership

*The European Union is a political and economic union of 27 member states that are located primarily in Europe.

STRATEGY GOALS

In supporting the development of quantum technology in their countries, two overarching policy goals can be identified.

First, governments may act as national conveners, gathering multiple stakeholders to build a network for research and design. There is a heavy emphasis on the role of research centres of excellence or innovation hubs (see below), where academic researchers can work in collaboration with government and industry to advance research, identify areas of application, and launch startups. Many governments have also initiated major strategic projects in quantum technology development that are led by industry-academic consortia.

The second policy goal is to facilitate the translation of research into applications and their commercialization. There is a strong incentive for countries to stake their ground in the global quantum economy by providing funding and resources towards nurturing a local ecosystem for the development of quantum technologies. Policy measures include establishing technology testbeds, supporting startups, strengthening the supply chain for components of quantum technology (such as the fibres and satellites needed for a quantum internet, or the chip fabrication and manufacturing infrastructure for quantum computers), and creating market opportunities for quantum applications. A number of governments, including those of China, South Korea and Germany, have placed an explicit emphasis in their quantum strategies on "technological sovereignty" or a need for local development and control of the core technologies of quantum systems.

An additional key consideration is in developing human capital, both in training the researchers who can advance the technology, and in creating a skilled workforce for a quantum-integrated economy.

POLICY MEASURES

Whether they are laid out in a coordinated national strategy or not, most governments have deployed a number of similar policy measures, beyond regular science funding mechanisms, to support quantum technology R&D within their jurisdiction. (See Table 3, Figure 3)

The most common and longstanding policy is the establishment of centres of excellence, applied R&D centres or innovation hubs to support quantum research and technology development. Some of these centres already have a history of around 20 years — the Australian Research Council's Centre of Excellence in Quantum Computation and Communication Technology dates back to 2000, while the Institute for Quantum Computing in Canada was founded in 2002 with philanthropic funding and subsequent government support. These centres — other examples include hubs such as QuTech and QuSoft in the Netherlands, or Singapore's Centre for Quantum Technology — play a central role in bringing together researchers across their respective country's universities, research institutes and national labs to pursue fundamental research; partnering with industry for technology development and commercialization; and training the academic and industry workforce. In many countries, these centres are funded for a defined period of several years by their respective national research councils through a competitive process open to all fields; the funding may be eligible for an extension or renewal in some funding schemes, but not in others (as is the case for the quantum institutes funded by the Canada First Research Excellence Fund). On the other hand, the coordinated national strategies of several countries specifically support the establishment of quantum-focused research hubs, such as the UK's national network of Quantum Technology Hubs. As part of its National Quantum Initiative, the US National Science Foundation (NSF) funds a series of Quantum Leap Challenge Institutes to promote multidisciplinary research, while the Department of Energy funds the Quantum Information Science Centers at its national laboratories to accelerate technology development.

Several countries have also used, or plan to use, targeted calls for proposals, competitions or Grand Challenges to provide support for quantum R&D. Since 2017, QuantERA has made two calls for proposals for collaborative projects, by international teams across its membership, to advance quantum technology. In 2018, Taiwan made a call for proposals as part of its Quantum Computer Project, which aimed to coordinate quantum technology R&D at a national level. In 2020, Canada's Natural Sciences and Engineering Research Council and UK Research & Innovation made a joint call for UK-Canada industry-academic consortia to develop quantum technologies.

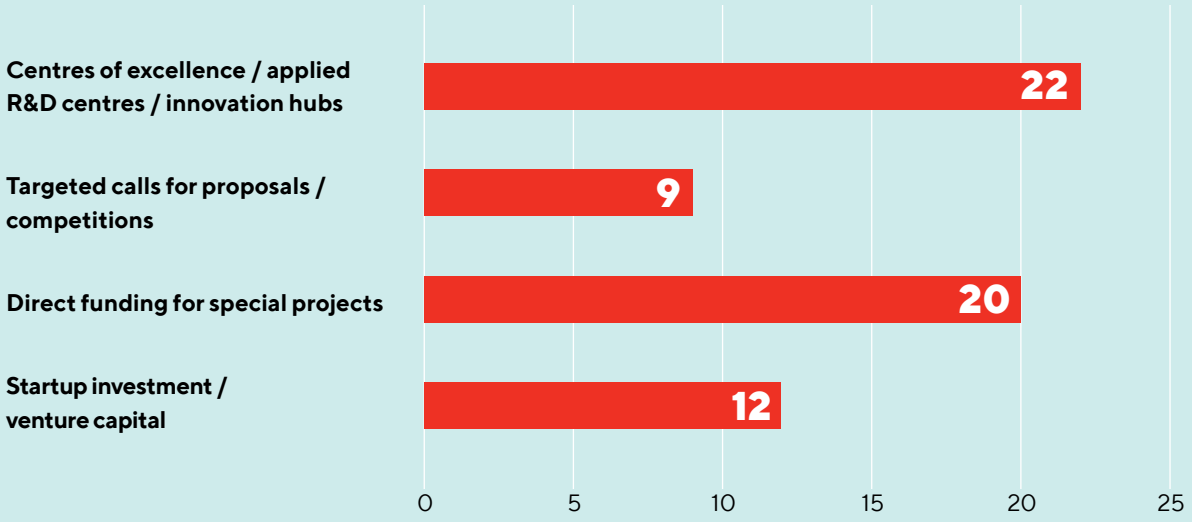
TABLE 3

Four broad measures for supporting quantum R&D and their use among national quantum policies.

COUNTRY (*INCLUDING THE EUROPEAN UNION)	CENTRES OF EXCELLENCE, APPLIED R&D CENTRES, INNOVATION HUBS	TARGETED CALLS FOR PROPOSALS OR COMPETITIONS	DIRECT FUNDING FOR SPECIAL PROJECTS	GOVERNMENT INVESTMENT OR VENTURE CAPITAL FOR STARTUPS
Australia	●	●	●	●
Austria	●			●
Canada	●	●	●	●
China	●		●	●
Denmark	●		●	
European Union*		●	●	
Finland	●		●	●
France	●	●	●	●
Germany	●	●	●	
Hungary	●			
India	●		●	
Ireland			●	
Israel	●		●	
Japan	●		●	●
Netherlands	●		●	
New Zealand	●			
Norway	●			
Russia	●		●	●
Singapore	●	●	●	●
South Korea			●	
Switzerland	●			
Taiwan	●	●	●	
United Arab Emirates	●		●	●
United Kingdom	●	●	●	●
United States	●	●	●	●

FIGURE 3

Number of countries deploying each of four primary policy measures for quantum R&D.



Beyond supporting quantum R&D through research grants and funding calls, governments may also provide direct, targeted funding for quantum projects that are deemed to be of national strategic importance, to accelerate the development of crucial technologies in a targeted manner. For example, various ministries and agencies of the Japanese government support a number of projects led by consortia of industry, universities and national research institutes, with goals including the development of a high-speed, high-precision quantum annealer; a quantum secure cloud with photonic technology; and a practical 100-qubit computer, with demonstration of effective quantum error correction, by 2030. Meanwhile South Korea, as part of its post-COVID "Digital New Deal", has selected several companies to develop a pilot nationwide QKD network.

Finally, a number of countries have put an emphasis on support for local quantum-focused companies. Many of the existing or proposed research centres and innovation hubs for quantum technologies provide support for startups and spinoffs with shared infrastructure such as nanofabrication facilities, technology transfer programs, services such as legal or marketing support, and incubators/accelerators. Several of the national quantum strategies, including those of Japan and France, also propose to provide direct financial support for startups by creating investment funds, with capital raised from government-affiliated financial entities as well as the private sector. Already, countries including the UK, Canada, Austria and Finland have made strategic investments in quantum startups, either through direct government grants or through their public development banks. Both the Australian federal government and the state of New South Wales are part-owners of Silicon Quantum Computing; while in November 2020, the Scottish National Investment Bank, Scotland's public development bank, took a 10-year equity stake in M Squared.

PROJECTS & APPLICATION AREAS

Many national strategies indicate that they will support all three of the primary areas of quantum technology (sensing, communication, computing). However, there is a clear near-term emphasis on developing quantum communication technologies, including quantum satellites, QKD, and quantum-safe cryptography. Individual countries like China and South Korea have launched significant government-backed projects in deploying a national fibre and/or satellite QKD network. At the same time, quantum communication presents an opportunity for global or regional collaboration. For example, the OpenQKD project, launched as part of the EU Horizon 2020 research program, brings together multiple countries to develop secure applications of quantum communication that can be applied in multiple sectors in society. OpenQKD acts as a testbed for technologies that will be used to build a EU-wide cybersecure Quantum Communication Infrastructure (QCI); 25 EU member states have signed on to a declaration on the EuroQCI, which will be developed with the support of the European Space Agency. Some European countries (such as Italy and the Netherlands) are already developing their local quantum networks that would eventually connect into the pan-European network. And since 2018, the North Atlantic Treaty Organization has been partnering with Malta to develop post-quantum cryptography and establish an undersea QKD link between Malta and Italy.

A number of countries, including the UK, Sweden and Japan, have made explicit mid-term goals (by 2030 or before) of building a practical logic gate-based NISQ computer locally. Many governments are also supporting projects where researchers and industry users can collaborate to explore use cases and applications that will create a market for quantum computers, which is crucial for the long term viability of the technology's development. Key application areas being considered include molecular simulations that are important for the chemicals, materials and pharmaceutical industries; modelling for the finance, logistics and energy sectors; and applications to AI and machine learning. Government- spearheaded initiatives, such as the US Quantum Economic Development Consortium (QED-C), are convening academic researchers, government agencies, industry stakeholders and the broader business community to identify specific applications that are important for end-users to spur the necessary technological development. Some countries intend to take advantage of existing national strengths in certain sectors. For example, the Israeli Ministry of Defense and its broader defence industry is a major stakeholder in their country's quantum research; Taiwan is working to leverage the strength of the local semiconductor industry; and South Korea aims to maintain and enhance the strategic advantage of the country's information and communication technology sector.

Countries have also established programs to support the development of quantum sensing technologies. These include the Quantum Sensors Challenge Program of the National Research Council of Canada, which will provide funding to academic, industry and nonprofit collaborators to develop applications for the environment, healthcare and defence; and the UK NQTP's Quantum Technology Hub Sensors and Timing, which brings together university researchers, the National Physical Laboratory and industry stakeholders.

Finally, within the national strategies or research initiatives of many countries is a focus on the discovery and engineering of new, more robust and controllable *quantum materials*. These materials, such as superconductors, topological materials, and more "conventional" materials (like silicon or diamond) with certain impurities or defects, have electronic and magnetic properties that make them suitable for use as quantum sensors, qubits, and other components of quantum computing and communication systems. The US NSF funded its first Quantum Foundry in 2019 to develop new materials and partner with industry to translate these into quantum technology, while the Center for Quantum Materials and Technology Eindhoven (QT/e) anchors one of the five innovation hubs of the Dutch National Agenda for Quantum Technology.

