- Research Report - APRC-FY2022-RR-01

Asia and Pacific Research Center

Policy and R&D trends of quantum technology in the leading countries of the Asia and Pacific regions

March 2023

Japan Science and Technology Agency

Established in April 2021, the Asia and Pacific Research Center (APRC) of the Japan Science and Technology Agency (JST) aims to contribute to building a foundation for innovation in Japan by expanding and deepening science and technology cooperation in the Asia-Pacific region based on the three pillars of research, information dissemination, and networking.
This report is compiled as part of a research that surveyed and analyzed science and technology innovation policies, research and development trends, and associated economic and social circumstances in the Asia-Pacific region. It is being made public on the APRC website and portal site to enable wide use by policymakers, associated researchers, and people with a strong interest in collaborating with the Asia-Pacific region; please see the websites below for more details.

APRC website:
https://www.jst.go.jp/aprc/en/index.html

Research Report (Japanese website):
https://spap.jst.go.jp/investigation/report.html

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Introduction

Quantum technology, which includes quantum computers, quantum encrypted communication, and quantum measurement and sensing, is attracting global attention. This technology has a significant impact on industry, information security, national defense, finance, and other areas, meaning that developed nations in Europe and the U.S., as well as countries such as Japan and China, are placing increasing importance on the successive development of quantum technology, and competition in global research and development is growing.

The Japan Science and Technology Agency (JST), led by its Center for Research and Development Strategy (CRDS), is gathering information and carrying out investigations and analysis to gain an understanding of the internal and external trends of quantum technology.[1] One result of this initiative was a survey report produced in FY2021, "International Trends in Quantum Technology from Papers and Patent Maps"[2]; adding to that report, the Asia and Pacific Research Center (APRC), also of JST, focused on the quantum technology trends in China, which is undergoing rapid development.

When the APRC investigated trends in China, it became clear that the importance of the Asia-Pacific region is increasing in quantum technology research and development. India has the highest average growth rate in terms of the number of papers in the field of quantum technology, with China coming second, followed by Taiwan, South Korea, and Singapore. Europe has the highest share of quantum papers by region at 40%, but the Asia-Pacific region is in hot pursuit with 30%. Although they are lagging behind developed nations, the policy makers in major countries and regions in the Asia-Pacific have strengthened their initiatives to promote quantum technology in recent years. Australia also has a high quantum technology research level, and its research community has a high affinity with Europe and the U.S.

This report aims to gain an understanding of quantum technology trends in six major countries and regions (China, India, Australia, South Korea, Singapore, and Taiwan) in the Asia-Pacific region whose importance is continuing to increase. To accomplish this, information gathered from open sources about quantum technology policy trends and research and development trends in each country and region, as well as on their major organizations (research institutions, universities, companies) and influential researchers, has been organized and analyzed. The report also strived to collect information on examples of cooperation with other countries in each country/region.

The Nobel Prize in Physics 2022 was awarded to three researchers who contributed to pioneering quantum information science. One of the laureates, an Austrian researcher, is famous in China as the advisor of a leading researcher known as the "Chinese Father of Quantum." With the increasing social attention on quantum information science in particular, it is apparent that international competition in the field of quantum technology will accelerate further. This report will clarify some of the international competition in the field of quantum technology in the Asia-Pacific region.

[1] Center for Research and Development Strategy, Japan Science and Technology Agency, "Tokushu: Ryoshi Gijutsu" [Special Feature: Quantum Technology], (May 2022).

[2] Center for Research and Development Strategy, Japan Science and Technology Agency, "Ronbun/Tokkyo Map de Miru Ryoshi Gijutsu no Kokusai Doko" [International Trends in Quantum Technology from Papers and Patent Maps], (March 2022).

Overview of the outcomes of this report

	China	Japan	India	Australia	South Korea	Singapore	Taiwan
Number of quantum papers 1990-2021	27,987	15,833	5,956	4,223	3,443	2,399	2,116
Source of quantum policy	National High-tech R&D Program (1986), National Program on Key Basic Research Project (1997)	The 5th Science and Technology Basic Plan (2016), the 6th Science, Technology, and Innovation Basic Plan (2021)	Quantum Enabled Information Science and Technology program (QuEST) (2017)	Selection of CoE for quantum research (2014)	Medium- to Long-term Strategy for Quantum Information and Communication (2014)	Expansion of Smart Nation concept (2018)	Quantum Computer Project (2018)
Main policies	Scientific and Technological Innovation Plan (2016), 14th Five-Year Plan (2021)	Integrated Innovation Strategy (2020, 2021, 2022)	National Mission on Quantum Technologies and Applications (NMQTA)	CSIRO's roadmap for quantum technology industrialization (2020), Blueprint for Critical Technologies (2021)	Quantum Computing Technology Development Project Plan (2019)	Quantum Engineering Program (QEP), Quantum Technologies for Engineering (QTE)	Establishment of quantum research hub, formation of 17 industry-academia-government collaborative research teams
Quantum strategy document	None	Quantum Technology and Innovation Strategy (2020), Vision of Quantum Future Society (2022), Quantum Future Industry	None	National Quantum Strategy (being created)	Quantum Technology Development Investment Strategy (2021)	None	None
Budget/investment	400 billion yen to build a quantum metropolitan area network; 2.6 billion yen for MOST quantum budget (2020)	42.1 billion yen (FY2023 budget), 43.8 billion yen (FY2022 supplementary budget), 33.9 billion yen (FY2022 budget), all of the above include funds	Around 140 billion yen over five years for NMQTA	9.4 billion yen to drive commercialization as one of the nine technologies of focus, 6 billion yen to establish a hub	4.5 billion yen for quantum core technology development for five years; quantum R&D budget of 6.03 billion yen (2022)	24 billion yen over four years and 5 billion yen over 2 years for the formation of two hubs in the National University of Singapore (NUS)	The full picture is unclear. 35 billion yen over 5 years for the creation of the hub in Tainan.
Priority R&D fields	Quantum communications, quantum computing	Quantum computer/quantum simulation, quantum measurement and sensing, quantum communication and cryptography, quantum materials	Quantum computing, quantum materials, quantum communication, quantum sensors	Quantum computing	Quantum communication, quantum computing	2D materials, ion trap computing, wide-area communication	Development of silicon-based quantum computing sub-systems
Human resource development	New undergraduate department in Tsinghua University. Cooperative framework between Shenzhen International Quantum Academy and Shenzhen Gezhi Middle School.	It covers a wide range of topics, including lectures and seminars at universities, scholarships for graduate students, development of online teaching materials, and training and training programs for engineers	Training 25,000 people, including researchers and engineers, from students of quantum	Efforts are focused on the Sydney Quantum Academy, a framework to support young researchers	STI human resource development (quantum information science), development of human resources for information communication transmission	Focused mainly on key hubs such as A*STAR and NUS	Emphasis on education in universities and research hubs
Main research centers	Accumulated in Hefei, Anhui Province and Beijing	10 Quantum Technology Innovation Hubs (5 universities and 5 national institutes)	Creation of the Centre for Development of Quantum Technology for NMQTA	Establishing the Quantum Commercialisation Hub; CSIRO has established a platform to promote commercialization	Future Quantum Convergence Forum	None in particular	Quantum research base under construction in Tainan City
Representative research institutions	University of Science and Technology of China, Chinese Academy of Sciences	AIST, NICT, NIMS, OIST, Osaka University, QST, RIKEN, Tohoku University, Tokyo Tech, The University of Tokyo	I-Hub Quantum Technology Foundation, Indian Institute of Science Education and Research, Pune; Indian Institute of Science	University of New South Wales, ANU, University of Melbourne	Korea Institute of Science and Technology, Electronics and Telecommunications Research Institute, Seoul National University, KAIST	NUS Centre for Quantum Technologies, NUS Centre for Advanced 2 Dimensional Materials Graphene Research Center	Academia Sinica, IBM Quantum Hub at National Taiwan University, Center for Quantum Technology, National Tsing Hua University
Representative companies	QuantumCTek, Hefei Origin Quantum Computing Technology, Shandong Institute of Quantum Science and Technology, etc.	Toshiba Corporation, NEC, Fujitsu, Ltd., NTT, Hitachi, Ltd., Mitsubishi Electric Corporation, Startups (Jij Inc., QunaSys, Quemix, Sigma-i Co., Ltd., LQUOM, Inc., QuEL, Inc., Nanofiber Quantum Technologies)	Startups such as QNu Labs, QpiAI	Startups such as Q-CTRL, Quantum Brilliance	SAMSUNG, three major communication companies	Startups such as SpeQtral and Horizon Quantum Computing	Hon Hai Research Institute's Quantum Computing Center, TSMC
Representative researchers	Pan Jianwei, Guo Guangcan (both University of Science and Technology of China)	Kitagawa Masahiro (Osaka University), Nakamura Yasunobu (The University of Tokyo), Sasaki Masahide (NICT), Katori Hidetoshi (The University of Tokyo), Tokura Yoshinori (The University of Tokyo)	Urbasi Sinha (Raman Research Institute)	A.S. Dzurak (University of New South Wales) L. Hollenberg (University of Melbourne)	Hyunseok Jeong (Seoul National University) Minhaeng Cho (IBS)	V. Vedral A.K. Ekert A.H. Castro-Neto (all NUS)	Gwo Shangjr (National Tsing Hua University) Chang Chingray (National Taiwan University) Chang Wenhao (National Yang Ming Chiao Tung University)
Noteworthy (young) researchers	Lu Chaoyang, Zhang Qiang, Chen Yuao, Wang Zhijun (all Chinese Academy of Sciences)	Fujii Keisuke (Osaka University)	Rajamani Vijayaraghavan (Tata Institute of Fundamental Research)	M.J. Biercuk (University of Sydney) S.J. Devitt (University of Technology Sydney)	Sekwon Kim (KAIST)	Gao Weibo (Nanyang Technological University)	Lin Hsin (Academia Sinica) Chang Tayrong (National Cheng Kung University) Hsieh Minhsiu (Hon Hai Research Institute)
Examples of international collaboration	Quantum teleportation with the University of Vienna and the 2021 China-Korea Quantum Information Workshop	the Tokyo Statement on Quantum Cooperation (w/ U.S., 2019), a joint workshop on advanced quantum technology for future innovation (w/ EU, 2019), High-Level Meeting: 'Quantum Innovation for a Better Future,' An Official Side Event of the G7 Science and Technology Ministers' Meeting (2023)	Research cooperation between governments of Israel, Australia, and BRICS. Quantum education support agreement with France	Government collaboration, especially with the U.S. and the UK, partnerships such as security frameworks	Promotion of joint research between the U.S. and South Korea, research cooperation with American and British universities	Government collaboration with the UK in wide-area communications, research cooperation between universities in France and Australia	Exploring collaboration with Europe via Slovakia

1 Trends in quantum research and development in the Asia-Pacific based on papers and patent information

This chapter provides an overview of trends in the Asia-Pacific region based on information on papers (including academic journals) and publicly available patent information, so as to provide common knowledge ahead of an analysis of each country/region. Based on the data used in the CRDS FY2021 investigative report (hereinafter referred to as the CRDS report)[1], it offers an understanding of the overall trends in quantum technology as well as the trends by field. It also offers hints as to the organizations and researchers to which attention should be paid by analyzing the quantum technology trends in each country.

1.1 Paper and patent databases and types of quantum research

1.1.1 The paper and patent data used in this report

The number of papers concerning quantum technology published around the world from 1990 to 2021 was 147,853. The number of patents issued around the world during this same period was 27,067.

For paper data, this report made use of the world's largest academic paper database, Scopus, provided by Elsevier; for patent data, the world's largest patent database, TotalPatent (provided by LexisNexis), in which patent information from 96 countries is registered, was used. Both of these contain information published/issued from 1990 to 2021, and the countries/regions/institutions issuing patents are: America, Europe, WIPO, China, Japan, South Korea, Germany, France, the UK, and Canada.

1.1.2 The four main fields of quantum research and research and development topics

This report assumes four research fields in quantum science and technology: quantum computing and simulators, quantum communication, quantum materials, and quantum fundamental technology (quantum measurement and quantum sensing); the frequent research and development topics in each of their search criteria are given in Table 1-1. For further details, see Table 3-1 in the CRDS report and CRDS strategy proposal Quantum 2.0.[2]

[1] Center for Research and Development Strategy, Japan Science and Technology Agency, "Ronbun/Tokkyo Map de Miru Ryoshi Gijutsu no Kokusai Doko" [International Trends in Quantum Technology from Papers and Patent Maps], March 2022.