PREPARING FOR THE SOCIETAL IMPLICATIONS OF QUANTUM TECHNOLOGY

As with other novel technologies that hold great promise for our economy and daily life, such as AI and genomics, quantum technology raises important societal and ethical questions that need to be addressed even as research and development is ongoing.

Perhaps the most obvious concern is the potential impact of quantum computers on cybersecurity, the stability of the global financial system, and the privacy of citizens; conversely, the possibility of "eavesdrop-proof" quantum communication could also have implications for law enforcement. There could also be broader geopolitical and security implications — the technology and resources needed to develop and build quantum systems (including rare earth metals or the helium needed for refrigerating quantum computers) could become a major limiting factor to the broad dissemination of these technologies, and countries that have taken a lead in the field or have control over certain resources or core technologies could gain significant economic and geopolitical advantage. International efforts to ensure healthy competition and cooperation could be crucial in this regard.

There is also a potential for the technology to be monopolized by certain countries and/or the multinational tech giants. Presently, many of the major early commercial developers of quantum computers have opened up access to their prototypes over the cloud. Governments might need to consider what policies, if any, they would want to pursue to ensure broad participation across all levels of society and the economy.

Quantum computers are also predicted to contribute to AI and machine learning by dramatically speeding up computer operations for search and optimization. Ethical issues associated with AI, including problems with "black box" decisions, could be exacerbated.

The lack of diversity in the science and engineering workforce remains a significant issue that will negatively impact the quantum sector. Data from the US NSF shows that the fields that feed most directly into quantum (physics, engineering, computer science) continue to be where the underrepresentation of women and racial/ethnic minorities (in particular Black and Latinx individuals) is among the starkest, in terms of degrees earned, employment, and salary. Data from other countries such as the UK paint a similar picture. Making progress on equality and inclusion in these fields will be crucial to ensure that quantum R&D can enlist the best ideas and benefit the broadest cross-section of society.

Some national governments have explicitly acknowledged a need to begin paying attention to social and ethical issues in their quantum policies. For example, the Quantum Software Consortium, funded by the Dutch Research Council, has set up a "Legal and Societal Sounding Board" to perform analyses of the ethical, legal and societal aspects (ELSA) of quantum technologies, and the Dutch National Agenda for Quantum Technology proposes to form a national ELSA committee for such conversations. With the development of quantum still at a relatively early stage, now would be the time to incorporate elements of responsible and ethical technological development throughout the field.

CONCLUSION AND OUTLOOK

Some twenty years since some of the earliest major government investments in quantum research centres, and seven years since one of the first coordinated national quantum strategies (the UK's National Quantum Technologies Programme), the past few years have seen a proliferation around the world of national initiatives or strategic projects, through which individual countries are hoping to position themselves in the race towards the 2nd quantum revolution.

While many of the strategies consist of similar policy measures, differences in priorities or emphasis may have a material impact on the policies' success — e.g., having a coordinated strategy rather than a suite of initiatives from different government departments; focusing support on research at universities and national labs vs. early engagement and partnerships with industry; or targeted but open-ended calls for proposals compared with strategic national projects.

Additional policy questions may include:

- How much have governments followed through on the published strategies and aligned resources or developed policies to support these strategies?
- What are the accountability mechanisms being put in place to track the implementation of the strategies and evaluate the value in creating such strategies?
- What kind of impact has the adoption of such strategies made on talent recruitment, research output or economic activities in the respective countries?

In its renewed strategic intent for its second phase, the UK NQTP highlighted the program's impact in producing research papers, training the workforce, creating spinoffs, and attracting private sector funding. As more of the various national strategies enter their third or fourth year, a comparative analysis may be instructive. Ultimately, the measure of success of a quantum strategy would lie in whether their technological goals have actually been achieved — the deployment of a secure quantum network, a practical quantum computer, or applications that are useful for industry and society. As quantum technology continues to make its rapid advance, the science policy around this field will be sure to evolve as well.

APPENDIX
NATIONAL QUANTUM TECHNOLOGY STRATEGY PROFILES

Each profile provides the following information, where available:

- **Strategy Goals**
- **Highlighted Projects**
- **Talent**
- **Government Funding** (Funding for national strategy, or significant funding since 2015, unless otherwise indicated)
- **Major Public Stakeholders**
- **Other Stakeholders**
- **Primary Sources** (Sources for all countries are listed on page 54)

AUSTRALIA

Category: No national strategy, but with significant government-led or endorsed initiatives

Strategy Goals

- In May 2020, CSIRO (Commonwealth Scientific and Industrial Research Organisation), Australia's national science research agency, published its "Growing Australia's Quantum Technology Industry" roadmap for Australia to maintain its competitive strengths in quantum technology R&D and develop a sustainable quantum technology industry. Its key recommendations to the Australian government include:
  - Develop a national quantum strategy
  - Support the demonstration and commercialization of quantum technologies
  - Build Australia's quantum workforce
  - Assess and build industrial capacities and infrastructure facilities
  - Establish projects to demonstrate commercial applications
  - Encourage local end-users and government engagement with quantum ecosystem

Highlighted Projects

- The Australian Research Council (ARC) supports four Centres of Excellence (CoE) focused on quantum research, each of which are collaborations between multiple universities, research insitutes and companies: Centre for Quantum Computation and Communication Technology (CQC2T, funded since 2000), Engineered Quantum Systems (EQUS), Exciton Science, Future Low-Energy Electronics Technologies (FLEET).
- In 2017, the Department of Defence provided its largest Defence Innovation Hub investment to QuintessenceLabs to develop QKD technology. In 2018, Defence launched a call-for-proposals to develop quantum technology, as part of the Next Generation Technologies Fund.
- The Pawsey Supercomputing Centre, a CSIRO joint venture, is partnering with Quantum Brilliance to install and provide access to a quantum emulator.
- Silicon Quantum Computing, a CQC2T spin-off partly owned by the governments of Australia and New South Wales, is working together with the French Atomic Energy and Alternative Energy Commission to build the first silicon quantum computer.
- Microsoft operates a Quantum Lab in Sydney.

Talent

- The Sydney Quantum Academy (SQA), a partnership of four universities, was established in 2019 to train the next generation of quantum scientists and engineers, providing undergraduate and PhD scholarships, fellowships for academics, a PhD experience program, start-up support, and community outreach.

Government Funding

- Between 2017-24, ARC is investing AU$130.85M (US$98.59M) in its four quantum-focused CoEs.
- In 2017, the governments of Australia and New South Wales invested AU$25M (US$18.8M) and AU$9M (US$6.8M), respectively, in Silicon Quantum Computing. The latter is from a AU$26M (US$19.6M) Quantum Computing Fund to support the commercialization of quantum technology.
- Defence invested AU$3.26M (US$2.46M) in 2017 in QuintessenceLabs, and AU$6M (US$4.5M) for its 2018 call-for-proposals.
- In 2019, the government of New South Wales invested AU$15.4M (US$11.6M) from its Quantum Computing Fund to establish the SQA.

Major Public Stakeholders

- Australian Research Council
- Commonwealth Scientific and Industrial Research Organisation (CSIRO)
- Department of Defence — Defence Science and Technology Group (DST)
- State government of New South Wales

Other Stakeholders

- Q-CTRL
- Quantum Brilliance
- QuintessenceLabs
- Silicon Quantum Computing
- Microsoft
- Commonwealth Bank of Australia
- Telstra

Primary Sources

See page 54.

AUSTRIA

Category: Coordinated national quantum strategy / Participant in international quantum partnerships
Title: Austrian Quantum Technology Initiative

Strategy Goals

- The Austrian Quantum Technology Initiative aims to increase cooperation of Austrian researchers and companies within Europe and internationally, enable development of quantum relevant skills and infrastructure, and support the transition of R&D results into application.

Highlighted Projects

- The Institute for Quantum Optics and Quantum Information (IQOQI) of the Austrian Academy of Sciences was established in 2003. Researchers from IQOQI and other Vienna-area institutions have jointly established a collaborative centre, the Vienna Center for Quantum Science and Technology (VCQ).
- IQOQI researchers are leading partners in the QUAPITAL project, which plans to build a fibre quantum network across central Europe.
- The Federal Ministry of Education, Science and Research supports the Erwin Schrödinger Center for Quantum Science and Technology (ESQ), which brings together research groups across universities and IQOQI, and provide funding for high risk research through the Discovery program.
- Austrian institutions and companies are participants in EU Quantum Flaghship and OpenQKD (for which Austrian Institute of Technology is the coordinator). The Austrian Science Fund and Austrian Research Promotion Agency are partners in QuantERA. Austria is a signatory on the EuroQCI declaration.

Talent

- VCQ operates a joint PhD program. ESQ funds a program for postdoctoral fellows

Government Funding

- €1M (US$1.2M)/year funding for ESQ.
- €32.7M (US$39.6M) for the ramp-up phase (2017-21) for the national R&D funding program for quantum research and technology, including support for EU Quantum Flagship projects.
- In 2018, the Austrian government provided €10M (US$12.1M) for spin-off company Alpine Quantum Technologies. Additional preseed funding was provided in 2019 by Austria Wirtschaftsservice Gesellschaft, the federal development bank.

Major Public Stakeholders

- Federal Ministry of Education, Science and Research (BMWFW)
- Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK)
- Federal Ministry for Digital and Economic Affairs (BMDW)
- Austrian Science Fund (FWF)
- Austrian Research Promotion Agency (FFG)
- Austrian Academy of Sciences (ÖAW)
- Austrian Institute of Technology (AIT)
- Austria Wirtschaftsservice Gesellschaft (AWS)

Other Stakeholders

- Alpine Quantum Technologies

Primary Sources

See page 54.

BELGIUM

Category: Participant in international quantum partnerships

Highlighted Projects

- Belgian experts sit on the EU Quantum Flagship Quantum Community Network. The Belgian Fund for Scientific Research and Research Foundation Flanders are partners in QuantERA. Belgium is a signatory on the EuroQCI declaration.

Government Funding

- See entry for European Union

Major Public Stakeholders

- Fund for Scientific Research (FNRS)
- Research Foundation Flanders (FWO)

Other Stakeholders

- imec (Interuniversity Microelectronics Centre)

Primary Sources

See page 54.

BULGARIA

Category: Participant in international quantum partnerships

Highlighted Projects

- Bulgarian institutions are participants in EU Quantum Flagship. The Bulgarian Science Fund is a partner in QuantERA. Bulgaria is a signatory on the EuroQCI declaration.