[2] Center for Research and Development Strategy, Japan Science and Technology Agency, Strategic Proposal, "Ryoshi 2.0: Ryoshi Kagaku Gijutsu ga Kirihiraku Aratana Chihei" [Quantum 2.0: New horizons opened up by quantum science and technology], January 2020.

(1) Quantum computing and simulators

Quantum computers carry out parallel computation using quantum mechanical phenomena (quantum states) such as quantum superposition and quantum entanglement; compared with conventional computers, they derive solutions in a far shorter time. At present, it is difficult to fully control a quantum state, so strengthening their overall structure to produce error-resistant quantum computers is a key research theme. Competition in the development of existing technology is currently unfolding regarding multiple methods, including the use of quantum bits (qubits) and trapped ions as system elements.

Quantum simulators (quantum simulation) artificially construct strong correlations in highly controllable quantum mechanical behaviors using cold atoms, below ultracold temperatures, and make use of simulated experiments to understand their properties.

Table 1-1: Search criteria in four key quantum research fields and R&D topics

Research field	R&D topics
Quantum computing/ simulators “quantum comput*”	Quantum entanglement, topological insulators, geometric topology, superconducting qubits, diluted magnetic semiconductors, random oracle models, cellular automaton, Bose-Einstein condensate, diamonds, imaging, single-molecule magnetism, electromagnetically induced transparency, block ciphers, exciton, intermolecular communication, particle swarm optimization, molybdenum disulfide, Josephson junctions, graphene, mathematics of additivity
Quantum communication “quantum commun*”	Quantum entanglement, orbital angular momentum, superconducting qubits, exciton, diamonds, electromagnetic transparency, molybdenum disulfide, metamaterials, computability, visible light communication, silicon photonics, Josephson junctions, topological insulators, photon echo, diluted magnetic semiconductors, CMOS image sensors, photonic-crystal fiber, random oracle models, Bose-Einstein condensate, network coding
Quantum fundamental technology “quantum measurement” OR “quantum sens*”	Quantum entanglement, diamonds, superconducting qubits, Bose-Einstein condensate, electromagnetic transparency, entropy, dark energy, molybdenum disulfide, Josephson junctions, exciton, symmetry, SERS, image encryption, diluted magnetic semiconductors, gravitational waves, geometric topology, topological insulators, axons, single-molecule magnetism, high harmonic generation
Quantum materials “quantum material*”	Topological insulators, molybdenum disulfide, cuprates, spin gaps, bulk modulus, iron-based superconductors, graphene, manganese oxides, Kondo effect, superconducting qubits, exchange bias, Perovskite solar cells, Vanadium dioxide, Bose-Einstein condensate, ferro-electrics, qubits, high harmonic generation, exciton, thermoelectric properties, electron beam tomography

Note: Researchers designated and searched for keywords on Web of Science, specifying and extracting “Web of Science Documents” 2015–2021 under InCites Benchmarking’s Citation Topics, level Micro.

(2) Quantum communication

Quantum communication technology uses a quantum state to ensure privacy and safety that cannot be achieved with conventional communication methods.

Quantum key distribution (QKD) began with the proposal of the BB84 Protocol in 1984; a theoretical foundation was established by 2010 through intensive research, and a theory of security that holds true even in the presence of incompleteness in devices was pioneered. On the other hand, there are limits to the transmission distance and speed of encryption keys. For example, the current performance of communications using the optical fiber in the BB84 Protocol is a distance of approximately 100 km due to the limits of the distance photons travel, and the speed in this case is around 1 kbps. Research and development focusing on extending and improving this distance and speed is underway, and basic experiments on wide-area communication using small satellites are also being carried out. Research and development on platforms to provide keys is also going ahead.

The establishment of quantum entanglement between separated nodes is technology needed to increase the distance of quantum communication. The key to this lies in quantum relay technology, which converts quantum entanglement between adjacent nodes to quantum entanglement between distant nodes.

Researchers are also involved in exploring a quantum Internet through which quantum data travels back and forth using quantum information processing devices such as quantum computers and quantum sensors as nodes. In addition to securely sending encryption keys, it is hoped that this will have a variety of applications, including secure access to cloud quantum computers, the realization of distributed quantum computation, the synchronization of optical lattice clocks, and the construction of a quantum sensor network.

(3) Quantum fundamental technology (quantum measurement and quantum sensing)

This technology attempts to achieve measuring and sensing that is attuned to the environment by taking advantage of the properties of a quantum state (i.e. it is vulnerable to changes in the environment such as temperature and magnetic field) in order to control the limits of measuring and sensing, the foundation of scientific technology. Research and development on gyroscopes (navigational application), optical lattice clocks, and quantum sensors (application in various fields, from biosensors such as those for measuring magnetism in the brain and in the heart, intracellular measurement, and protein structural analysis, to detecting defects in metals). The development of measuring technology that makes use of optical and physical quantum entanglement (quantum entanglement sensing) is also going ahead; a quantum entanglement microscope is a representative example of this, and it is known that this is applicable in imaging, including quantum optical coherence tomography (quantum OCT).

Multiple startups have been launched, and, from the perspective of industrialization, it is apparent that markets will also be gradually established in the future.

(4) Quantum materials

Quantum materials is drawing attention as a concept that crosses multiple fields, including condensed matter physics, quantum information, and chemical and materials engineering. It was originally introduced to emphasize novel quantum phenomena, quantum phase, and so on. in solid state physics, but it is now transforming into an interdisciplinary field that enables interchange as new materials and the quantum state that is realized from them are offered as a basis for research on quantum information, and conversely, researchers gain an understanding of the behavior of quantum many-body systems in materials using the concept of quantum information and its methods.

1.2 Quantum research trends based on information on papers

1.2.1 Analysis of papers on quantum technology from around the world

As was stated in 1.1.1, between 1990 and 2021 147,853 quantum research papers were published around the world. Looking at the percentages of these in each region[3] reveals 63,659 papers (33%) in the Asia-Pacific region, 44,018 (22%) in North America, and 80,113 (41%) in Europe (Figure 1-1)[4]. Thus, Europe has the highest accumulated number of papers published, but in recent years a striking increase in the number of papers in the Asia-Pacific region is apparent (Figure 1-2). Notably, a look at the average growth rates of the number of papers in the last 10 years (2011–2021) shows this to be 11% in the Asia-Pacific region, higher than the rate in Europe, North America, and the world as a whole (Table 1-2). Within this region, the number of papers from China was 27,987, making up 44% of papers in the Asia-Pacific region.

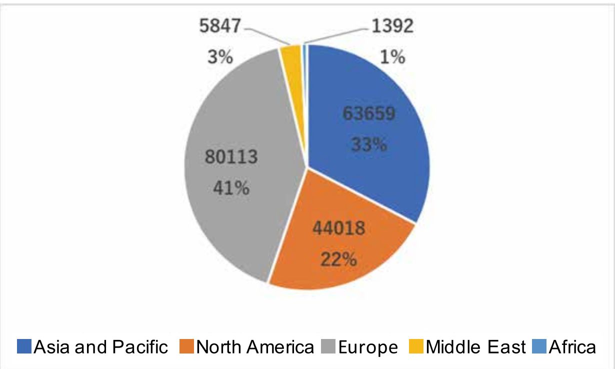


Figure 1-2: Share of papers in each region of the world

Source: Prepared by APRC

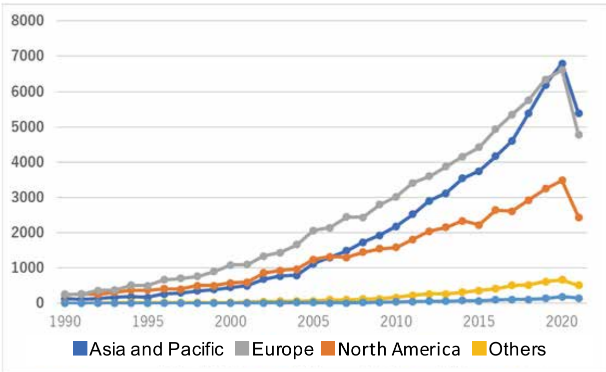


Figure 1-3: Trends in paper numbers in each region over time

Source: Prepared by APRC

Table 1-2: Average growth rate of number of papers in major regions (2011–2021)

Regions	Number of papers (2011)	Number of papers (2021)	Average growth rate
World	8,249	13,813	7%
Asia and Pacific	2,527	5,384	**11%**
North America	1,817	2,440	3%
Europe	3,412	4,771	4%

Source: Prepared by APRC

[3] Regional classifications are based on those set out by the Ministry of Foreign Affairs of Japan.

[4] Here, the number of papers is given in integer form, but each percentage is calculated separately using fractions.

To continue, this section will break down the number of papers published in the major countries/regions of the Asia-Pacific region, similar to the way this was done for the world as a whole. The number of papers in each country/region is shown in Figure 1-4. In the Asia-Pacific region, the countries/regions with the most papers, excluding Japan, are, in order (starting from the highest number of papers): China, India, Australia, South Korea, Singapore, and Taiwan. Including Japan, these seven countries published 59,969 papers—over 90% of the total number of papers in the Asia-Pacific region (63,659). From this, it is assumed that investigating the trends in the top six countries/regions by number of papers (China, India, Australia, South Korea, Singapore, and Taiwan) is important.

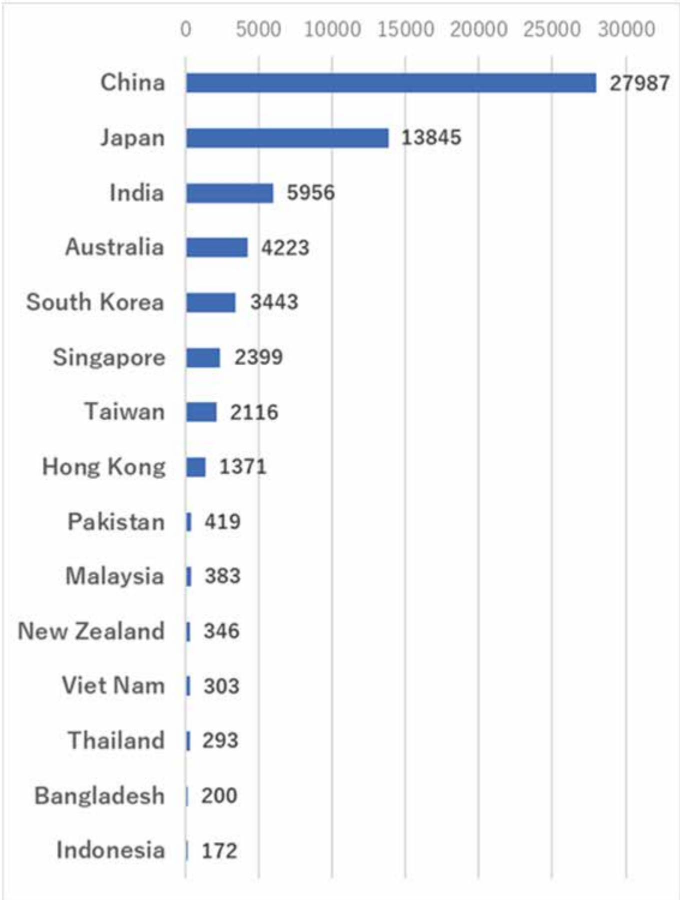


Figure 1-4: Number of papers in major countries/regions in the Asia-Pacific region

Source: Prepared by APRC

Looking at the number of papers published in each country from 2011 to 2021, China stands out with a lot of papers in Figure 1-5, but the number of papers in India has been increasing, surpassing those of South Korea and Australia. Moreover, when it comes to the average growth rate of the number of papers in each country in the last 10 years, Figure 1-6 shows that the growth rate in China and India is especially high. On the other hand, when Japan is compared with the major countries/regions in the Asia-Pacific, it comes second after China in terms of the number of papers, but the growth rate is low compared with other countries.