Government Funding

- See entry for European Union

Major Public Stakeholders

- Bulgarian Science Fund (NSFB)

CANADA

Category: Coordinated national quantum strategy (in development)

Strategy Goals

- In 2016, the Canadian federal government launched a series of activities, including consultations and symposia, towards the formulation of a Quantum Canada strategy, the goal of which is to develop a cohesive vision for Canada's national interests in quantum, ensure that Canada maintains and expands its current advantage, and expand R&D to drive social, economic, and environmental solutions for Canada. As of Jan 2021, a national quantum strategy has not been completed.

Highlighted Projects

- The Institute for Quantum Computing (IQC) at University of Waterloo was founded with philanthropic funding in 2002, and supported by the Canadian federal government (since 2009) and the provincial government of Ontario (2006-19).
- The Canada First Research Excellence Fund (CFREF), administered by the Tri-Council of research funding agencies, supports three quantum institutes/initiatives: Institut Quantique at Université de Sherbrooke, Stewart Blusson Quantum Matter Institute at University of British Columbia, and Transformative Quantum Technologies at University of Waterloo.
- Since 2017, the Canadian Space Agency (CSA) is working with the IQC and Honeywell on the Quantum Encryption and Science Satellite (QEYSSat) mission to demonstrate space QKD.
- In Dec 2019, the provincial government of British Columbia established the Quantum Algorithms Institute, hosted at Simon Fraser University, that brings together multiple universities and companies to develop quantum computing software for various applications.
- Since Sept 2020, the National Research Council of Canada's (NRC) Security and Disruptive Technologies Research Centre is creating a Quantum Sensors Challenge program to enable the development of quantum sensors for applications to the environment, natural resources, health care, and defence.
- In Nov 2020, NSERC and UK Research and Innovation announced support for eight UK-Canada industry-academia consortia for developing quantum technologies.
- The NRC, Defence and Research Development Canada (DRDC, the Department of National Defence agency focusing on developing new technological solutions), and the Communications Security Establishment (CSE, the national cryptologic agency) have formed the Quantum Security Technology Access Centre (QSTAC) to coordinate and strengthen internal government efforts on quantum research relevant to policy issues. In Dec 2020, Anyon Systems announced that it will deliver Canada's first logic gate-based quantum computer to DRDC.
- Several public investment entities, including the Business Development Bank of Canada, Sustainable Development Technology Canada, and two provincial pension funds (OMERS and Public Sector Pension Investments), are investors in quantum companies including D-Wave and Xanadu.

Talent

- In 2020, the CREATE quantum computing graduate program was established by Quantum BC, a joint initiative of universities in the province, to provide master's and PhD students with research training and industry internships.

Government Funding

- In 2015-16, the Canada First Research Excellence Fund (CFREF) provided C$176.3M (US$138.0M) to three quantum institutes.
- From 2018, the federal government provided C$15M (US$11.7M) over three years to IQC.
- In 2019, the CSA awarded a C$30M (US$23.5M) contract to Honeywell for QEYSSat. The Federal Economic Development Agency for Southern Ontario (FedDev Ontario) invested C$33.7M (US$26.5M) in one non-profit and two startups in the Waterloo area.
- In Dec 2019, the British Columbia provinicial government announced funding of C$17M (US$13.3M) over five years to establish the Quantum Algorithms Institute. In June 2020, the Quebec government invested C$4.5M (US$3.5M) in Institut Quantique to establish an IBM Q Hub. In Oct 2020, the Alberta government provided C$3M (US$2.3M) to Unversity of Calgary and the Quantum Alberta network.
- In June 2020, NSERC provided C$1.65M (US$1.29M) to the Quantum BC graduate program. In Nov 2020, NSERC provided C$4.4M (US$3.4M) to the Canada-UK joint call for proposals on quantum technology.

Major Public Stakeholders

- Innovation, Science and Economic Development Canada (ISED)
- Natural Sciences and Engineering Research Council (NSERC)
- National Research Council of Canada (NRC)
- Canada Foundation for Innovation (CFI)
- Communications Security Establishment (CSE)
- Defence Research and Development Canada (DRDC)
- Canadian Space Agency (CSA)
- Natural Resources Canada (NRCan)
- Business Development Bank of Canada (BDC)
- Sustainable Development Technology Canada (SDTC)
- OMERS
- Public Sector Pension (PSP) Investments
- Provincial governments of Quebec, Ontario, Alberta, British Columbia

Other Stakeholders

- CIFAR
- Mitacs
- Creative Destruction Lab
- Quantum Valley Ideas Lab (QVIL)
- Lazaridis Family Foundation
- 1QBit
- Anyon Systems
- D-Wave Systems
- ISARA
- Quantum Benchmark
- Xanadu
- Zapata Computing

Primary Sources

See page 54.

CHINA

Category: Coordinated national quantum strategy

Strategy Goals

- Quantum technology R&D had been identified as a strategic industry and area for innovation in China's Five Year Plans (China's social and economic development plans) since the 11th plan (2006-10), and in "Made in China 2025" (China's 2015 strategic plan for its manufacturing sector).
- In an Oct 2020 speech to the Politburo (the Communist Party's central executive body), Chinese president Xi Jinping outlined the need to accelerate the development of quantum technology to promote development and ensure national security, with emphasis on:
  - coordinating quantum technology R&D and cultivating strategic industries
  - strengthening policy support and increasing investment
  - accelerating the implementation of quantum S&T projects
  - making breakthroughs in key core technologies and ensuring the safety of the industrial supply chain
  - cultivating high-level talents
  - promoting collaboration between industry, universities and research institutes

Highlighted Projects

- The Chinese Academy of Sciences (CAS) Center for Excellence in Quantum Information and Quantum Physics (CCE-QIQP) was established in 2014, bringing together researchers from several universities and CAS institutes. The CAS-Alibaba Quantum Computing Lab was opened in Shanghai in 2015. In 2019, CAS and the municipal government of Shanghai agreed to build the Shanghai Research Center for Quantum Sciences. The CCE-QIQP's National Quantum Laboratory (NQL) in Hefei is under construction and was slated to open by the end of 2020.
- In 2017, the Beijing municipal government, in partnership with CAS and a number of universities, established the Beijing Academy of Quantum Information Sciences.
- As part of CAS's Quantum Experiments at Space Scale (QUESS) project, China launched the first "quantum satellite", Micius, in 2016 to experiment with a space-to-ground QKD link. The satellite has been used to secure calls between CAS in Beijing and its collaborator at the Austrian Academy of Sciences in Vienna.
- In 2017, the CAS-initiated "Beijing-Shanghai Quantum Secure Communication Backbone", a 2,032-km fibre-optic QKD trunkline connecting multiple metropolitan QKD networks, opened, with plans for further expansion across the country. Initial uses include secure banking transactions.
- In Dec 2020, a team led by CCE-QIQP published results for a (non-programmable) photonic quantum computer that have achieved quantum supremacy, completing in 200 seconds a calculation that would have taken a supercomputer 2.5 billion years.

Talent

- A key emphasis of China's quantum strategy will be on talent development: establishing training programs for quantum specialists, strengthening academic programs, and optimizing the appraisal mechanism for technical personnel.

Government Funding

- Government funding for the construction and operation of NQL is ¥100B (US$15.3B) over five years
- In Feb 2021, Origin Quantum, a CCE-QIQP spinoff, raised "several hundred million yuan" in funding, including from several government-affiliated investors led by China Internet Investment Fund.

Major Public Stakeholders

- Ministry of Science and Technology (MOST)
- Ministry of Industry and Information Technology (MIIT)
- National Development and Reform Commission (NDRC)
- National Natural Science Foundation of China (NSFC)
- Chinese Academy of Sciences (CAS)
- Industrial and Commercial Bank of China
- China Construction Bank
- China Internet Investment Fund
- China Reform Fund
- Municipal governments of Shanghai and Beijing

Other Stakeholders

- Alibaba
- Baidu
- Huawei
- Origin Quantum
- QuantumCTek
- Tencent

Primary Sources

See page 54.

CROATIA

Category: Participant in international quantum partnerships

Highlighted Projects

- Croatian experts sit on the Quantum Flagship Quantum Community Network. The Croatian Science Foundation is a partner in QuantERA. Croatia is a signatory on the EuroQCI declaration.

Government Funding

- See entry for European Union

Major Public Stakeholders

- Croatian Science Foundation (HRZZ)

CYPRUS

Category: Participant in international quantum partnerships

Highlighted Projects

- Cypriot experts sit on the Quantum Flagship Quantum Community Network. Cyprus is a signatory on the EuroQCI declaration.

Government Funding

- See entry for European Union

CZECH REPUBLIC

Category: Participant in international quantum partnerships

Highlighted Projects

- Czech institutions and companies are participants in EU Quantum Flaghship and OpenQKD. The Czech Ministry of Education, Youth and Sports is a partner in QuantERA. The Czech Republic is a signatory on the EuroQCI declaration.

Government Funding

- See entry for European Union

Major Public Stakeholders

- Czech Ministry of Education, Youth and Sports

Primary Sources

See page 54.

DENMARK

Category: No national strategy, but with significant government-led or endorsed initiatives / Participant in international quantum partnerships

Highlighted Projects

- Innovation Fund Denmark made its largest single investment in Qubiz — the Quantum Innovation Center, alongside academic and industrial partners, to promote scientific research for quantum technology (2016-18). In 2020, it invested in two academic-industry consortia developing technology for secure quantum communication, FIRE-Q and CryptQ project.
- The Danish National Research Foundation is currently supporting four centres for quantum-related research: Center for Complex Quantum Systems (CCQ), Center for Macroscopic Quantum States (bigQ), Center for Hybrid Quantum Networks (Hy-Q), Center for Quantum Devices (QDev).
- The Novo Nordisk Foundation is funding two new centres/collaborations: Solid-state Quantum Simulators for Biochemistry (Solid-Q) and Quantum for Life.
- Microsoft operates two Quantum Labs, in Copenhagen and Lyngby.
- Danish institutions are participants in EU Quantum Flaghship and OpenQKD. Innovation Fund Denmark is a partner in QuantERA. Denmark is a signatory on the EuroQCI declaration.

Government Funding

- 80M DKK (US$12.8M) for Qubiz (2016-18) and 40.3M DKK (US$6.6M) for two quantum cryptography projects (2020) by Innovation Fund Denmark
- 302.8M DKK (US$48.9M) by Danish National Research Foundation for four research centres (2012-26)
- 108.6M DKK (US$17.5M) by Novo Nordisk Foundation for two research centres/collaborations (2020)

Major Public Stakeholders

- Innovation Fund Denmark
- Danish National Research Foundation
- Niels Bohr Institute

Other Stakeholders

- Novo Nordisk
- Microsoft
- Danske Bank
- Energienet

Primary Sources

See page 54.

ESTONIA

Category: Participant in international quantum partnerships

Highlighted Projects

- Estonian institutions and companies are participants in EU Quantum Flaghship. Estonia is a signatory on the EuroQCI declaration.