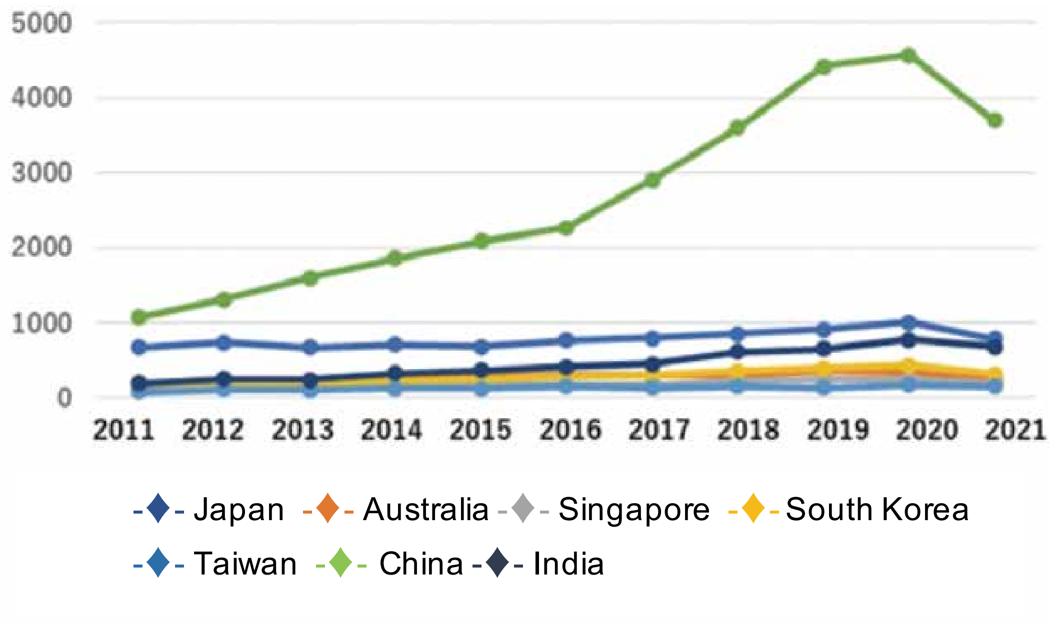


Figure 1-5: Trends in paper numbers in six countries/regions and Japan over time

Source: Prepared by APRC

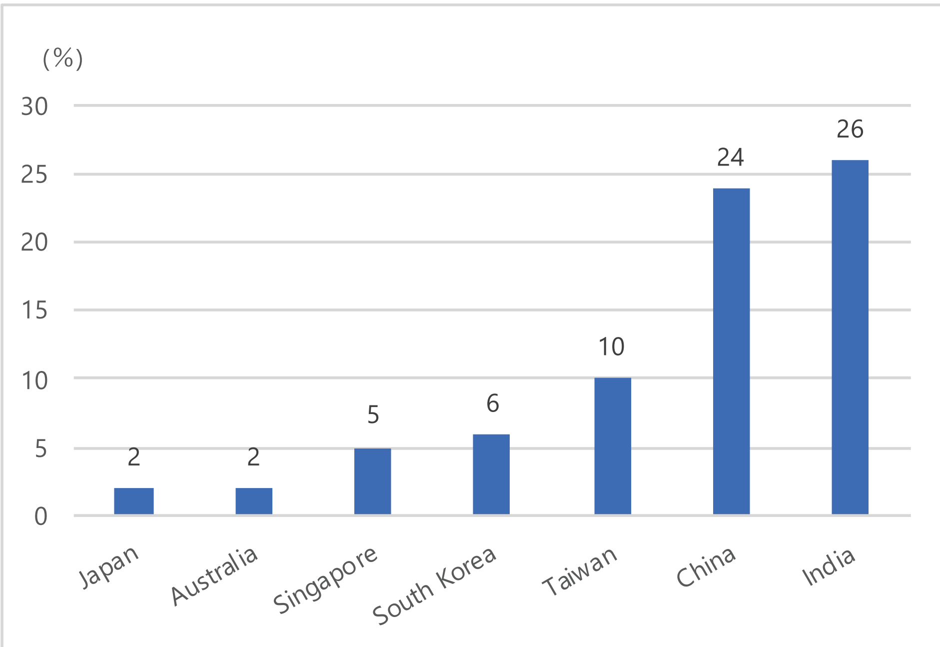


Figure 1-6: Average growth rate of number of papers

Source: Prepared by APRC

1.2.2 Analysis by field

This section indicates the percentages of the total number of papers in each country/region from 2011 to 2021 in accordance with the four research fields described in 1.1.2 (Figure 1-7). In China, India, South Korea, Singapore, and Taiwan, quantum materials papers numbered the most among research papers. Meanwhile, in Australia, it was quantum foundational technology (measurement, sensing) papers that had the highest percentage.

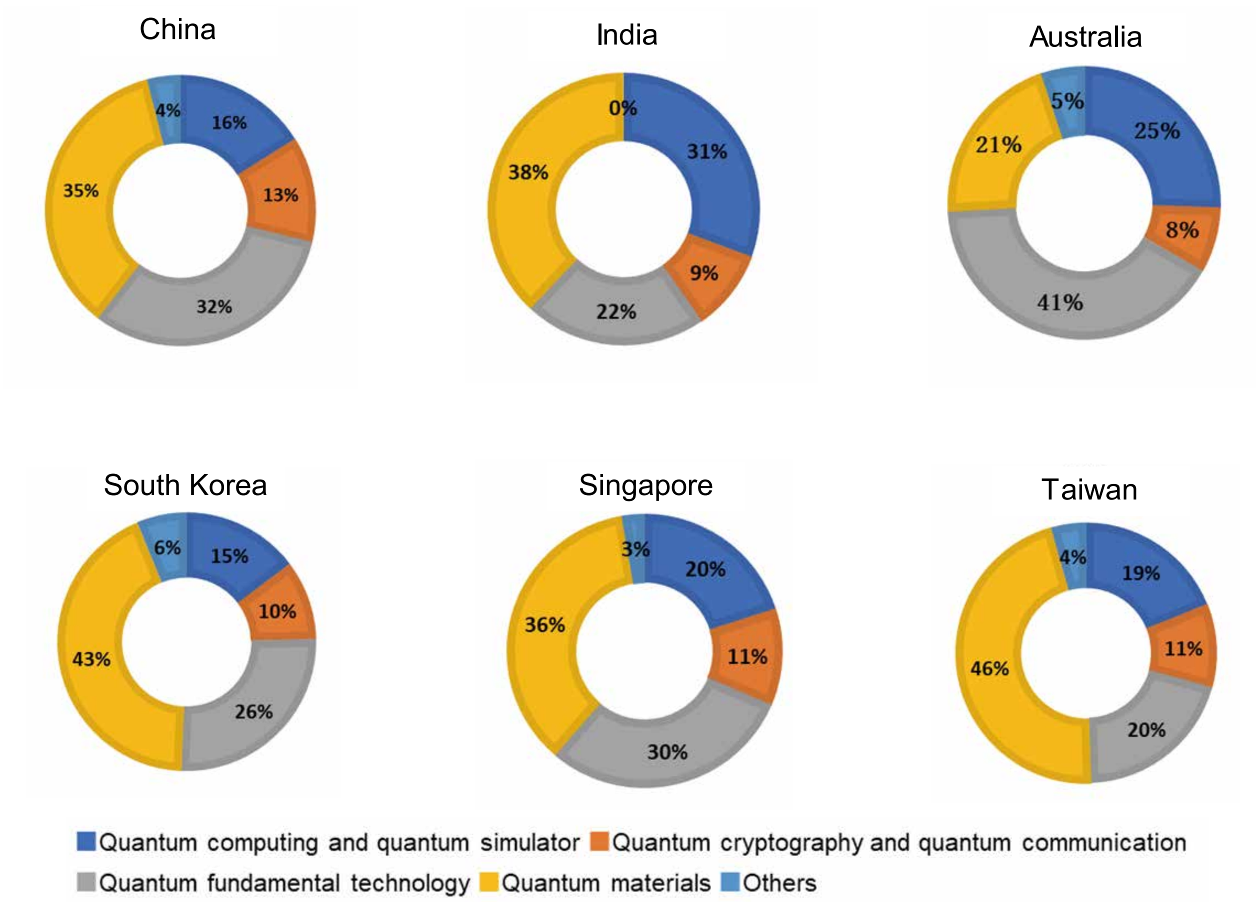


Figure 1-7: Number of papers in each country/region, by technology category

Source: Prepared by APRC

To continue, the researchers looked at the changes in the number of papers published every five years based on the same four categories (Figure 1-8). In the most recent five years, all countries/regions showed a significant growth in the number of quantum materials papers; India's quantum communications and simulators papers increased, as did the number of quantum fundamental technology papers in Australia, Singapore and China.

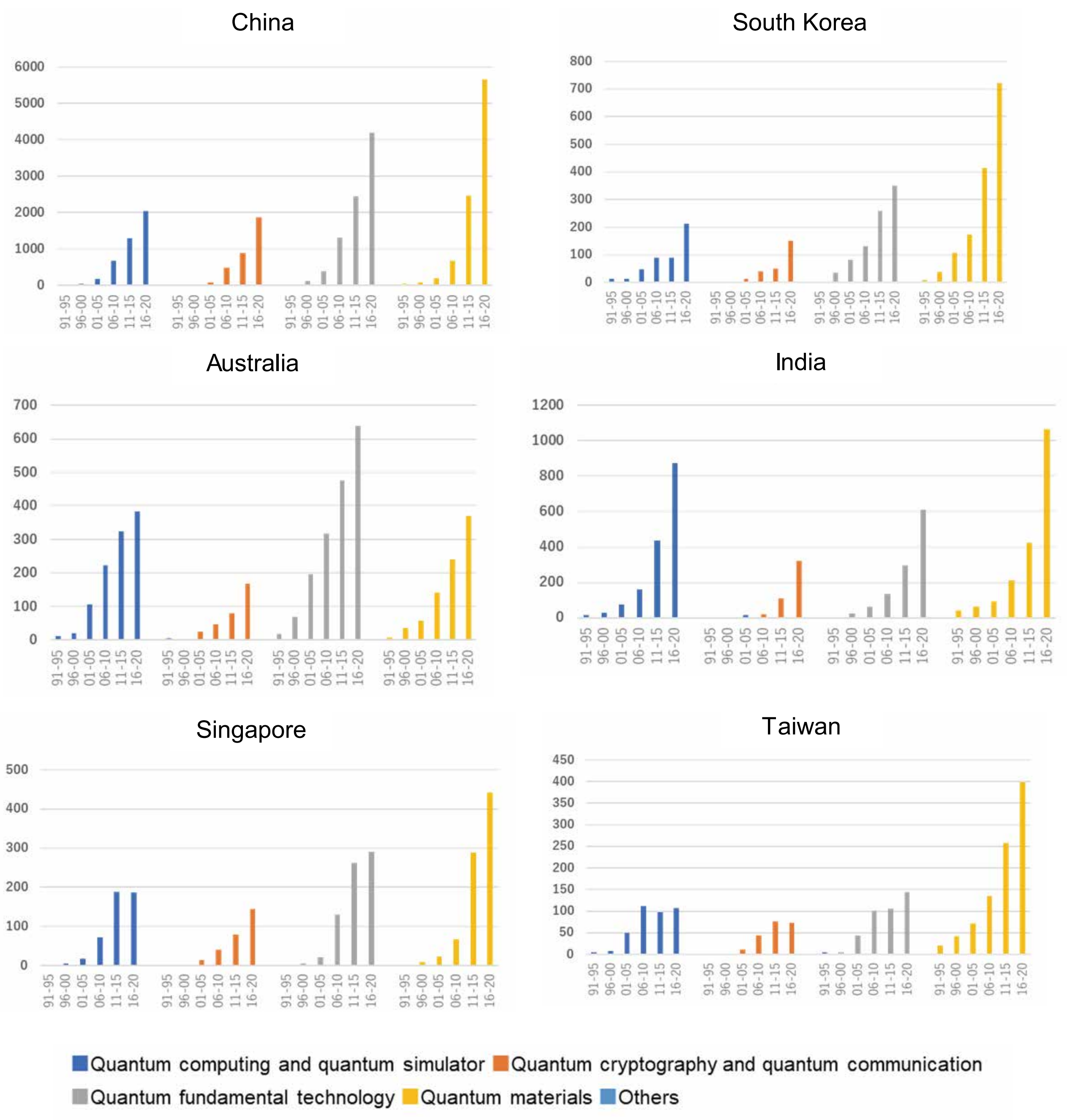


Figure 1-8: Changes every five years in the number of papers published, by technology category

Source: Prepared by APRC

1.3 Quantum technology trends based on patent information

As was stated in 1.1, the number of publicly available patents associated with quantum technology between 1990 and 2021 was 27,067 worldwide. Looking at the percentages of this total in each region reveals that 9,026 (63%) were in the Asia-Pacific region, 3,656 (26%) were in North America, and 1,612 (11%) were in Europe. The Asia-Pacific region had an overwhelmingly large proportion of the total number (Figure 1-9). Moreover, looking at the trends over time in the number of patent applications over the last 10 years (2011–2021), it is evident that there was a certain growth in North America, but there has been a more precipitous growth in the Asia-Pacific region since 2016 (Figure 1-10).