Government Funding

- See entry for European Union

EUROPEAN UNION

Title: Quantum Technologies Flagship

Strategy Goals

- The Quantum Technologies Flagship, launched in October 2018, aims to convene research institutions, industry, public funders to promote European research in the quantum field. The goal of this program is create a competitive industry for commercialization in Europe that is backed by European research.
- Additionally, EU member states, the European Commission and the European Space Agency have agreed to work together towards a European Quantum Communication Infrastructure (EuroQCI), laying the groundworks for a secure Europe-wide quantum internet.

Highlighted Projects

- The Quantum Flagship currently consists of 21 technical projects across five areas (communications, simulation, sensing and metrology, computing, basic science) plus 3 horizontal activities, funded by EU's research funding framework (Horizon 2020 / Horizon Europe). Each project is a collaboration of multiple universities, research institutes and companies across multiple European countries.
- A Quantum Industry Consortium was founded in 2020 to develop the European quantum industry ecosystem.
- The EU research framework additionally funds other quantum-related projects, including QuantERA (a consortium of research funding agencies across Europe to coordinate international, interdisciplinary funding through calls for proposals) and OpenQKD (a consortium of industry, university and national institutes to advance quantum key distribution technology).
- The European Space Agency went into agreement in 2018 with the QUARTZ (Quantum Cryptography Telecommunication System) consortium led by satellite operator SES, with other companies and research organizations, to develop a satellite-based QKD system.

Talent

- In Sept 2020, QTEdu was launched as part of the Quantum Flagship to create a "quantum aware public and quantum ready workforce". Proposed actions include scaling up training and education programs (with focus on secondary, tertiary and industry training) and connecting masters students to industry.
- The Quantum Future Academy, first held in Germany in 2018 and jointly in Germany and France in 2019, will go pan-European in 2021. Bachelor and master's students from 30 countries in Europe and the Middle East will attend lectures, workshops, and industry networking.

Government Funding

- Quantum Flagship is a 10-year, billion-euro program. In the current ramp-up phase (Oct 2018 - Sept 2021), the allocated budget is €152M (US$181M)
- €39.8M (US$48.8M) total budget (2016-22) for QuantERA, including €11.5M (US$14.1M) of EU funding.
- €15M (US$18.4M) of EU funding over 3 years (2019-22) for OpenQKD

Major Public Stakeholders

- EU member states
- European Commission
- European Space Agency

Other Stakeholders

- Thales
- Atos
- IQM
- SES S.A.

Primary Sources

See page 54.

FINLAND

Category: No national strategy, but with significant government-led or endorsed initiatives / Participant in international quantum partnerships

Highlighted Projects

- The Academy of Finland funds Quantum Technology Finland, the National Centre of Excellence in Quantum Technology, which supports fundamental research and research infrastructure for creating solid state quantum applications.
- The Finnish government is funding VTT, a state-owned R&D company, and IQM, a spinoff from VTT and Aalto University, to build Finland's first quantum computer.
- Microsoft's office at Espoo provides fabrication expertise for the company's quantum program
- Finnish institutions are participants in EU Quantum Flagship. Academy of Finland is a partner in QuantERA. Finland is a signatory on the EuroQCI declaration.

Government Funding

- €20.7M (US$25.0M) for VTT quantum computer project
- €3.3M (US$4.0M) investment (2020) in IQM by Business Finland, a government organization for innovation funding

Major Public Stakeholders

- VTT Technical Research Centre of Finland
- Academy of Finland
- Business Finland

Other Stakeholders

- IQM
- Nokia

Primary Sources

See page 54.

FRANCE

Category: Coordinated national quantum strategy / Participant in international quantum partnerships
Title: National Strategy for Quantum Technologies

Strategy Goals

- The French Quantum Plan, launched in January 2021, aims to enable France to be among the first nations to develop a universal quantum computer, ensuring technological sovereignty and contributing to the strategic autonomy of Europe. The strategy will strengthen France's scientific and technological capabilities, the industrial value chain, human capital development, and the anticipation of skills needs of future markets.
- Key objectives:
  - Master 5 strategic areas of technology: NISQ accelerators and simulators; large-scale quantum computers and software; sensors; communication; cryptography
  - Become the first state to develop a prototype for a general quantum computer, by 2023
  - Master the critical industrial sectors in quantum technology, including enabling technologies
  - Become a world leader in lasers and cryogenics
  - Establish a complete industrial production chain for Si-28, for the production of qubits
  - Develop skills and human capital, strengthen technological infrastructure, create an environment favourable to intensified entrepreneurship and technology transfer, and attract global talent

Highlighted Projects

- The Quantum Plan will be led by an interministerial coordinator within the Interministerial Innovation Council. The strategy is defined by the government in cooperation with the major research organizations, with three hubs/clusters in Paris, Saclay and Grenoble.
- Key elements of the plan include:
  - Call for projects via "Program and Equipment for Priority Research" (PEPR) focused on 4 areas: solid-state qubits, cold atoms, quantum algorithms, frontiers of computability and security
  - Grand Challenge on the development of first-generation NISQ quantum accelerators
  - Industrial Development Program to support near-market public-private collaborative R&D on enabling technologies including Si-28, lasers and cryogenics
  - Technology Maturation Program to support medium term public-private collaborative R&D on sensors, error-correction protocols and post-quantum algorithms
  - Develop manufacturing platforms and a quantum metrology platform
  - Incubators and "hub" type initiatives to promote technology transfer
  - Matching fund for startups through government funds such as French Tech Seed and French Tech Souveraineté
  - Public procurement of quantum technologies for computation and defence
- Silicon Quantum Computing (partly owned by the Australian government) and the French Atomic Energy and Alternative Energy Commission are working together to build the first silicon quantum computer.
- French institutions and companies are participants in EU Quantum Flagship and OpenQKD. The French National Research Agency is a partner in QuantERA. France is a signatory on the EuroQCI declaration.

Talent

- Train 5000 new talents in quantum technologies and 1700 young researchers, including 200 new doctoral theses, 200 new postdoctoral contracts, and around 10 young talent grants per year.
- Implement interdisciplinary programs combining quantum physics, algorithms and engineering in engineering schools and master's programs.
- Introduce quantum technology training modules in 2-year undergraduate technical diplomas (DUTs).

Government Funding

- Total investment over 5 years of €1.8B (US$2.2B), including €1B (US$1.2B) from the government (including funding from the 4th Future Investments Plan, as part of COVID recovery), with the rest from the private sector and EU sources

Major Public Stakeholders

- Atomic Energy and Alternative Energy Commission (CEA)
- French National Research Agency (ANR)
- French National Centre for Scientific Research (CNRS)
- French Institute for Research in Computer Science and Automation (INRIA)
- Bpifrance (French public investment bank)
- SGPI (General Secretariat for Investment)
- Électricité de France

Other Stakeholders

- Atos
- Airbus
- Orange
- Thales
- Total

Primary Sources

See page 54.

GERMANY

Category: Coordinated national quantum strategy / Participant in international quantum partnerships
Title: Quantum Technologies — From Basic Research to Market

Strategy Goals

- The focus of the German quantum technologies framework, released in Sept 2018, is on:
  - Developing the quantum technology research landscape
  - Creating research networks for new applications
  - Establishing industrial competitiveness through lighthouse projects
  - Ensuring security and technological sovereignty
  - Shaping international collaboration
  - Getting Germany's population involved

Highlighted Projects

- Under the framework, the German Federal Ministry of Education and Research (BMBF) will establish a Centre of Excellence for Quantum Technologies at the National Metrology Institute (PTB), with a particular focus on supporting industry in transferring research into applications. BMBF also plans to issue calls for proposals for academic-industry collaborative projects, launch a grand challenge competition in quantum communication, and fund up to three Clusters of Excellence in quantum computing.
- The German Research Foundation (DFG) currently funds 7 Clusters of Excellence with a quantum-related focus:
  - Matter and Light for Quantum Information (ML4Q)
  - Munich Center for Quantum Science and Technology (MCQST)
  - QuantumFrontiers
  - Complexity and Topology in Quantum Materials (CT.QMAT)
  - CUI: Advanced Imaging of Matter
  - STRUCTURES
  - Cyber Security in the Age of Large-scale Adversaries (CASA)
- The first five, along with the cluster PhoenixD (Photonics.Optics.Engineering Innovation Across Disciplines) and the Center for Integrated Quantum Science and Technology (IQST, with funding by the state of Baden-Württemberg), are joined in the Quantum Alliance consortium to coordinate activities.
- The BMBF, Fraunhofer-Gesellschaft, Max Planck Institute and German Aerospace Center are collaborating on QuNET, to design a central platform for quantum communications towards the development of a quantum internet in Germany and a European data space.
- The Fraunhofer-Gesellschaft and IBM are collaborating to build Europe's first quantum computer by 2021, with access for companies and research institutions provided through competence centres in six states.
- As part of COVID recovery, the German government will support quantum technology research, with the goal of awarding contracts to suitable consortia to build at least two quantum computers.
- German institutions and companies are participants in EU Quantum Flagship and OpenQKD. The German Federal Ministry of Education and Research is a partner in QuantERA. Germany is a signatory on the EuroQCI declaration.

Talent

- "Junior research groups" to train future executives in quantum technology, supporting young scientists who can bridge the gap between basic research and applications, and would qualfy for leadership in industry.
- "Quantum Futur" academy for advanced university students.
- Create a catalogue of best practices for integrating quantum technologies into courses other than physics, to develop stronger interdisciplinary links.

Government Funding

- The German federal government announced €650M (US$786M) (2018-22) to support its quantum technologies framework.
- The BMBF is providing an initial grant of €25M (US$30M) for QuNET.
- The state of Baden-Württemberg is providing €40M (US$48M) for the IBM-Fraunhofer collaboration.
- As part of COVID recovery, the German government will allocate €2B (US$2.4B) to quantum technology.

Major Public Stakeholders

- Federal Ministry of Education and Research (BMBF)
- Ministry of Economics
- Ministry of the Interior
- Ministry of Defence
- German Aerospace Center (DLR)
- National Metrology Institute of Germany (PTB)
- German Research Foundation (DFG)
- The state governments of Bavaria and Baden-Württemberg
- Fraunhofer-Gesellschaft
- Max Planck Society
- Helmholtz Association
- Leibniz Association

Other Stakeholders

- Deutsche Telekom
- IBM
- Volkswagen

Primary Sources

See page 54.

GREECE

Category: Participant in international quantum partnerships

Highlighted Projects

- Greek experts sit on the Quantum Flagship Quantum Community Network. The General Secretariat for Research and Technology (GSRT) of the Greek Ministry of Education, Research and Religious Affairs is a partner in QuantERA. Greece is a signatory on the EuroQCI declaration.

Government Funding

- See entry for European Union

Major Public Stakeholders

- General Secretariat for Research and Technology (GSRT) of the Ministry of Education, Research and Religious Affairs

Primary Sources

See page 54.

HUNGARY

Category: Coordinated national quantum strategy / Participant in international quantum partnerships
Title: National Quantum Technology Programme

Strategy Goals

- The Hungarian National Quantum Technology Programme will strive to connect Hungary to the currently developing European quantum internet, maintain and improve the competitiveness of researchers in quantum technology and raise the number of quantum technology engineers and researchers in Hungary.

Highlighted Projects

- The HunQuTech consortium is responsible for the Strategy's implementaion, and brings together universities, research institutes and inudstry partners. The consortium's focus is on quantum communication and cryptography, but also has projects on sensing, memory, qubit manipulation and other topics.
- Hungarian experts sit on the Quantum Flagship Quantum Community Network. The Hungarian National Research, Development and Innovation Office is a partner in QuantERA. Hungary is a signatory on the EuroQCI declaration.

Government Funding

- HUF 3.5B (US$11.8M) over 4 years (2018-22)

Major Public Stakeholders

- National Research, Development and Innovation (NRDI)
- Hungarian Academy of Sciences

Other Stakeholders

- Bonn Hungary Electronics
- Ericsson Hungary
- Nokia-Bell Labs
- Femtonics

Primary Sources

See page 54.

INDIA

Category: Coordinated national quantum strategy
Title: National Mission on Quantum Technologies & Applications

Strategy Goals

- India launched a National Mission on Quantum Technologies & Applications in its Union Budget 2020, which will focus on fundamental science, translational research, technology development, and entrepreneurship in four areas: computing, materials, communications, sensing/metrology.

Highlighted Projects

- Under the National Mission, India will establish 4 research parks and 21 quantum hubs (each of which will conduct basic and translational R&D, technology development, training, and startup incubation). The Technology Information, Forecasting and Assessment Council is currently setting up expert committees and consultation to draft a Detailed Project Report for the Mission.
- In 2019, the Department of Science and Technology began funding the Quantum-Enabled Science & Technology (QuEST) program to support collaborative projects that lay the research and infrastructure groundwork for quantum computing and communications.
- Since 2017, the Raman Research Institute and ISRO have collaborated on satellite-based quantum communications.

Talent

- A focus of the National Mission is on human resource development and training the next generation workforce.

Government Funding

- ₹80B (US$1.08B) over 5 years (2020-24) for the National Mission.
  ₹800M (US$10.8M) over 3 years (2019-21) for QuEST.

Major Public Stakeholders

- Department of Science and Technology (DST)
- Technology Information, Forecasting and Assessment Council (TIFAC)
- Raman Research Institute
- Indian Institute of Science
- Indian Space Research Organisation (ISRO)
- Defence Research and Development Organisation (DRDO)
- Department of Atomic Energy (DAE)

Primary Sources

See page 54.

IRAN

Category: Coordinated national quantum strategy

Strategy Goals

- The Atomic Energy Organization of Iran announced in Sept 2019 that a development roadmap for quantum technology had been completed.

Highlighted Projects

- A lab for QKD research was opened at Iranian National Center of Laser Science and Technology in July 2018.

Talent

- The AEOI has launched a public information campaign on quantum physics

Major Public Stakeholders

- Atomic Energy Organization of Iran

Primary Sources

See page 54.

IRELAND

Category: No national strategy, but with significant government-led or endorsed initiatives / Participant in international quantum partnerships

Highlighted Projects

- The Ireland Centre for High-End Computing established the Quantum Programming Ireland (QPI) initiative in 2018 to develop software for quantum applications in AI, chemistry and energy.
- The Quantum Computing in Ireland (QCoir) project, led by a consortium of industry, university and research institutes, was launched in Oct 2020. The project aims to develop a qubit technology-agnostic software platform for potential applications of quantum computing in areas such as logistics, finance and drug discovery.
- Irish institutions are participants in EU Quantum Flagship. Science Foundation Ireland is a partner in QuantERA.

Government Funding

- In Mar 2019, Intel and Enterprise Ireland provided €150K (US$181K) to ICHEC on the Quantum Natural Language Processing project within QPI.
- The QCoir is a €11M (US$13M) project, with €7.3M (US$8.8M) provided by the Disruptive Technologies Innovation Fund, a collaboration fund run by the Department of Enterprise, Trade and Employment, with the rest from industry partners.

Major Public Stakeholders

- The Irish Centre for High-End Computing (ICHEC)
- Tyndall National Institute
- Science Foundation Ireland (SFI)
- Department of Business, Enterprise and Innovation
- Enterprise Ireland

Other Stakeholders

- Intel
- IBM
- Mastercard

Primary Sources

See page 54.

ISRAEL

Category: Coordinated national quantum strategy / Participant in international quantum partnerships
Title: National Program for Quantum Science and Technology

Strategy Goals

- In 2018, the Ministry of Defense, the Council for Higher Education and the Israel Science Foundation acted on the recommendation of the National Advisory Committee for Quantum Science and Technology to establish a research fund for quantum science and technology to form the basis for a quantum ecosystem, with a focus on quantum communication, simulation, sensing and materials.
- In 2019, the TELEM forum (National Infrastructure Forum for R&D) approved a national plan for quantum R&D, with a focus on developing applications and peripheral hardware.

Highlighted Projects

- Recommendations of the TELEM-approved plan include: establishing new research labs; building national quantum computing hardware infrastructure; establishing an applied R&D centre, supporting industries in quantum sensing, communications, and components; and speeding up application projects in industry and defence.
- In Sept 2018, the Israel Innovation Authority, in partnership with the Ministry of Defense's Administration for the Development of Weapons and Technological Infrastructure, launched the Quantum Technologies Consortium (QTC), a MAGNET consortium (a mechanism for supporting pre-competitive R&D) that brings together universities and industry.
- IBM Research - Haifa conducts research on quantum circuit simulation.
- Israeli institutions and companies are participants in EU Quantum Flagship and OpenQKD. The Israel Industry Center for R&D is a partner in QuantERA.

Talent

- The TELEM plan recommends a focus on human resources, including recruitment of academic staff, establishment of academic programs and scholarships, and measures to attract overseas researchers.

Government Funding

- The 2018 research fund earmarks ₪100M (US$30.7M) over five years (2018-22). In the 2019 plan, the government plans to invest ₪1.25B (US$380M) over 6 years, ₪190M (US$58M) of which would be new funding.

Major Public Stakeholders

- Ministry of Defense - Administration for the Development of Weapons and Technological Infrastructure (MAFAT)
- Ministry of Finance
- Ministry of Science & Technology
- Israel Science Foundation
- Council for Higher Education
- Israel Innovation Authority
- Israel Academy of Sciences and Humanities - TELEM forum (National Infrastructure Forum for R&D)
- Israel Aerospace Industries
- Rafael Advanced Defense Systems
- Israel Industry Center for R&D

Primary Sources

See page 54.

ITALY

Category: No national strategy, but with significant government-led or endorsed initiatives / Participant in international quantum partnerships

Highlighted Projects

- The National Institute for Metrological Research (INRIM) has constructed a fibre-optic Italian Quantum Backbone from the French border, through Turin, Milan, Florence, Bologna,Rome, Naples, to Matera. This is serving as a testbed for QKD, gravity measurement, and space geodesy. Current and future projects include a regional network between Udine and Trieste with eventual links to the QUAPITAL network in central Europe, and from Sicily to Malta.
- Italian institutions and companies are participants in EU Quantum Flaghship and OpenQKD. The Italian Ministry for Education, University and Research and National Research Council are partners in QuantERA. Italy is a signatory on the EuroQCI declaration.

Government Funding

- See entry for European Union

Major Public Stakeholders

- Ministry for Education, University and Research (MIUR)
- National Research Council (CNR)
- National Institute of Metrological Research (INRIM)
- National Institute of Optics (INO)
- National Institute for Astrophysics (INAF)
- Italian Space Agency (ASI)
- European Laboratory for Non-linear Spectroscopy (LENS)

Primary Sources

See page 54.

JAPAN

Category: Coordinated national quantum strategy
Title: Quantum Technology Innovation Strategy

Strategy Goals

- The Strategy's final report, published in Jan 2020, lays out principles and strategies for the next 10-20 years, including:
  - Develop roadmaps for 4 priority technological areas (quantum computing and simulation, quantum sensing and metrology, quantum communications and cryptography, quantum materials) for strategic support
  - Develop roadmaps for 3 integrated innovation areas (quantum AI, quantum biotechnology, quantum security) as the most important areas of future development for Japanese industry
  - Set up 5 or more quantum innovation centres to bring together universities/research insitutes and industry
  - Establish a Quantum Technology Innovation Council consisting of universities, research institutes, companies, etc. for each technological area
  - Create 10 or more venture companies via investments by government-affiliated financial institutions or the Innovation Network Corporation of Japan, startup support programs, government procurement, etc

Highlighted Projects

- The Ministry of Education's Quantum Leap Flagship Program (Q-LEAP) is a 10-year (2018-27) R&D program to establish research networks in three technological areas (quantum information technology, quantum metrology and sensing, next-generation laser) to carry out a flagship project each and supporting basic research.
- The New Energy and Industrial Technology Development Organization's 10-year (2018-27) Project for Innovative AI Chip and Next-Generation Computing Technology Development funds industry-academia consortia in four R&D streams, two of which are quantum-related: to realize a high-speed, high-precision quantum annealer and the necessary software platform.
- The Cross-ministerial Strategic Innovation Promotion Program (SIP) is a national project for science, technology and innovation spearheaded by the Cabinet Office's Council for Science, Technology and Innovation. One of the themes selected for the second period of SIP (2018-22) is Photonics and Quantum Technology for Society 5.0, one R&D stream of which is photonic quantum communication, with a focus on developing quantum secure cloud technology.
- Goal 6 of the Moonshot Research and Development Program, a 10-year program launched by the Cabinet Office in 2020, proposes to support R&D towards developing a practical 100-qubit NISQ computer and demonstrating effective quantum error correction by 2030; demonstrating a distributed NISQ computer connected by a secure quantum communications network, and using quantum algorithms with error correction to perform useful tasks, by 2040; and realizing large-scale, fault-tolerant quantum computers by 2050.
- IBM and the University of Tokyo launched the Quantum Innovation Initiative Consortium (QIIC), with other academic and industry partners, to build a quantum computer in Japan by 2021, expand academia-industry-government collaboration, and advance R&D for quantum and supporting technologies.

Talent

- Innovation Strategy proposes to promote human resource development through systematic educational programs at universities, recruit overseas talent (e.g., through the quantum innovation centres), and foster a "quantum native" generation through enhanced science and math curriculum in high schools and technical colleges and science communication activities.