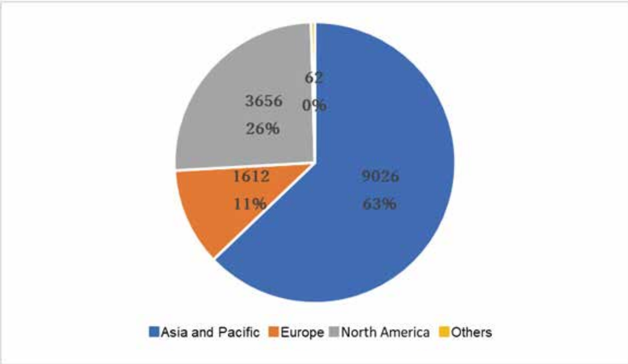


Figure 1-9: Share of patent applications by region around the world

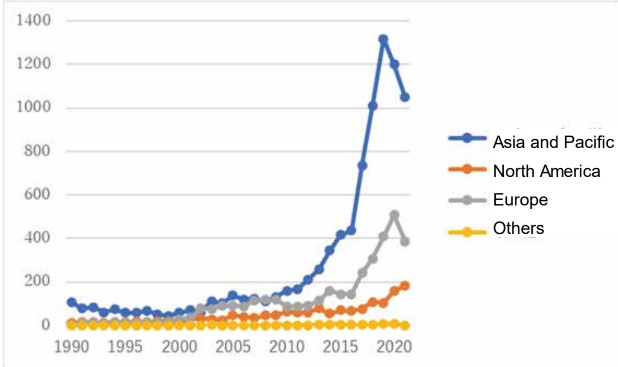


Figure 1-10: Trends in patent application numbers over time by region

Source: Prepared by APRC

1.4 Notable organizations and researchers, based on the trends of each country and region

This section will provide an overview of research institutions, universities, companies, and researcher trends in the six target countries/regions based on paper information and patent information.

1.4.1 Notable research institutions and universities

Looking at the countries/regions to which the authors of papers belong, 25 Chinese research institutions are ranked in the top 100, making up 56% of the total (Figure 1-11). Although the numbers are fewer, the National University of Singapore (NUS) and the Indian Institutes of Technology (IIT) also publish a lot of papers in the quantum technology field. Among the target countries and regions, Taiwan alone has no institutions in the top 100 worldwide.

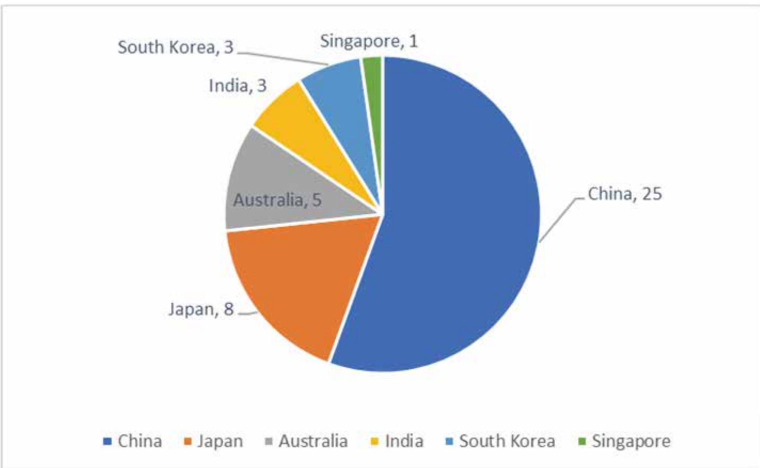


Figure 1-11: Top research institutions in the six countries/regions and Japan (within the top 100 in the world)

Source: Prepared by APRC

1.4.2 Notable companies

Meanwhile, looking at patent applicants, the global top 100 is mainly taken up by Chinese and Japanese companies (Table 1-2). South Korea's Samsung Electronics is ranked 16th, and Taiwan has just one company in this list (Taiwan Semiconductor Manufacturing Company (TSMC)); Singapore, Australia, and India have not emerged into the top ranks.

Table 1-2: Breakdown of world' s top 100 patent applicants by country/region

Country/region of patent applicant	Number of applicants
China	53
Japan	15
South Korea	7
Taiwan	1
Grand Total	76

Source: Prepared by APRC

1.4.3 Notable researchers

Noteworthy researchers have been selected after comprehensive consideration of factors such as important positions in government and/or foundational research institutions as well as international visibility, while keeping in mind paper and patent information.

Figure 1-12 shows the distribution of people by country/region (the country/region of the organization to which they have belonged most recently) by picking out researchers from among the 500 researchers with the highest number of papers around the world. The countries/regions that are the focus of this investigation all have researchers in the top 500.

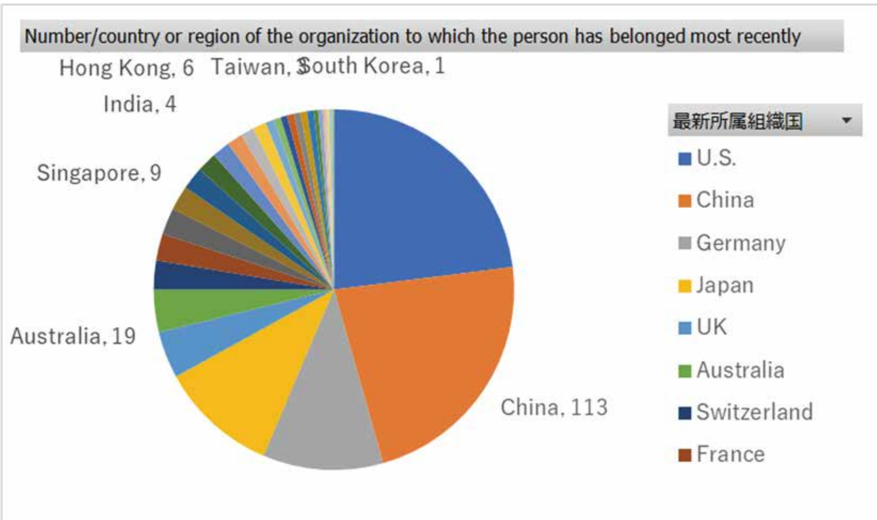


Figure 1-12: Distribution by country/region of researchers in the top 500, based on number of papers

Source: Prepared by APRC

2 Quantum technology trends in China

Quantum research in China grew rapidly from the second half of the 1990s, and from 2006 it has occupied a prominent position in the country's various national plans. Amounts of funding, for example from the National Natural Science Foundation of China (NSFC), also dramatically increased from this period, and since 2016, China has constantly driven world trends in technological development, including launching a quantum science experiment satellite and developing quantum computers. The amount of funding and the number of papers published are both overwhelming, and China is continuing to move at the cutting edge of global quantum research together with America and Europe.

2.1 Quantum technology policy

Research on quantum technology in China has advanced with financial assistance from policies such as the National High-tech R&D Program (863 Program)[1] and the National Program on Key Basic Research Project (973 Program)[2]. In 1998, Zhang Qiang (张强)[3] of the University of Science and Technology of China (USTC) took the opportunity given by a quantum information science forum held in Beijing by the NSFC to state that universities and research institutions such as USTC, Shanxi University, and the Institute of Physics of the Chinese Academy of Sciences (CAS) had started experimental research in the quantum information field. In 1999, Guo Guangcan (郭光灿) of USTC, who had begun research on quantum optics in the first half of the 1980s, established a laboratory dedicated to quantum information in CAS. In 2001, Pan Jianwei (潘建伟), who obtained his degree in Austria in 1999 and later became known as the "Chinese Father of Quantum," returned to China from his study abroad and set up a quantum physics/quantum information laboratory in USTC at a young age. From this point research in China on quantum technology proceeded in earnest.

In 2006, the State Council announced its National Medium- and Long-Term Program for Science and Technology Development (2006–2020), a long-term basic policy for science, technology and innovation; for the first time, this designated quantum regulation as one of the four major research areas to be promoted[4]. The Outline states the objective for China is to "attain a series of high world impact S&T achievements and join the ranks of innovative countries" by 2020, aiming to expand research and development funding and strengthen key fields. More specifically, it mentions research related to quantum as an area with the potential for technological breakthroughs in a short time, that can fill the country's strategic blanks connected to products, foundational technologies, and engineering, and that can elevate the technology that is the foundation of next-generation high-tech industries to

[1] 中华人民共和国科学技术部 (1986)「国家高技术研究发展计划（863 计划）」

[2] 中华人民共和国科学技术部 (1997)「国家重点基础研究发展计划（973 计划）」

[3] Zhang, Q., Xu, F., Li, L., Liu, N. and Pan, J. (2019) Quantum information research in China. *Quantum Science and Technology,* Volume 4, No.4, 040503

[4] 国务院 (2006)「国家中長期科学技術発展規画綱要 (2006-2020 年)(国家中长期科学和技术发展规划纲要 (2006-2020 年)) 」『国务院』

world class technology that can significantly increase China's international competitiveness.[5]

With the 12th Five-Year Plan (2011–2015),[6] the Chinese government started to increase support with consideration for the rapid development of quantum information and the potential effects on secure communications. Made in China 2025,[7] announced in 2015, included the active promotion of quantum computing development as a priority matter for the next-generation information technology industry. Moreover, the 13th Five-Year Plan (2016–2020),[8] which began in 2016, also clearly focused on quantum technology. In that same year, the National 13th Five-Year Scientific and Technological Innovation Plan,[9] formulated based on the 13th Five-Year Plan, incorporated quantum regulation and quantum information as a scientific challenge that should be tackled with strategic foresight, quantum communications and quantum computing as large-scale newly developed science and technology projects, and quantum communication and quantum computers as key projects for the Science, Technology, and Innovation 2030 Program. In a similar vein, the National Innovation-Driven Development Strategy Outline (2016–2030)[10] mentioned the quantum anomalous Hall effect and quantum communication in the context of understanding new dynamics in the development of science, technology and innovation; cloud computing and quantum computing as new-generation information technology development; quantum information in the context of the development of innovative technology that will lead industrial change, and quantum navigation in terms of the development of technology for the exploration, development, and use of air and space. In addition, the 14th Five-Year Plan (2021–2025)[11] emphasizes quantum information in the context of starting a new journey to fully achieve socialist modernization, adherence to innovation-driven development, and fully achieving new advantages in development; and quantum computers and quantum communication in the context of accelerating the development of digitalization and building a digital China. It also clearly states the objective of developing quantum science technology to accelerate the modernization of national defense and the military and to realize the integration of a prosperous nation and a strong army.

In addition to this, quantum technology is one of the targets for emphasis and enhancement in the military-civil fusion strategy promoted by the XI Jinping administration. According to the 13th Five-Year Special Plan for S&T Military-Civil Fusion Development (August 2017), quantum information and computing, including satellites (wide-area communications), are included in projects, and the construction of science, technology and industry systems for advanced national defense; training systems for military personnel; a system for the secure socialization of military affairs; and a mobilization system for national defense are to be strongly promoted.[12] To continue, the Shandong Province Quantum Technology Innovation and Development Program,[13] in accordance with Shandong

5 Junko Okayama (2008), "Chugoku no Kagaku Gijutsu Seisaku to Chiteki Zaisan Sennryaku" [China' s Science and Technology Policy and Intellectual Property Strategy], *Journal of Intellectual Property*, Volume 1, pp.53-60.

6 国务院「中华人民共和国国民经济和社会发展第十二个五年规划纲要」March 16, 2011

7 国务院「国务院关于印发《中国制造 2025》的通知」国发（2015）28 号、May 8, 2015

8 国务院「中华人民共和国国民经济和社会发展第十三个五年规划纲要」March 17, 2016

9 国务院「国务院关于印发"十三五"国家科技创新规划的通知」国发（2016）43 号、July 28, 2016

10 See note 9.

11「中华人民共和国国民经济和社会发展第十四个五年规划和 2035 年远景目标纲要」March 13, 2021

12 科技部 ; 中央军委科学技术委员「"十三五"科技军民融合发展专项规划」国科发资（2017）85 号

13 山東省科技厅「山東省量子技术创新发展规划（2018-2025 年）」16p.

Province's New and Old Kinetic Energy Conversion Plan,[14] accelerates the development of quantum technology innovation, clearly stating it will "promote the bidirectional conversion and application of military-civil science and technology outcomes, especially quantum information technology, and the collaborative construction and sharing of military-civil innovative resources." Moreover, Shandong Province's capital city, Jinan, has issued the Shandong Province Key Research Plan (S&T Military-Civil Fusion),[15] which clearly specifies not just quantum technology but also military-civil fusion in science and technology.

When it comes to financial support linked to the abovementioned policies, from 1998 to 2006 NSFC provided support of 10 million USD, from 2006 to 2010 the Ministry of Science and Technology (MOST), NSFC and the Chinese Academy of Sciences (CAS) gave assistance of 150 million USD, from 2011 to 2015 MOST, NSFC, CAS, and the National Development and Reform Commission provided 490 million USD, and 340 million USD was given by MOST from 2016 to 2019.[16] In terms of China's budget for quantum technology, Kania and Costello (2018)[17] estimate it to be billions of USD, and similarly Brennen et al., (2021)[18] place it on the scale of a billion USD. Kung and Fancy (2021)[19] surmise a budget of 15.3 billion USD over five years, including the construction of national laboratories, and Parker et al., (2022)[20] and others suppose it is somewhere from 84 million USD to nearly 3 billion USD per year. The numbers from all of these authors are quite different to those published by the Chinese government.

Finally, this section shows some of the trends in regional government. In 2021, the Ministry of Human Resources and Social Security issued a notice calling for applications based on the theme of advanced training in FY2021 for a project to update the knowledge of specialist personnel,[21] and through this Anhui Province invested a total of 2.02 billion yuan (41 billion yen at a rate of 1 Chinese yuan = 20.3 yen)[22] in theoretical research and cutting-edge research in the quantum field, as a way of obtaining high-level science and technology independence and self-improvement, and was set to begin building the new-generation Hefei quantum metropolitan area network. Regarding quantum technology policy trends, although detailed project numbers and budgets have not been published, documents have been issued that specify the promotion of projects associated with quantum technology in Tianjin City,[23] Hebei

[14] 山東省人民政府「山東省人民政府关于印发山东省新旧动能转换重大工程实施规划的通知」鲁政发（2018）7 号

[15] From the Shandong Province Municipal Government website. Last confirmed: August 31, 2022. This was no longer accessible as of December 20, 2022.

[16] From note 3 and MOST

[17] Kania, E.B., and Costello, J. (2018) *Quantum Hegemony? China's Ambitions and the Challenge to U.S. Innovation Leadership,* Center for a New American Security, 46p.

[18] Brennen, G., Devitt, S., Roberson, T., and Roh, P. (2021) *An Australian strategy for the quantum revolution,* Policy Brief Report No. 43, Australian Strategic Policy Institute, 33p.

[19] Kung, J., and M. Fancy (2021) *A Quantum Revolution: Report on Global Policies for Quantum Technology*, Toronto, ON: CIFAR, 56p.

[20] Parker, E., Gonzales, D., Kochhar, A.K., Litterer, S., O'Connor, K., Schmid, J., Scholl, K., Silberglitt, R., Chang, J., Eusebi, C.A., and Harold, S.W. (2022) *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology,* Santa Monica, CA: RAND Corporation, 124p.

[21] 人力资源和社会保障部「关于征集专业技术人才知识更新工程 2021 年高级研修项目选题的通知」人社厅函（2021）2 号

[22] 安徽省人民政府「我省奋力打造具有重要影响力科技创新策源地」。Last confirmed: August 31, 2022. This was no longer accessible as of December 20, 2022.

[23] 天津市人民政府「天津市人民政府办公厅关于印发天津市智慧城市建设"十四五"规划的通知」津政办发（2021）52 号

Province,[24] Heilongjiang Province,[25] Shanxi Province,[26] and the Guangxi Zhuang Autonomous Region.[27] In 2022, Henan Province invested a budget of 11.5 million yuan (233.5 million yen) in one research project on quantum communication,[28] [29].

2.2 Quantum technology research and development

2.2.1 Major projects based on quantum technology

Based on the analysis of papers and patents in Chapter 1, the number of papers from China (27,987) makes up 44% of the total number of papers from the Asia-Pacific region (63,659). Moreover, a remarkable increase in papers is apparent from 2016, with an average growth rate of 24%, second to India, while still maintaining high standards. The number of patent applications (6,000) makes up 66% of the total patent applications in the Asia-Pacific region (9,000). This also puts China in the lead, considerably ahead of America (3,600).[30] Thus, the scale of China's quantum research can be seen as being the greatest in the world.

This section introduces research and development trends since the 2000s, especially major research projects. According to USTC's Zhang Qiang, during the period of the 11th Five-Year Plan from 2006 to 2010, China launched several large-scale research projects with a focus on quantum information.[31] For example, MOST announced its national Quantum Control project and NSFC launched its major research project "Single quantum state detection and interaction," CAS began its "Long distance quantum communication" and "Key technology research and verification of quantum experiments at space scale" projects, and at the time, the total amount of financial support it received was approximately 150 million USD. Considering the rapid development of quantum information and the possible effects on secure communication, MOST continued supporting the "Quantum Control" national major project, and NSFC announced a large-scale research project on "Quantum metrology" and another on "National major scientific research instruments and equipment development." CAS also started strategic leading science and technology projects based on its past space quantum project: "Quantum experiments at space scale," "Coherent control of quantum systems" and "Metrology physics in atomic systems." The National Development and Reform Commission (NDRC) launched the "Beijing–Shanghai Quantum Secure Communication Backbone" project with Anhui Province, Shandong Province, and CAS to develop industrial applications for quantum key

[24] 河北省人民政府「河北省人民政府办公厅关于印发河北省建设全国产业转型升级试验区"十四五"规划的通知」冀政办字(2021) 143 号。Last confirmed: August 31, 2022. This was no longer accessible as of December 20, 2022.

[25] 黑龙江省人民政府「黑龙江省人民政府关于印发黑龙江省中长期科学和技术发展规划（2021-2035 年）的通知」黑政发（2021）11 号

[26] 山西省人民政府「山西省人民政府关于印发山西省 "十四五" 未来产业发展规划的通知」晋政发（2021）16 号

[27] 广西壮族自治区商务厅「广西壮族自治区人民政府办公厅关于印发广西大众创业万众创新三年行动计划（2021-2023 年）的通知」桂政办发（2021）10 号

[28] 河南省人民政府「河南省人民政府办公厅关于印发河南省加快传统产业提质发展行动方案等三个方案的通知」豫政办（2022）4 号

[29] From the 河南省科学技术厅 website

[30] Center for Research and Development Strategy, Japan Science and Technology Agency (2022), "Ronbun/Tokkyo Map de Miru Ryoshi Gijutsu no Kokusai Doko" [International Trends in Quantum Technology from Papers and Patent Maps], CRDS-FY2021-RR-08, 97p. (Especially pages 31–32)

[31] See note 3.

distribution (QKD), and it is estimated that the funds procured between 2011 and 2015 totaled 490 million USD.

In January 2010, the "Quantum information research based on quantum states" project, the first National Key Scientific Research Program in quantum research led by MOST, was officially started in Taiyuan, the capital of Shanxi Province.[32] On the government side, the participants consisted of the Vice Governor of the Shanxi Province government, the Vice Minister of the Ministry of Science and Technology, the Head of the Shanxi Provincial Department of Science and Technology and a Deputy Prosecutor, while participants on the research institution side included Nanjing University, East China Normal University, Fudan University, members of a project advisory committee from Shanxi University, the main points of contact and relevant scholarly teams.,[33 34] Moreover, there were six projects in the field of quantum control research when it came to the 2009 National Key Scientific Research Program; only the "Quantum information research based on quantum states in the field of optics" project was a research project lead by a local institution.

In 2014, a group consisting of Professor Pan and his colleagues updated the secure communication distance for quantum key distribution systems, and in 2016 they succeeded in sending quantum entangled photons and also in quantum teleportation experiments using the world's first quantum scientific experimental satellite (known as Quantum Experiments at Space Scale [QUESS] or Micius).[35] In 2017, they created the Beijing-Shanghai trunk line,[36] the world's first wide-area communication network that connects space and Earth; this and more means that China's research and development capacity in the field of quantum communication is a step above the rest. In 2021, USTC succeeded in creating Zuchongzhi 2, a prototype programmable 66-qubit superconducting quantum computer. Its random quantum circuit sampling computational speed was said to be over 10 million times that of the world's fastest supercomputer at the time, and it is claimed that quantum supremacy, considered the key to the next-generation information revolution, was experimentally demonstrated with two physical systems (a super conducting quantum system and an optical quantum system).[37]

In 2021, FENG Mang (馮芒)[38] of the Innovation Academy for Precision Measurement Science and Technology, CAS provided proof that the quantum information reading speed is determined by changes in the entropy of the quantum system, as well as proving principles concerning the energy consumption required to improve quantum precision measurement technology and quantum operational efficiency. This is connected to the discovery of a method to simultaneously increase the speed and accuracy of quantum operations, and is credited with demonstrating a new path for the development of quantum computers[39, 40, 41].

[32] 科技部 (2010)「国家重大科学研究计划"基于光场量子态的量子信息研究"项目正式启动」

[33] See note 14.

[34] 王海、彭堃墀、谢常德 , 张宽收 , 郜江瑞 , 韦联福 (2014) 基于光场量子态的量子信息研究 . 科技纵览 (11), 3.

[35] 中国科学院 (2016)「揭秘全球首颗量子卫星」。

[36] 中国科学院「京沪干线」。

[37] 中国科学院 (2021)「"祖冲之二号"实现量子计算优越性」。

[38]「冯芒」中国科学院大学

[39] 中国科学院精密测量科学与技术创新研究院 (2021)「精密测量院等演示非循环非绝热的几何量子逻辑门」。

[40] Yan, L.-L., Zhang, J.-W., Yun, M.-R., Li, J.-C., Ding, G.-Y., Wei, J.-F., Bu, J.-T., Wang, B., Chen, L., Su, S.-L., Zhou, F., Jia, Y., Liang, E.-J., and Feng, M. (2022) Experimental Verification of Dissipation-Time Uncertainty Relation. *Physical Review Letters,* Volume 128, 050603.

[41] Wei, J.-F., Guo, F.-Q., Wang, D.-Y., Jia, Y., Yan, L.-L., Feng, M., and Su, S.-L. (2022) Fast multiqubit Rydberg geometric fan-out gates with optimal control technology. *Physical Review A,* Volume 105, Issue 4, 042404.

In 2022, LI Chuanfeng (李 传 锋) and ZHOU Zongquan (周 宗 权), members of the research laboratory of Academician GUO Guangcan (郭光灿) of USTC, significantly advanced the application of integrated quantum memory in quantum networks.[42] Their research provides a foundation to create quantum networks based on polarization coding by making use of the polarization degree of freedom of the photon in the field of integrated quantum storage; it notes that the polarization degree of freedom provides the degree of freedom for filtering that is effective in controlling the noise of integrated devices, and it is important in the use of integrated quantum storage.[43]

Also in 2022, several remarkable outcomes became apparent in the quantum communication field; these are introduced below in the order they were reported. In May 2022, Academician Pan Jianwei of USTC and his team succeeded in using the Micius satellite for the remote transfer of a quantum state between two stations, 1,200 km above Earth. The distance and quality of quantum entanglement is affected by factors such as channels and quantum decoherence, so how to overcome the limits of teleportation distance was a central issue in global quantum communication research in the past.[44] In July 2022, China succeeded in launching the world's first quantum micro-nano satellite Jinan 1 via the carrier rocket Lijian 1. It was stated that the successful development of this satellite made it possible to achieve real-time satellite-ground station quantum key distribution between the micro-nano satellite and a reduced-size ground station, for the first time in the world. This project was the result of joint research between a laboratory based in Hefei, the University of Science and Technology of China (USTC); Jinan Institute of Quantum Technology; the Innovation Academy for Microsatellites, Chinese Academy of Sciences; Shanghai Institute of Industrial Physics; and others.[45] Academician Pan Jianwei and his team reported that they had worked in cooperation with WANG Jianyu (王建宇) of the Hangzhou Institute for Advanced Study and his team to send a compact quantum key between Tiangong 2, launched in September 2016, and four satellite ground stations, thus realizing experimental verification of a quantum secure communication network between space and Earth. It was reported that this is potentially one of the most promising means for the creation of a global quantum communication network, as Tiangong 2's moderately inclined orbit means that it can pass by one ground station multiple times in one night, increasing the number of keys that can be generated.[46] The 21st Century Business Herald reported that China's largest quantum metropolitan area network (the Hefei Quantum Metropolitan Area Network), which was officially started in August 2021, formally opened in September. The optical fibers of its quantum key distribution network have a total length of 1,147, and it has eight core sites and 159 access sites. The network is able to provide quantum secure access service and data transmission encryption service to two levels of party/government institutions in the city/area. It is thought that it will increase the security protection standard of electronic administration across the board, and in the future, Hefei City will further expand, investigate and develop an abundance of quantum security application products based on the Hefei Quantum Metropolitan Area Network.[47]

[42] 中国科学院量子信息与量子科技创新研究院 (2022)「中国科大实现光子偏振态的可集成固态量子存储」。

[43] Jin,M. Ma,Y.-Z., Zhou, Z.-Q., Li, C.-F., Guo, G.-C. (2022) A faithful solid-state spin-wave quantum memory for polarization qubits. *Science Bulletin,* Volume 67, Issue 7, pp.676-678.