Government Funding

- ¥21.5B (US$206M) was allocated in the FY2020 budget towards the Quantum Technology Innvoation Strategy, which encompasses the Q-LEAP, NEDO and SIP projects and others.
- The proposed 5-year budget for the entire Moonshot program is ¥100B (US$960M)

Major Public Stakeholders

- Cabinet Office (CAO)
- Ministry of Education, Culture, Sports, Science and Technology (MEXT)
- Ministry of Economy, Trade and Industry (METI)
- Japan Science and Technology Agency (JST)
- New Energy and Industrial Technology Development Organization (NEDO)
- RIKEN
- National Institute of Informatics
- National Institute of Advanced Industrial Science and Technology (AIST)
- National Institutes for Quantum and Radiological Science and Technology (QST)
- National Institute of Information and Communications Technology (NICT)

Other Stakeholders

- IBM
- Fujitsu
- Hitachi
- Mitsubishi
- NEC
- NTT
- Toshiba
- Mizuho Financial Group

Primary Sources

See page 54.

LATVIA

Category: Participant in international quantum partnerships

Highlighted Projects

- Latvian companies and experts are participants in EU Quantum Flaghship. The Latvian State Education Development Agency is a partner in QuantERA.

Government Funding

- See entry for European Union

Major Public Stakeholders

- State Education Development Agency (VIAA)

LITHUANIA

Category: Participant in international quantum partnerships

Highlighted Projects

- Lithuanian experts sit on the Quantum Flagship Quantum Community Network. Lithuania is a signatory on the EuroQCI declaration.

Government Funding

- See entry for European Union

MALTA

Category: Participant in international quantum partnerships

Highlighted Projects

- NATO SPS launched two joint projects with Malta, as a member country of NATO Partnership for Peace, on post-quantum cybersecurity and secured communication. The first project will develop post-quantum cryptographic protocols. The second will develop a fibre optics quantum communication link between Malta and Italy.
- Maltese institutions and experts are participants in the EU Quantum Flagship. Malta is a signatory on the EuroQCI declaration.

Major Public Stakeholders

- University of Malta

Primary Sources

See page 54.

NETHERLANDS

Category: Coordinated national quantum strategy / Participant in international quantum partnerships
Title: National Agenda for Quantum Technology

Strategy Goals

- The National Agenda, published in Sept 2019, aims to position the Netherlands as a leading international centre and hub for quantum technology, the Quantum Delta NL. There are 4 key actions:
  - Promote research and innovation in 6 fields (computing, simulation, communication, sensing, algorithms, cryptography)
  - Develop an ecosystem, create a market, and establish infrastructure
  - Build human capital by focusing on education, knowledge and skills
  - Promote a social dialogue on quantum technology
- The Agenda also defines three catalyst programs to bring together ecosystem actors and accelerate the introduction of quantum technology into society:
  - Build the first European quantum computing platform, with application development
  - Create a National Quantum Network
  - Develop quantum sensing applications

Highlighted Projects

- 5 innovation hubs, each with a different focus, will bring together universities, research institutes, companies, and startups:
  - QuTech (Advanced Research Center for Quantum Computing and Quantum Internet), Delft
  - Quantum.Amsterdam, anchored by QuSoft (Research Centre for Quantum Software)
  - QT/e (Center for Quantum Materials and Technology Eindhoven)
  - aQa (Applied Quantum Algorithms – Leiden)
  - a hub in Twente focused on nanotechnology for quantum applications
- To build an ecosystem, the Agenda proposes to create field labs to test and implement targeted solutions to challenges facing various industries, expand national cleanroom facilities, and establish a technology transfer program with support for startups.
- Quantum Software Consortium (formed by QuTech, QuSoft and Leiden) has established a Legal and Societal Sounding Board. The Agenda also proposes to form a national ELSA (ethical, legal and social aspects) committee and initiate national and international dialogues to create regulatory and ethical frameworks for quantum technologies.
- Intel Labs has been collaborating with QuTech since 2015 on advancing quantum computing. Microsoft also opened a Quantum Lab in Delft in 2019.
- Dutch institutions are participants in EU Quantum Flaghship and OpenQKD. The Netherlands Organisation for Scientific Research is a partner in QuantERA. The Netherlands is a signatory on the EuroQCI declaration.

Talent

- Building on the QuTech Academy in Delft, the Quantum Information Module and QuSoft master's in Amsterdam, and the Quantum Materials & Technologies Certificate at QT/e, the Agenda proposes to expand and strengthen educational programs. Other proposals include industry internships and courses for those currently in industry, activities for teachers and the public, and measures to attract international talent (e.g., professorships or posts for entrepreneurs).

Government Funding

- The proposed investment for the National Agenda over 7 years is €700M (US$850M). €23.5M (US$30.0M) over 5 years was announced in 2020.

Major Public Stakeholders

- Ministry of Economic Affairs and Climate
- Netherlands Organisation for Applied Scientific Research (TNO)
- Netherlands Organisation for Scientific Research (NWO)
- Techleap.nl

Other Stakeholders

- Microsoft
- Intel
- Shell
- ABN AMRO

Primary Sources

See page 54.

NEW ZEALAND

Category: No national strategy, but with significant government-led or endorsed initiatives

Highlighted Projects

- The Dodd-Walls Centre for Photonic and Quantum Technologies is a national Centre of Research Excellence, bringing together a network of six universities to undertake fundamental research and promote innovation by supporting commercialization and developing prototypes.

Talent

- The Dodd-Walls Centre trains graduate students and provides them with networking/ recruitment opportunities with industry.

Government Funding

- Centre of Research Excellence (CoRE) funding for the Dodd-Walls Centre was NZ$5.04M (US$3.57M) per year from 2015-21. It was renewed in Oct 2020 for NZ$36.75M (US$26.06M) over seven years (2021-28).

Major Public Stakeholders

- Tertiary Education Commission (TEC)

Primary Sources

See page 54.

NORWAY

Category: No national strategy, but with significant government-led or endorsed initiatives / Participant in international quantum partnerships

Highlighted Projects

- The Research Council of Norway funds QuSpin, a research centre of excellence focusing on quantum spintronics.
- SINTEF, Norway's largest independent research organization, launched a strategic project in 2019 to research algorithms for applications of quantum computing, including optimization and machine learning.
- Norwegian companies and experts are participants in the EU Quantum Flagship. The Research Council of Norway is a partner in QuantERA.

Government Funding

- NOK 129.2M (US$14.7M) over 10 years (2017-27) for QuSpin

Major Public Stakeholders

- Research Council of Norway

Other Stakeholders

- SINTEF

Primary Sources

See page 54.

POLAND

Category: Participant in international quantum partnerships

Highlighted Projects

- Polish institutions and companies are participants in EU Quantum Flaghship and OpenQKD. The Polish National Science Centre is the coordinator of QuantERA, and the National Centre for Research and Development is a partner. Poland is a signatory on the EuroQCI declaration.

Government Funding

- See entry for European Union

Major Public Stakeholders

- National Science Centre (NCN)
- National Centre for Research and Development (NCBR)
- Ministry of Science and Higher Education
- Poznan Superconmputing and Networking Centre (affiliated with the Polish Academy of Sciences)

Other Stakeholders

- Foundation for Polish Science

Primary Sources

See page 54.

PORTUGAL

Category: No national strategy, but with significant government-led or endorsed initiatives / Participant in international quantum partnerships

Highlighted Projects

- QuantaLab is a consortium of the International Iberian Nanotechnology Laboratory (a Portugal-based institute jointly funded by the governments of Spain and Portugal), University of Minho, INESC TEC (a research institute focusing on both R&D and technology transfer), and Ceiia (Centre for Excellence and Innovation in the Automotive Industry). It is also an IBM Q Hub.
- Portugese institutions are participants in the EU Quantum Flagship. The Portugese Foundation for Science and Technology is a partner in QuantERA. Portugal is a signatory on the EuroQCI declaration.

Talent

- The Quantum Portugal Initiative is a call for PhD scholarships opened by the INL and the Portugese Foundation for Science and Technology.

Government Funding

- See entry for European Union

Major Public Stakeholders

- Foundation for Science and Technology (FCT)
- International Iberian Nanotechnology Laboratory (INL)
- INESC TEC (Institute for Systems and Computer Engineering, Technology and Science)
- Instituto de Telecomunicações (IT)

Other Stakeholders

- Ceiia
- IBM

Primary Sources

See page 54.

ROMANIA

Category: Participant in international quantum partnerships

Highlighted Projects

- Romanian experts sit on the Quantum Flagship Quantum Community Network and Strategic Advisory Board. The Romanian Executive Agency for Higher Education, Research, Development and Innovation Funding is a partner in QuantERA. Romania is a signatory on the EuroQCI declaration.

Government Funding

- See entry for European Union

Major Public Stakeholders

- Romanian Executive Agency for Higher Education, Research, Development and Innovation Funding (UEFISCDI)

Primary Sources

See page 54.

RUSSIA

Category: Coordinated national quantum strategy
Title: Russian Quantum Technologies Roadmap

Strategy Goals

- The Russian federal government announced support in Dec 2019 for the Quantum Technologies Roadmap, which details plans and metrics for quantum technology research and development in the country, in order for Russia to keep pace with other developed countries and maintain national security and technological independence.
- 3 state-owned organizations are responsible for different parts of the roadmap — Rosatom (State Atomic Energy Corporation) for quantum computing, RZD (Russian Railways) for quantum communications, Rostec (State Corporation for Assistance to Development, Production and Export of Advanced Technology Industrial Product) for quantum sensing/metrology

Highlighted Projects

- The Roadmap proposes to build a 30-100 qubit computer by 2024 and a 1000 qubit computer by 2030.
- A National Quantum Laboratory was launched in Nov 2020 to bring together universities, research institutes and companies. The NQL will build infrastructure such as a nanofabrication centre; provide legal, marketing, financial and intellectual property support; and create an incubator and accelerator for startups.
- RZD has developed a road map for advancing quantum communication technology to create secure communication infrastructure. A pilot quantum internet is planned for launch in 2021, with support by the Russian Venture Company (RVC).

Talent

- The Roadmap proposes to increase quantum-related instruction in general education, develop standards for quantum technology programs in higher education, and attract foreign specialists (including Russian-speakers abroad).
- In 2019, the RVC, RQC and National University of Science and Technology MISIS partnered to develop a master's program in project management in quantum communications, as well as three commercial continuing education programs.

Government Funding

- The budget of the roadmap is ₽51.1B (US$691 million) over five years, with ₽8.7B (US$120M) from private companies
- The RVC, Russian state's fund of funds and institutional investor, provides venture investment in early stage companies and projects, through the Venture Fund of National Technology Initiative as well as funds that will be launched in 2021 in partnership with RZD.

Major Public Stakeholders

- Ministry of Science and Higher Education
- Russian Science Foundation
- Russian Foundation for Basic Research
- Russian Foundation for Advanced Research Projects
- Russian Quantum Center (RQC)
- Tsifrum
- Rosatom
- RZD
- Rostec
- Skolkovo Institute of Science and Technology
- Russian Academy of Sciences
- Russian Venture Company (RVC)
- Sberbank
- Gazprom (Gazprombank, Gazprom Neft)

Other Stakeholders

- SIBUR

Primary Sources

See page 54.