[44] 中国科学技术大学 (2022)"墨子号"实现 1200 公里地表量子态传输 , 中国科学技术大学 .

[45] 济南量子技术研究院 (2022) 世界首颗量子微纳卫星"济南一号"成功发射入轨 , 济南量子技术研究院 .

[46] 中国科学院 (2022)"量子星座"研究首次披露 " 天宫二号"曾立大功 , 中国科学院 .

[47] 21 世纪经济报道 (2022) 合肥量子城域网开通 , 21 世纪经济报道 .

Moreover, SHEN Qi (沈奇) of USTC and his team carried out a world-first experiment concerning high precision time and frequency transfer in free space over around 100 km; when they did so, the instability of the time transfer reached the femtosecond level, and although previously the instability of the frequency transfer was E-19 level, they reported that here it exceeded 4E-19 (a clock-induced error of no more than approximately 1 second per 100 billion years), making it possible to meet the demand for time transfer for the current most accurate optical clock.[48] Du Jiangfeng (杜 江 峰) of USTC and his team advanced quantum simulation of topological phase transition, reporting that they realized quantum simulations of triply degenerate topological monopoles by developing high-spin ion trap control system technology and that phase transition between monopoles with different topological charge demonstrated spin tensor during observation.[49] Physics World listed ZHAO Bo, Pan Jianwei, and USTC and CAS in the Top 10 Breakthroughs of the Year for 2022.[50]

In the same year, ZHANG Haoran (张 浩 然) of USTC and his team created a new system in quantum communication using a phase quantum state and time-bin quantum state. They succeeded in achieving quantum direct communication over 100 km, the longest distance in the world, greatly exceeding the previous longest distance for quantum direct communication (18 km).[51]

In recent years, China has begun offering quantum education in courses within university departments. Two specific examples are introduced below.

In 2021, Tsinghua University officially established an undergraduate course on quantum information, and employed Turing Award-winner Andrew Chi-Chih Yao as the head of this department. This is Tsinghua University's first program to foster human resources in the quantum information field at the undergraduate level. This project set up by Professor Yao to train innovative top human resources is the third initiative after the computer science experimental class and the artificial intelligence class, making a significant contribution to student education.[52] Moreover, May 22, 2022 saw the signing ceremony for the strategic cooperation framework agreement between Shenzhen International Quantum Academy and Shenzhen Gezhi Middle School, the unveiling ceremony for its academic nameplate, and the opening ceremony for its quantum computing center.[53] This collaboration will fully implement the Digital Longhua Urban Core development strategy, attempting to promote the high-quality development of education, fostering students' understanding of advanced technological industries and interest in science and technology, and enabling support for students' futures through quantum technology.

[48] Shen, Qi., Guan, Jian-Yu., Ren, Ji-Gang., Zeng, Ting., Hou, Lei., Li, Min., Cao, Yuan., Han, Jin-Jian., Lian, Meng-Zhe., Chen, Yan-Wei., Peng, Xin-Xin., Wang, Shao-Mao., Zhu, Dan-Yang., Shi, Xi-Ping., Wang, Zheng-Guo., Li, Ye., Liu, Wei-Yue., Pan, Ge-Sheng., Wang, Yong., Li, Zhao-Hui., Wu, Jin-Cai., Zhang, Yan-Yan., Chen, Fa-Xi., Lu, Chao-Yang., Liao, Sheng-Kai., Yin, Juan., Jia, Jian-Jun., Peng, Cheng-Zhi., Jiang, Hai-Feng., Zhang, Qiang., Pan, Jian-Wei (2022) Free-space dissemination of time and frequency with 10−19 instability over 113 km, Nature, Volume 610, pp.661-666. DOI: 10.1038/s41586-022-05228-5

[49] Zhang, M., Yuan, X., Li, Y., Luo, X., Liu, C., Zhu, M., Qin, X., Zhang, C., Lin, Y., Du, J., (2022) Observation of Spin-Tensor Induced Topological Phase Transitions of Triply Degenerate Points with a Trapped Ion, *Phys. Rev* . Lett. 129, 250501

[50] https://physicsworld.com/a/physics-world-reveals-its-top-10-breakthroughs-of-the-year-for-2022/

[51] Zhang, H., Sun, Z., Qi, R., Yin, L., Long, G., Lu, J. (2022) Realization of quantum secure direct communication over 100 km fiber with time-bin and phase quantum states. *Light: Science & Applications,* Volume 11, No.83.

[52] 清华大学 (2021)「清华大学成立量子信息班 姚期智院士领衔」

[53] 深圳量子科学与工程研究院 (2022)「量子研究院与格致中学签订战略合作框架协议，建设大湾区第一个高中量子计算中心」

2.2.2 Funding

Funding for science and technology research and development in China is broadly split into the following three categories.

① **Competitive research funding given by the central government:** This includes the National Natural Science Foundation of China (NSFC)[54] and National Key Research Program (MOST)[55], with both top-down and bottom-up research programs. The central government's science and technology plans included the National High-tech R&D Program (863 Program), the National Program on Key Basic Research Project (973 Program), the National S&T Support Program, the Special Project for International Science and Technology Cooperation and Exchange, the National Development and Reform Commission, and the Ministry of Industry and Information Technology, but the State Council integrated these into five categories (National Natural Science Foundation of China, National Major S&T Project, National Key R&D Program, Special Project (Fund) of Technical Innovation, and Special Project for Base and Talent) with the aim of further increasing the effective use of government funding.[56]

② **Funding provided by the Ministry of Education:** University funding is generally distributed by the Ministry of Education. A high level of funding is given to institutions designated as key universities. Moreover, institutions such as CAS have internal competitive funding for organizations under their authority.

③ **Competitive research funding given by regional governments:** Local governments such as those of local provinces and cities provide competitive research funding to universities, research institutions, and companies based on major policies from the central government.

Additionally, the survey of papers confirmed that much of the main funding comes from NSFC, followed by the Ministry of Education, MOST, and regional governments (Figure 2-1).

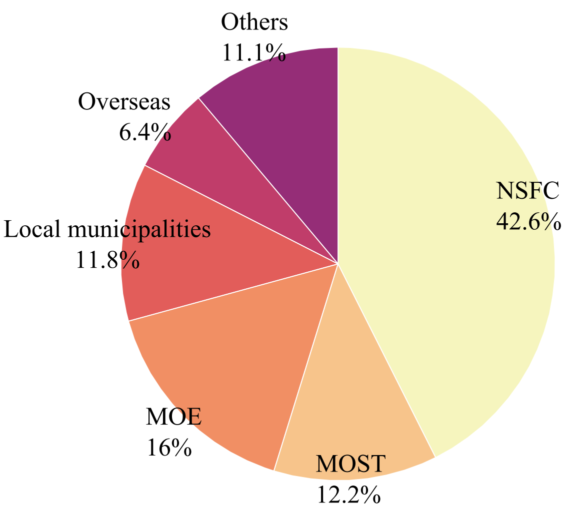


Figure 2-1: Breakdown of funding for Chinese papers from main funding organizations

Source: Web of Science (data from 2010–2021)

[54] From the 国家自然科学基金委员会 website.

[55] From the 中华人民共和国科学技术部 website.

[56] 国务院 (2014)「国务院印发关于深化中央财政科技计划（专项、基金等）管理改革方案的通知」国发（2014）64 号

First, this focuses on NSFC, organizing the information in accordance with the number of selected projects in each program containing the keyword "quantum" (Table 2-1). The Major Research Plan provides long-term support for specific research areas based on the national development strategy; major programs and key programs are almost all top-down projects from the government. On the other hand, general programs and the programs under the Science Fund for Young Scholars are bottom-up projects. Incidentally, there are lots of applications from graduate students for programs under the Science Fund for Young Scholars.

Table 2-1: Projects selected by NSFC and trends in overall budget (1997–2021)

	General programs		Key programs		Major programs		Major Research Plan		Science Fund for Young Scholars	
	Number of projects selected	Total number of projects selected	Number of projects selected	Total number of projects selected	Number of projects selected	Total number of projects selected	Number of projects selected	Total number of projects selected	Number of projects selected	Total number of projects selected
1997	21	1,242	1	85	0	43	0	0	4	318
1998	20	1,229	1	95	1	95	0	0	2	352
1999	18	1,217	0	54	0	35	0	0	5	344
2000	30	1,288	0	43	0	3	0	0	4	380
2001	30	3,507	2	124	0	1	12	122	5	716
2002	28	2,373	3	95	0	14	7	194	5	570
2003	33	2,665	3	104	0	37	6	68	14	648
2004	35	3,282	2	94	0	52	6	160	14	787
2005	52	3,866	2	120	0	19	0	53	10	920
2006	56	4,206	2	117	0	0	1	109	26	1,099
2007	64	4,417	7	155	0	0	1	235	28	1,523
2008	92	5,025	7	185	0	56	0	181	25	2,478
2009	82	5,652	8	159	8	27	8	236	51	3,444
2010	161	13,174	5	444	0	69	19	444	100	8,334
2011	172	15,478	5	518	0	69	17	432	144	13,103
2012	174	16,865	8	536	0	93	9	333	145	13,865
2013	166	16,154	10	562	0	114	16	368	165	15,310
2014	171	14,983	9	604	1	115	17	453	175	16,369
2015	182	16,680	9	624	4	105	6	512	173	16,109
2016	186	16,915	9	612	2	122	8	501	161	16,072
2017	193	18,127	10	667	0	210	5	535	177	17,504
2018	215	18,938	16	701	7	185	7	513	185	17,658
2019	190	18,995	11	742	9	247	5	526	201	17,965
2020	209	19,357	12	737	0	0	15	449	202	18,273
2021	195	ND	12	ND	0	ND	17	ND	200	ND

From 2010, the number of projects selected increased overall (Table 2-1, Figure 2-1). This appears to coincide with the period in which China began significantly investing in science and technology—not only quantum research but other research fields too, in addition to officially starting projects in the National Key Scientific Research Program led by MOST.

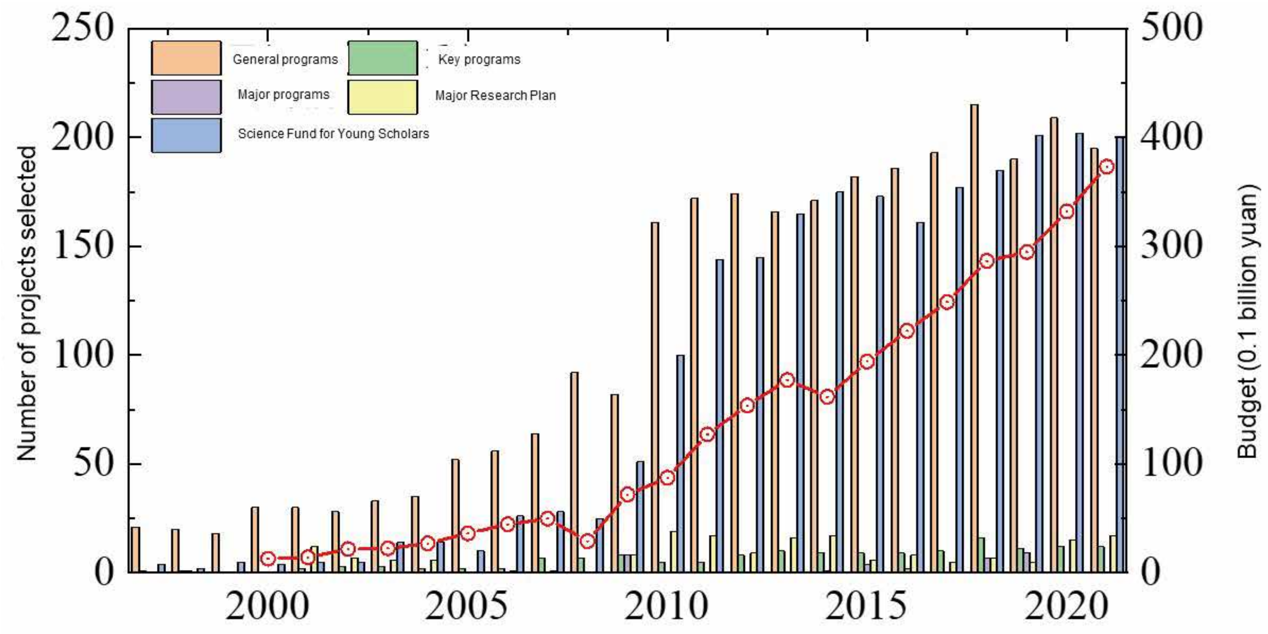


Figure 2-1: Overview of the National Key Research Program in terms of quantum research
Source: MOST "Introduction to the Quantum control and quantum information key R&D project," Sciping, etc.