SINGAPORE

Category: Coordinated national quantum strategy
Title: QEP — the Quantum Engineering Program

Strategy Goals

- QEP, a national program supported by the Prime Minister's Office, was launched in 2018 to fund research and ecosystem-building towards applying quantum technologies to solve user-defined problems. Industry and user-agencies can collaborate, with cash or in-kind contributions. Funded projects are expected to generate IP and industrial outcomes (e.g., spin-offs or prototypes). QEP will support the development of systems (both quantum instruments and enabling technologies) that will demonstrate quantum advantage.

Highlighted Projects

- QEP is currently supporting projects in quantum computing, communication and sensing; a quantum foundry to build capacity for designing, fabricating and characterizing chips for quantum technologies; and a collaboration with IBM to provide access to its quantum cloud.
- The Centre for Quantum Technologies (CQT) at the National University of Singapore (NUS), a research centre of excellence supported by the National Research Foundation, was established in 2007 to conduct basic quantum research and build quantum technologies.
- SGInnovate, a government-owned investment entity, is collaborating with CQT to commercialize quantum innovations. Three CQT spin-offs have been established so far.
- CQT is part of the NUS-Singtel Cyber Security Research and Development Laboratory, set up in 2016 to develop QKD technology for the telecom's fibre network.
- UK's RAL Space and CQT have partnered to launch QKD Qubesat, a joint space program to build a secure QKD testbed, by 2021.

Talent

- One of the pillars of CQT's work is education, through a doctoral program, internships for undergraduate and master's students, and training workshops for industry and users.

Government Funding

- From 2018-25, the NRF is investing SG$121.6M (US$90.9M) for the QEP.
- From 2007-17, the NRF and the Ministry of Education has provided SG$195M (US$146M) in core funding to the CQT; another SG$100M (US$74.8M) is provided for 2017-22.

Major Public Stakeholders

- Ministry of Education
- SGInnovate
- National Research Foundation Singapore

Other Stakeholders

- Singtel
- IBM

Primary Sources

See page 54.

SLOVAKIA

Category: Coordinated national quantum strategy / Participant in international quantum partnerships
Title: QUTE.sk - Slovak National Research Platform for Quantum Technologies

Strategy Goals

- The goal of the QUTE.sk platform is to create an environment in Slovakia for R&D of quantum technologies and training of the next generation of experts. The Ministry of Education, Science, Research and Sports supports this initiative in accordance to the EU Quantum Flagship.

Highlighted Projects

- QUTE.sk establishes a virtual institute, iQUTE, to coordinate research activities of eight cross-institute research groups on five goals: quantum information structures and metrology, quantum electronics for quantum communication and computing, implementations of quantum bits, quantum simulations and quantum complexity, quantum and postquantum cryptography
- Slovak researcher is leading the joint NATO-Malta project on Secure Communication in the Quantum Era.
- Slovakian experts sit on the Quantum Flagship Quantum Community Network and Strategic Advisory Board. The Slovak Academy of Sciences is a partner in QuantERA. Slovakia is a signatory on the EuroQCI declaration.

Talent

- The education iniaitive of QUTE.sk, eduQUTE, proposes to establish postgraduate study programs and scholarships in quantum, doctoral summer schools, and support for postdoctoral researchers.

Government Funding

- The Slovak Ministry of Education, Science, Research and Sports had provided €100K (US$121K) to support initiation of QUTE.sk

Major Public Stakeholders

- Slovak Academy of Sciences
- Ministry of Education, Science, Research and Sports

Primary Sources

See page 54.

SLOVENIA

Category: Participant in international quantum partnerships

Highlighted Projects

- Slovenian institutions and companies are participants in EU Quantum Flaghship. The Slovenian Ministry of Education, Science and Sport is a partner in QuantERA. Slovenia is a signatory on the EuroQCI declaration.

Government Funding

- See entry for European Union

Major Public Stakeholders

- Slovenian Ministry of Education, Science and Sport

Primary Sources

See page 54.

SOUTH AFRICA

Category: Coordinated national quantum strategy (in development)
Title: Framework for Quantum Computing and Quantum Technology

Strategy Goals

- In Dec 2019, the Department of Science and Innovation (DSI) set up a National Working Group to develop a Framework for Quantum Computing and Quantum Technology (NWG:QC&QT) for South Africa. After analyzing the current landscape, the NWG:QC&QT will identify priority areas, infrastructure needs, and alignment with the DSI's decadal plan.

Highlighted Projects

- In June 2019, IBM Research at Johannesburg partnered with the University of Witwatersrand to expand the IBM Q Network into Africa and provide access to the other 15 research universities across Africa within the African Research Universities Alliance (ARUA).

Major Public Stakeholders

- Department of Science and Innovation (DSI)

Other Stakeholders

- IBM

Primary Sources

See page 54.

SOUTH KOREA

Category: Coordinated national quantum strategy
Title: Quantum Computing Technology Development Project

Strategy Goals

- In Jan 2019, the South Korean Ministry of Science and ICT announced a 5-year Quantum Computing Technology Development Project to ensure the continued competitiveness and strategic advantage of South Korea's ICT industry, particularly through the development of next-generation core technologies and research ecosystem.
- Additionally, as part of the post-COVID "Digital New Deal", South Korea will be piloting a national-wide QKD network.

Highlighted Projects

- The Development Project has two primary goals:
  - Develop the core hardware for quantum computers and simulators, specifically, (a) by 2023, implement a practical 5-qubit machine with 90% reliability, and (b) demonstrate use cases for quantum simulators with societal and economic benefits
  - Develop the software needed for quantum computers, such as new architectures and algorithms

Talent

- A core pillar of the Development Project is to create a robust national quantum research ecosystem, through the establishment of 33 quantum computing research groups, including 7 key teams for core technologies.

Government Funding

- ₩44.5B (US$40.9M) over 5 years (2019-23)

Major Public Stakeholders

- The Ministry of Science and ICT (MSIT)
- National Research Foundation of Korea
- KRISS (Korea Research Institute of Standards and Science) Quantum Technology Institute

Other Stakeholders

- SK Telecom
- KT
- Samsung
- LG
- Hanwha Systems

Primary Sources

See page 54.

SPAIN

Category: No national strategy, but with significant government-led or endorsed initiatives / Participant in international quantum partnerships

Highlighted Projects

- The Spanish National Research Council (CSIC) Platform for Quantum Technologies (QTEP) brings together researchers from CSIC institutes across Spain and industry collaborators. Partners include BBVA (on the development of quantum algorithms for financial applications) and the IBM Q Network.
- Spanish institutions and companies are participants in EU Quantum Flaghship and OpenQKD. The Spanish State Research Agency is a partner in QuantERA. Spain is a signatory on the EuroQCI declaration.

Government Funding

- See entry for European Union

Major Public Stakeholders

- Ministry of Economy, Industry and Competitiveness (MINECO) — State Research Agency (AEI)
- Spanish National Research Council (CSIC)
- Centro de Supercomputación de Galicia (CEGSA)

Other Stakeholders

- Telefónica
- BBVA
- IBM

Primary Sources

See page 54.

SWEDEN

Category: No national strategy, but with significant government-led or endorsed initiatives / Participant in international quantum partnerships
Title: The Wallenberg Centre for Quantum Technology (WAQCT)

Highlighted Projects

- The Knut and Alice Wallenberg Foundation, a major private research foundation, is supporting the establishment of a national quantum research centre to build broad competence in quantum technology in Sweden and to develop a Swedish quantum computer. The core project of the WAQCT is to build a 100-qubit quantum computer in 10 years. An excellence program supports research in quantum computing, simulation, communciation and sensing.
- Swedish institutions and companies are participants in the EU Quantum Flagship. The Swedish Research Council is a partner in QuantERA. Sweden is a signatory on the EuroQCI declaration.

Talent

- The WAQCT establishes a graduate school with 60 doctoral students (including 20 industrial doctoral students), a postdoctoral program with 30 fellows, funding for 12 assistant professors, and a program for short-term guest professorships

Government Funding

- The WACQT is a SEK 1B (US$118M) initiative over 10 years (2018-27), with SEK 600M (US$70.9M) from the Wallenberg Foundation and the rest from industry and participating universities.

Major Public Stakeholders

- Swedish Research Council (VR)

Other Stakeholders

- Knut and Alice Wallenberg Foundation
- Ericsson

Primary Sources

See page 54.

SWITZERLAND

Category: No national strategy, but with significant government-led or endorsed initiatives / Participant in international quantum partnerships

Strategy Goals

- In Oct 2020, the Swiss Science Council (federal science advisory body) published a White Paper on "Quantum technology in Switzerland" to provide recommendations on how Switzerland can exploit its full potential and strategic advantages in the domain of quantum technology.

Highlighted Projects

- The Swiss National Science Foundation currently funds two National Centres of Competence in Research (NCCR) focused on quantum research — NCCR QSIT (Quantum Science and Technology), focused on sensing, communication, simulation and materials; and NCCR SPIN, whose goal is to develop a silicon-based quantum computer.
- IBM Research - Zurich is an important quantum research hub, including multiple EU-funded projects.
- Swiss institutions and companies are participants in EU Quantum Flaghship and OpenQKD. The Swiss National Science Foundation is a partner on QuantERA.

Talent

- A master's program in quantum engineering was recently started at ETH Zurich. The SSC recommends the establishment of industrial PhD and postdoctoral programs, as well as a greater role for universities of applied sciences.

Government Funding

- The SNSF funds each NCCC for three 4-year terms. It currently provides CHF 14.95M (US$16.8M) to QSIT (third and final term, 2018-21) and CHF 17M (US$19M) to SPIN (first term, 2020-23).

Major Public Stakeholders

- Swiss National Science Foundation (SNSF)
- Services Industriels de Genève (SIG)
- Swiss Center for Electronics and Microtechnology (CSEM)
- CERN

Other Stakeholders

- ID Quantique
- Qnami
- Zurich Instruments
- IBM

Primary Sources

See page 54.

TAIWAN

Category: Coordinated national quantum strategy
Title: Quantum Computer Project

Strategy Goals

- The Quantum Computer Project was launched in 2018 to coordinate quantum technology R&D at a national level. The Project plans to integrate resources of the strong semiconductor industry to develop domestic manufacturing capacity of quantum components, while also promoting development in quantum communications, and algorithms. A collaborative alliance will also be created with industry.

Highlighted Projects

- The Quantum Computer Project funds a number of individual projects by academia and industry over 5 years (2018-22), including support for establishing the Center for Quantum Technology at National Tsing Hua University and the IBM Q Hub at National Taiwan University.
- From 2021-25, the Project proposes to support the development of silicon-based quantum computing at the Taiwan Semiconductor Research Institute.