The tables below show an overview of the projects selected from 2017 to 2020 (tables 2-2 to 2-5).

Table 2-2: Overview of National Key Research Program selection in 2017

No.	Project number	Project name	Associated organization	Representative	Funding (10 million yuan)	Period (years)
1	2017YFA0302900	Quantum effects and correlated electron control	Institute of Physics, Chinese Academy of Sciences	Tao Xiang	11,057	5
2	2017YFA0303000	Exploring novel 2D layered unconventional superconductors and clarifying their mechanisms	University of Science and Technology of China	Xianhui Chen	2,800	5
3	2017YFA0303100	Evolving quantum states in heavy fermions and their control mechanisms	Zhejiang University	Huiqiu Yuan	2,652	5
4	2017YFA0303200	Research on topological magnetic structures and their heterojunction physics and devices	Nanjing University	Bogen Wang	2,801	5
5	2017YFA0303300	Spin and charge control in topological composite small quantum systems	Peking University	Qingfeng Sun	2,747	5
6	2017YFA0303400	Controlling the quantum state of low-dimensional solid polar structures and prototype devices for this	Institute of Semiconductors , Chinese Academy of Sciences	Haiqing Lin	2,737	5
7	2017YFA0303500	Quantum control confined in a small quantum system in a local magnetic field	University of Science and Technology of China	Yi Luo	2,814	5
8	2017YFA0303600	Quantum mechanical control and dynamics of complex oxide surface interfaces	Institute of Physics, Chinese Academy of Sciences	Jiandong Guo	2,777	5
9	2017YFA0303700	Quantum and quantum-like effects in artificial microstructures and functional integrated photonic chip	Nanjing University	Yanqing Lu	10,039	5
10	2017YFA0303800	Generation and modulation of spatial light fields and their interaction with microstructures with topological properties	Nankai University	Zhigang Chen	2,877	5
11	2017YFA0303900	Space-Earth integrated wide-area quantum communication network technology	University of Science and Technology of China	Chengzhi Peng	11,184	5
12	2017YFA0304000	High performance single-photon detection technology	Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences	Lixing You	5,584	5
13	2017YFA0304100	Solid-state quantum memory	University of Science and Technology of China	Chuanfeng Li	4,751	5
14	2017YFA0304200	Quantum simulation based on optical lattice supercooled quantum gas	Shanxi University	Liantuan Xiao	3,873	5
15	2017YFA0304300	Multiplexed superconducting qubit integrated system with quantum error correction and quantum memory function	University of Science and Technology of China	Xiaobo Zhu	5,298	5
16	2017YFA0304400	High precision atomic light clock	Wuhan Institute of Physics and Mathematics, Chinese Academ	Kelin Gao	6,308	4.5
17	2017YFA0304500	Precision measurement based on associations with atom, ion, and photon few bodies	Wuhan Institute of Physics and Mathematics, Chinese Academ	Xiwen Guan	2,797	5
18	2017YFA0304600	Novel 2D unconventional superconducting thin film/heterojunction fabrication and exploration of anomalous physics	Tsinghua University	Canli Song	477	5
19	2017YFA0304700	Materials, physical properties, and devices for correlated electron systems	Institute of Physics, Chinese Academy of Sciences	Zhiguo Chen	465	5
20	2017YFA0304800	Experimental research on quantum information using Rydberg atoms	University of Science and Technology of China	Dongsheng Ding	485	5
21	2017YFA0304900	Research on quantum reference ultra-high resolution microwave measurement	Tsinghua University	Feng Xie	466	5
22	2017YFA0305000	Experimental research concerning the preparation of single spins with ultra-long coherence times at room temperature	University of Science and Technology of China	Ya Wang	465	5
23	2017YFA0305100	Research on optical/acoustic topological characteristics in artificial microstructures	Nanjing University	Cheng He	466	5
24	2017YFA0305200	Basic research on quantum information based on integrated photonic devices	Sun Yat-sen University	Xiaoqi Zhou	440	5
25	2017YFA0305300	Spin quantum control mechanisms in III-V low dimensional narrowband semiconductors	Institute of Semiconductors , Chinese Academy of Sciences	Dahai Wei	459	5
26	2017YFA0305400	Tuning electronic structures in topological quantum materials and developing devices	ShanghaiTech University	Zhongkai Liu	440	5
27	2017YFA0305500	III-V semiconductor 3D heterogeneous nanowires: in-situ construction and application to infrared detection	Shandong University	Zaixing Yang	488	4

Source: High-level Technology and Research Development Center, MOST

Table 2-3: Overview of National Key Research Program selection in 2018

No.	Project number	Project name	Associated organization	Representative	Funding (10 million yuan)	Period (years)
1	2018YFA0305600	Quantum states in correlated systems such as topological superconductors	Peking University	Jian Wang	1,806	5
2	2018YFA0305700	New correlated electron materials and quantum state control in comprehensive extreme environments	Institute of Physics, Chinese Academy of Sciences	Changqing Jin	1,852	5
3	2018YFA0305800	Theoretical design of new 2D quantum functional materials, controllable preparation, high-precision characterization, prototyping realization, quantum effects and their control in multiscale small quantum complex systems under high pressure	University of Chinese Academy of Sciences	Gang Su	1,771	5
4	2018YFA0305900	Research on molecular magnetic quantum materials and devices	Jilin University	Bingbing Liy	1,804	5
5	2018YFA0306000	Research on quantum transport mechanisms in semiconductor composite quantum structures and quantum devices	Nanjing University	Jinglin Zuo	1,811	5
6	2018YFA0306100	Research on mid-infrared photoelectric coupling mechanisms and avalanche detection devices and research concerning the application of artificial microstructures	Institute of Semiconductors, Chinese Academy of Sciences	Zhichuan Niu	1,859	5
7	2018YFA0306200	New super-high-speed light fields and coherent control of quantum states in micro and nano systems	Shanghai Institute of Technical Physics, Chinese Academy of Sciences	Xiaoshuang Chen	1,889	5
8	2018YFA0306300	Research on key technology for high-performance quantum key distribution	East China Normal University	Jian Wu	1,813	5
9	2018YFA0306400	Research on the many-body effects of heteronuclear quantum simplex mixed gases	University of Science and Technology of China	Zhengfu Han	1,838	5
10	2018YFA0306500	Quantum coherent control in diamond color centers and its applications	Tsinghua University	Li You	3,658	5
11	2018YFA0306600	Theories, methods, and tools of quantum programing	University of Science and Technology of China	Jiangfeng Du	7,163	5
12	2018YFA0306700	Discovery of 2D topological quantum materials, evaluation of their characteristics and exploration of devices	Institute of Software, Chinese Academy of Sciences	Mingsheng Ying	858	5
13	2018YFA0306800	2D quantum functional materials and the creation of their heterostructure and transport characteristics	Nanjing University	Yi Zhang	436	5
14	2018YFA0306900	Modulation and related quantum devices	Peking University	Yu Ye	465	5
15	2018YFA0307000	Novel quantum properties induced by strong spin orbit coupling and its multifield regulation under complex extreme conditions	Huazhong University of Science and Technology	Gang Xu	447	5
16	2018YFA0307100	Topological quantum state control based on the quantum anomalous Hall effect and an exploration of its applications	Tsinghua University	Jinsong Zhang	471	5
17	2018YFA0307200	Many-body system physics research on ultracold quantum gases in optical lattices	Zhejiang University	Bo Yan	441	5
18	2018YFA0307300	Room temperature operation and integration of van der Waals heterojunction artificial microstructure mid-infrared detector	Nanjing University	Xiaomu Wang	440	5
19	2018YFA0307400	Experimental research on multi-channel quantum channels in the optical communication band	University of Electronic Science and Technology of China	Qiang Zhou	474	5
20	2018YFA0307500	The creation and application of total optical binding ion quantum states	Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences	Yao Huang	470	5
21	2018YFA0307600	Impurities physics and new quantum states in heteronuclear simple gases	Institute of Physics, Chinese Academy of Sciences	Xiaoling Cui	456	5

Source: High-level Technology and Research Development Center, MOST

Table 2-4: Overview of National Key Research Program selection in 2019

No.	Project number	Project name	Associated organization	Representative	Funding (10 million yuan)	Period (years)
1	2019YFA0307700	Precise measurement of transient quantum processes of atomic and molecules	Jilin University	Jianmin Yuan	1,875	5
2	2019YFA0307800	Multifield control of 2D low dimensional superconducting/magnetic quantum materials, exploration of microscopic mechanisms, creation of quantum prototype devices	University of Chinese Academy of Sciences	Jinhai Mao	476	5
3	2019YFA0307900	Ferroelectric material domains in low dimensional magnetoelectric coupling materials and topology multifield control and prototyping	University of Science and Technology of China	Yuewei Yin	468	5
4	2019YFA0308000	Exploring and modulating quantum behavior in 2D superconducting materials	Institute of Physics, Chinese Academy of Sciences	Yuan Huang	478	5
5	2019YFA0308100	Quantum coherent control of collective excitation in spin systems	Zhejiang University	Dawei Wang	416	5
6	2019YFA0308200	Experimental research on quantum optical integrated chips and quantum information physics using lithium niobate thin film	Shandong University	He Lu	475	5
7	2019YFA0308300	Super-high spatial and temporal resolution precision measurement of atoms and molecules in attoseconds sub Å	Huazhong University of Science and Technology	Yueming Zhou	478	5

Source: High-level Technology and Research Development Center, MOST

Table 2-5: Overview of National Key Research Program selection in 2020

No.	Project number	Project name	Associated organization	Period (years)
1	2020YFA0308800	Low dimensional spin quantum functional materials and their super-high speed tuning	Beijing Institute of Technology	5
2	2020YFA0308900	Topological state modulation in low-dimensional intrinsic magnetic materials and device exploration	Southern University of Science and Technology	5
3	2020YFA0309000	Modulation of quantum many-body effects in low dimensional graphene materials	Shanghai Jiao Tong University	5
4	2020YFA0309100	Quantum-derived phenomena from new self-supporting low dimensional systems and control through multi-electric fields	Institute of Physics, Chinese academy of sciences	5
5	2020YFA0309200	Terahertz light modulation in low dimension spin and correlated electron systems and the development of prototype devices	Nanjing University	5
6	2020YFA0309300	Super-high speed dynamics of topological spin structures in multi-electric field modulation	Nankai University	5
7	2020YFA0309400	Research on quantum enhanced magnetometer using spin systems	Shanxi University	5
8	2020YFA0309500	Research on highly efficient high dimensional quantum storage using cold atoms	South China Normal University	5
9	2020YFA0309600	Research on the exotic properties of twisted graphene and other Moiré superlattices	The Hong Kong University of Science and Technology	5

Source: High-level Technology and Research Development Center, MOST

It is apparent that in each of these years, many projects were selected from CAS and the institutions involved in international joint research described in 2.6. Looking at this closely shows that USTC obtains around 30% of the budget, while the Institute of Physics, CAS and Nanjing University have around 10% each. The CAS system, when put together, has over 60% of the budget, followed by Nanjing University, Tsinghua University, Peking University, and Shanxi University (no data is available for 2020, so there may be discrepancies.) In terms of the number of projects selected, USTC is followed by Nanjing University and the Institute of Physics, CAS, with the CAS system involved in over 40% of projects.