Talent

- The Project will foster the masters and PhD level talent necessary for the future of quantum technologies.

Government Funding

- Annual funding for current initiatives within the Quantum Computer Project is about NT$120M (US$4.25M). Proposed annual funding for the silicon project at TSRI is NT$150M (US$5.32M).

Major Public Stakeholders

- Ministry of Science and Technology (MOST)
- Academia Sinica
- Taiwan Semiconductor Research Institute (TSRI)

Other Stakeholders

- IBM
- Taiwan Semiconductor Manufacturing Company

Primary Sources

See page 54.

THAILAND

Category: Coordinated national quantum strategy (in development)

Strategy Goals

- In Sept 2020, the Minister of Higher Education, Science, Research and Innovation announced that part of the country's new scientific research and innovation development scheme will be focused on quantum technology, with a focus on applications to computing, sensing and medical imaging.

Highlighted Projects

- As part of the 2020 scheme, Thai quantum experts will discuss plans to establish a National Institute of Quantum Technology within five years.

Government Funding

- ฿200M (US$6.6M) over eight years (2021-28)

Major Public Stakeholders

- Ministry of Higher Education, Science, Research and Innovation
- Thailand Centre of Excellence in Physics
- National Institute of Metrology
- National Astronomical Institute of Thailand

Primary Sources

See page 54.

TURKEY

Category: Participant in international quantum partnerships

Highlighted Projects

- Turkish experts sit on the EU Quantum Flagship Quantum Community Network. TÜBİTAK is a partner in QuantERA.

Major Public Stakeholders

- TÜBİTAK (Scientific and Technological Research Council of Turkey) - BİLGEM (Informatics and Information Security Research Center), UME (National Metrology Institute)

Primary Sources

See page 54.

UNITED ARAB EMIRATES

Category: No national strategy, but with significant government-led or endorsed initiatives / Participant in international quantum partnerships

Strategy Goals

- UAE considers quantum computing a major pillar of its science and technology policy. It hopes to work towards developing quantum technologies which will allow for more secure communication, data analytics, better imaging, machine learning, artificial intelligence, material science, and harvesting energy.

Highlighted Projects

- The Quantum Computing Research Group at Khalifa University is engaging with academia and industry to work towards a research base for quantum computing and quantum communications, focusing on applications such as secure communication, data analytics, imaging, machine learning, artificial intelligence, material science, and energy harvesting. Projects include a collaboration with D-Wave and Oak Ridge National Lab to optimize financial portfolios.
- The Dubai Electricity and Water Authority (DEWA) is collaborating with Microsoft to develop quantum-inspired solutions for energy optimization and sustainability efforts.
- In Nov 2020, Abu Dhabi's Advanced Technology Research Council established the Quantum Research Centre, a centre of excellence within the new Technology Innovation Institute.
- Mubadala Capital, one of Abu Dhabi's largest sovereign funds, is a major investor in Maryland-based IonQ.

Major Public Stakeholders

- Dubai Electricity and Water Authority (DEWA)
- Mudabala Investment Company
- Advanced Technology Research Council

Other Stakeholders

- Microsoft
- D-Wave

Primary Sources

See page 54.

UNITED KINGDOM

Category: Coordinated national quantum strategy / Participant in international quantum partnerships
Title: National Strategy for Quantum Technologies

Strategy Goals

- The UK National Quantum Technologies Programme (NQTP) was launched in 2013 to create a coherent academic, government and industry quantum technology community, to position the UK as a world leader in the quantum market, and to enhance the value of UK industries. In 2020, the renewed strategic intents are:
  - Stimulate market growth, unleash innovation, and grow a thriving ecosystem
  - Maintain and build the UK's excellence in research and technology
  - Build a resilient network of national assets and mutually beneficial international relationships
  - Grow, attract and retain talent

Highlighted Projects

- As part of the UK National Quantum Technologies Programme, the EPSRC funds a national network for 4 quantum technology hubs, each bringing together multiple universities, research institutes and industry to turn research strengths into technology:
  - UK Quantum Technology Hub Sensors and Timing
  - QuantIC (quantum enhanced imaging)
  - Quantum Computing & Simulation Hub (formerly Networked Quantum Information Technologies Hub)
  - Quantum Communications Hub
- The National Quantum Computing Centre (NQCC) was launched in Sept 2020 to address the challenges of scaling up quantum computing. Priorities include working with industry to develop use cases, promote the formation of a UK-based quantum supply chain, and develop a 100+ qubit NISQ device by 2025.
- The National Physical Laboratory will open the Advanced Quantum Metrology Laboratory in 2021.
- The Science and Technology Facilities Council's RAL Space and National University of Singapore's Centre for Quantum Technologies have partnered to launch QKD Qubesat, a joint space program to build a secure QKD testbed, by 2021.
- An academic-industry consortium led by Rigetti plans to build UK's first quantum computer by 2023.
- Wave 3 of the Industrial Strategy Challenge Fund (ISCF), a competition for academic-industry consortia to bring technology to market, with matched private sector funding, will support additional quantum projects.
- UK institutions and companies are participants in EU Quantum Flagship and OpenQKD. UKRI is a partner in QuantERA.

Talent

- The NQTP supports training of doctoral students within quantum fields through EPSRC-funded Centres for Doctoral Training. The council also funds Training and Skills Hubs in Quantum Systems Engineering to train students in both engineering and entrepreneurship, provide career development and industry placement, etc.

Government Funding

- £400M (US$540M) in public funding for the first phase of NQTP (2014-19). In the second phase (2019-24), the government will invest £94M (US$126M) in the four quantum hubs, £93M (US$125M) in the NQCC, £153M (US$205M) for ISCF quantum projects, and at least £11.6M (US$15.6M) for Centres for Doctoral Training.
- British Business Bank, the UK government's development bank, has made investments in a number of quantum startups, including long-term stake held by its National Security Strategic Investment Fund. In Nov 2020, the Scottish National Investment Bank, Scotland's public development bank, made a £12.5M (US$16.5M) 10-year equity stake in M Squared.

Major Public Stakeholders

- UK Research and Innovation (UKRI) - Engineering and Physical Sciences Research Council (EPSRC)
- National Physical Laboratory (NPL)
- Defence Science and Technology Laboratory (Dstl)
- Government Communications Headquarters (GCHQ)
- RAL Space
- UK Space Agency
- British Business Bank
- Scottish National Investment Bank

Other Stakeholders

- AstraZeneca
- BAE Systems
- BP
- BT
- GlaxoSmithKline
- HSBC
- Toshiba
- Cambridge Quantum Computing
- M Squared
- Oxford Instruments
- Oxford Quantum Circuits
- Rigetti

Primary Sources

See page 54.

UNITED STATES

Category: Coordinated national quantum strategy
Title: National Quantum Initiative

Strategy Goals

- The main objectives of the National Quantum Initiative Act (signed into law in December 2018) are:
  - Developing the scientific approach to solve the challenges identified for transformative progress
  - Develop a quantum workforce that can meet the growth of the industry
  - Promote industry engagements to create public-private partnerships
  - Promote economic growth
  - Ensure national security
  - Promote and develop international partnerships and collaboration

Highlighted Projects

- A National Quantum Coordination Office was established by the White House to implement and coordinate a 10-year National Quantum Initiative (NQI) Program for quantum technology and information science applications.
- The National Science Foundation (NSF) has established three Quantum Leap Challenges Institutes, bringing together researchers from universities, national labs and industry, to promote multidsciplinary research and educate a quantum-ready workforce. These are:
  - Q-SEnSE: Quantum Systems through Entangled Science and Engineering
  - HQAN: Hybrid Quantum Architectures and Networks
  - Institute for Present and Future Quantum Computing
- Through its broader "Quantum Leap", NSF has also established a Quantum Foundry, bringing together researchers and industry to develop new materials for quantum technologies; and the Center for Quantum Networks, with the goal of building an error-corrected quantum network.
- The Department of Energy (DOE) is partnering with major industrial players and academic institutions to establish five Quantum Information Science Centers at its national laboratories to pursue research, create prototypes, provide testbeds, and accelerate translation and commercialization. These are:
  - Q-NEXT: Next Generation Quantum Science and Engineering (Argonne National Lab)
  - C2QA: Co-design Center for Quantum Advantage (Brookhaven National Lab)
  - SQMS: Superconducting Quantum Materials and Systems Center (Fermilab)
  - QSA: Quantum Systems Accelerator (Lawrence Berkeley National Lab)
  - QSC: The Quantum Science Center (Oak Ridge National Lab)
- The DOE is also conducting work towards a blueprint for a nationwide quantum internet.
- Through the National Institute for Standards and Technology (NIST), a Quantum Economic Development Consortium (QED-C) of industry, academic and government stakeholders was established to create a quantum industry and the supply chains to support it.
- In addition to the NQI Centers, various US government agencies are continuing longstanding support of quantum research, including work at the NIST joint institutes, DOE national labs, NSF centres, and NASA's Quantum Artificial Intelligence Laboratory (QuAIL).
- In March 2020, DARPA began the Optimization with Noisy Intermediate-Scale Quantum devices (ONISQ) program to explore combining NISQ and classical systems to solve combinatorial optimization problems. DARPA and IARPA support additional quantum research programs.

Talent

- The National Q-12 Education Partnership is spearheaded by the White House OSTP and NSF to create a diverse and equitable quantum workforce. The partnership of industry, academic societies, educators, and the NSF-funded Q2Work program will develop curriculum materials (from middle school to college) and professional development for teachers.

Government Funding

- The National Quantum Initiative Act authorized up to US$1.275B in spending across the Department of Energy, the National Science Foundation, and the National Institute of Standards and Technology. According to the White House OSTP, in FY20 US$579M in funding for Quantum Information Science research was enacted by the federal government.
- The federal government supports quantum-focused startups and other companies through grants and contracts from agencies such as DARPA, IARPA, and the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. Addtionally, In-Q-T, the non-profit venture fund backed by the CIA, NSA and other government agencies, have invested in quantum-focused companies including Q-CTRL, QuintessenceLabs and D-Wave.

Major Public Stakeholders

- White House Office of Science and Technology Policy (OSTP)
- Department of Energy (DOE)
- Deparment of Defense (DOD)
- Defense Advanced Research Projects Agency (DARPA)
- Intelligence Advanced Research Projects Activity (IARPA)
- National Science Foundation (NSF)
- National Institute of Standards and Technology (NIST)
- National Aeronautics and Space Administration (NASA)
- National Science and Technology Council (NSTC) Subcommittee on Quantum Information Science (SCQIS)
- In-Q-T

Other Stakeholders

- Google
- Honeywell
- IBM
- Intel
- IonQ
- Microsoft
- PsiQuantum
- Rigetti
- SRI International
- Amazon
- Boeing
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- Lockheed Martin
- Northrop Grumman
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MaRS Centre, West Tower
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