2.3 Notable research institutions and universities

The information below and Figure 2-2 show examples of noteworthy research institutions and universities.[57]

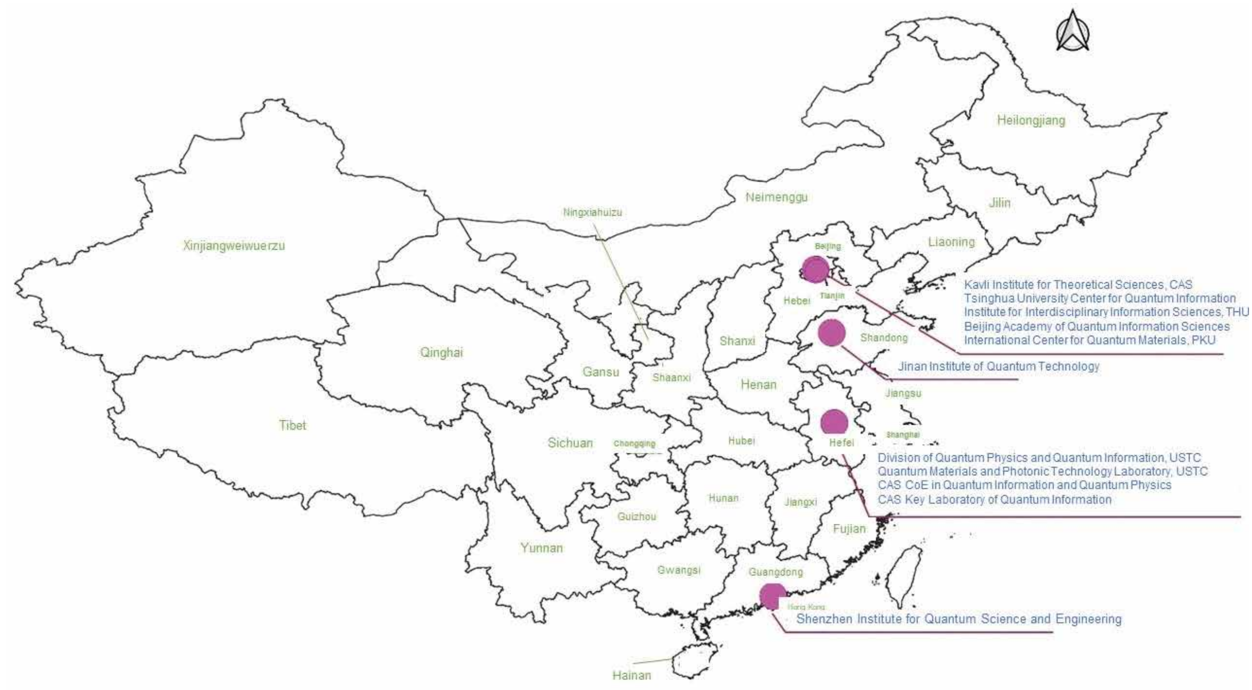


Figure 2-2: Noteworthy research institutions and universities

2.3.1 Division of Quantum Physics and Quantum Information, University of Science and Technology, China (量子物理与量子信息研究部)

As was stated in 2.2, this institution leads quantum research in China at a global level, contributing to the launch of the quantum scientific experimental satellite Micius; its research is led by Guo Guangcan and Pan Jianwei. The Division was established in 2001, when CAS acknowledged Professor Pan's research laboratory in USTC as a key experimental laboratory. It has set the strategic goal of building a complete aerial integrated wide-area quantum communication system and ensuring its broad utility in the fields of national defense and politics. When it comes to the launch of the quantum scientific experimental satellite Micius, it is engaged in organizing and coordinating research activities for experiments, in addition to taking charge of/leading teams of researchers from other research institutions. Its main research fields are quantum mechanics, quantum communication between major urban areas based on optical fiber, wide-area quantum communications based on satellites, quantum storage and quantum relay, optical quantum computing, superconducting quantum computing, and the fundamental principles of ultracold atomic quantum.

The figures below show the papers submitted and the top 10 recipients of submissions since the laboratory was set up (Figures 2-3 and 2-4). Every year, large numbers of papers are published, including in Nature (IF: 49.96) in 1997. To date, the total is 644. From around 2010, the number greatly increased. It is conceivable that this

[57] For more details, please see Center for Research and Development Strategy, Japan Science and Technology Agency (2022) 5.3.

was affected by the medium- and long-term plan issued in 2006, as well as the increased budget for science and technology in China, as shown in Figure 2-3. Many papers are also published in Science (IF: 47.73) as well as in Physical Review Letters (IF: 9.185), and it is apparent that these have had a considerable impact on the world of quantum mechanics.

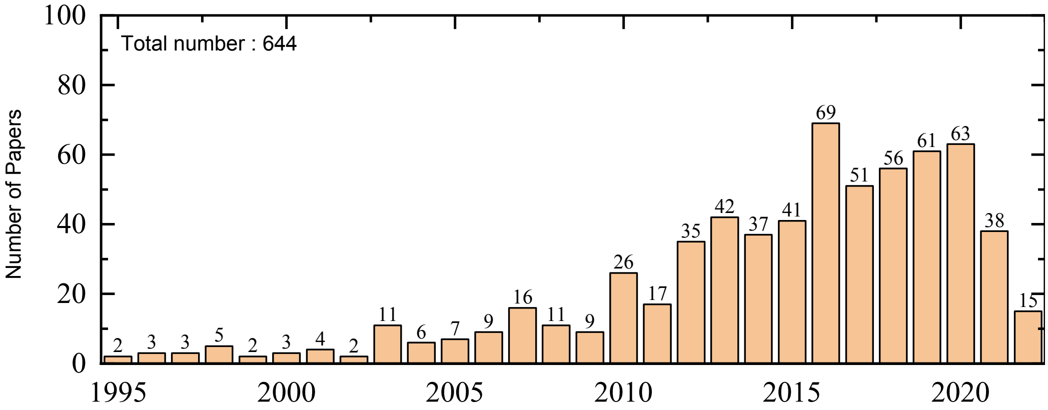


Figure 2-3: Number of papers submitted since the laboratory was established

Source: 论文发表

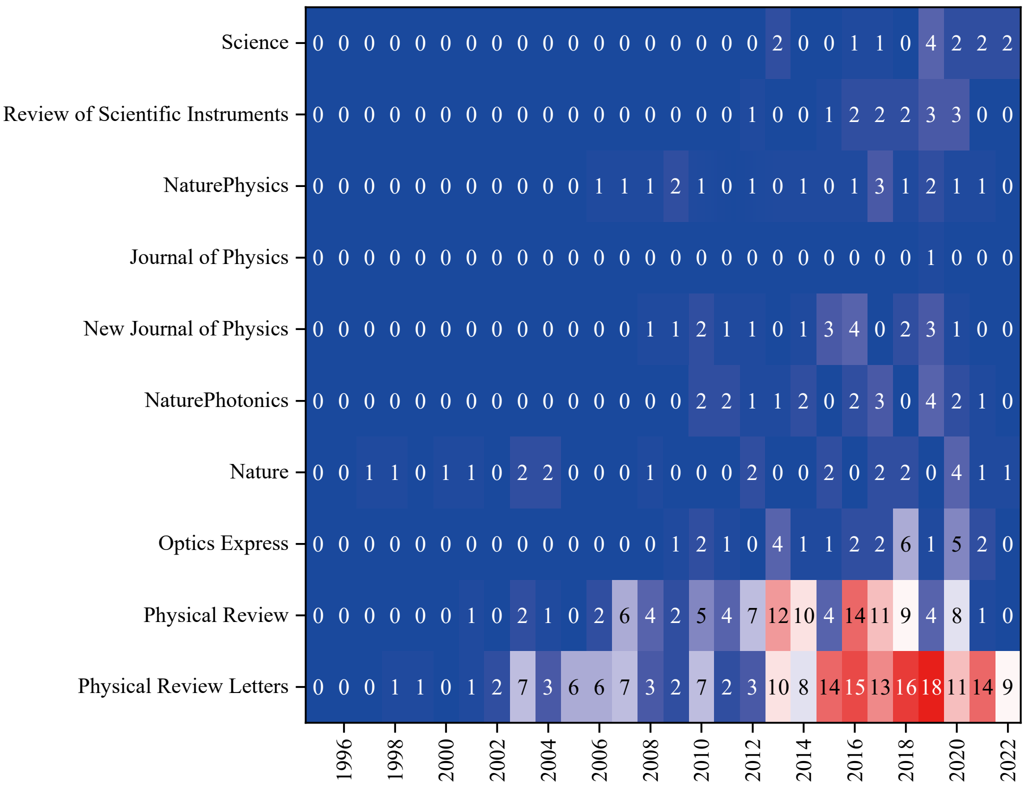


Figure 2-4: Top 10 recipients of submissions since the laboratory was established

2.3.2 Quantum Materials and Photonic Technology Laboratory, USTC (中国科学技术大学 量子材料与光子技术实验室)

This facility was officially established in 2016 by Lu Yalin (陆亚林),[58] who was previously a member of USTC's quantum functional materials research group. It aims to confront the scientific frontiers of quantum information processes, energy, and the environment using multi-parameter composite quantum functional materials, achieving major quantum creation and breakthroughs in demonstrations of functional materials for device performance, through advanced optical and electronic spectroscopy characterization technology. It also serves as an organization that carries out work entrusted to USTC by CAS research institutes and MOST-approved research centers; it takes on work from the CAS Center for Excellence in Quantum Information and Quantum Physics (below), as well as the National Research Center for Physical Sciences at the Microscale and the High-end Science and Technology Anhui Laboratory Platform.

2.3.3 CAS Center for Excellence in Quantum Information and Quantum Physics (中国科学院量子信息与量子科技创新研究院)

This institution was commissioned by the Chinese Ministry of Science and Technology for USTC, preemptively seeking to establish a "national laboratory." In August 2016, Anhui Province and CAS set up the Joint Conference for the Construction of the National Laboratory for Quantum Information Sciences, and signed a comprehensive innovation cooperation agreement. After the unification of the Quantum Collaborative Innovation Center and the Center of Excellence for Quantum Information and Quantum Science, Anhui Province and CAS established this core facility as Hefei's research base in July 2017. Its aim is to make effective use of the innovative elements and advantageous resources of universities, research institutions, and relevant businesses across China, and to engage in shared construction of Chinese science and technology with USTC. The Center has set up four research units (the Quantum Communication Research Department, the Quantum Computing Research Department, the Quantum Precision Measuring Research Department, and the Engineering Support Department) and is engaged in joint research with CAS' Shanghai Institute of Technical Physics, the Institute of Semiconductors, the Institute of Optics and Electronics, the Institute of Physics, the Shanghai Institute of Microsystem and Information Technology, the Innovation Academy for Microsatellites, the Wuhan Institute of Physics and Mathematics, the University of Chinese Academy of Sciences, and the CAS National Information Communication Center; joint innovation units outside of CAS include Peking University, Tsinghua University, Fudan University, Shanghai Jiao Tong University, Nanjing University, the National University of Defense Technology, Zhejiang University, Beihang University, East China Normal University, Beijing Computational Science Research Center, and relevant teams from other higher education institutions and research institutions.

[58] 「陆亚林 中国科学技术大学杰出讲席教授」

2.3.4 CAS Key Laboratory of Quantum Information (中国科学院量子信息重点実験室)

This is one of China's key hubs for training personnel in quantum information research. Its predecessor was the CAS Quantum Optics Research Organization, founded in 1983, and this was reorganized into the USTC Quantum Communication and Quantum Measurement Open Lab in 1999, with support. In 2001, with the approval of CAS, it was renamed the CAS-USTC Quantum Information Key laboratory, and it became the CAS Key Laboratory of Quantum Information in 2005. It has engaged in theoretical and experimental research on quantum communication and quantum computing over many years, and continues to produce innovative scientific research outcomes. As it is managed by USTC, it is located in the Hefei City Campus in Anhui Province, but administratively it belongs to CAS; its main research is solid state quantum computing, quantum entanglement networks, quantum integrated optical chips, the development of new quantum encryption protocols and practical quantum devices, and quantum theory. In 2005, it achieved single-vector sub-key distribution over 125 km via an actual communication light path (a world first), and in 2009 it constructed the world's first quantum administrative network in Wuhu. In 2011, it succeeded in entangling eight photons, as well as achieving a solid-state quantum memory of a photon polarization state with 99.9% fidelity for the first time. In 2013, it even realized a quantum memory of orbital angular momentum of photons via the cold atom research unit for the first time.

2.3.5 Kavli Institute for Theoretical Sciences, CAS (中国科学院卡弗里理論物理研究所)

This institution was established in 2006, with the joint support of funding from CAS and the American Kavli Foundation and support from the University of Chinese Academy of Sciences (UCAS). As one of the 20 Kavli research institutes around the world, it has the important role of promoting theoretical physics research in China and hosting international programs in physics and relevant interdisciplinary fields. At first, it was set up as the Kavli Institute for Theoretical Physics, China (KITPC) in collaboration with CAS' Institute for Theoretical Physics, but was later reorganized into its current form. It has four institutions—Divisions I and II, KITS, and the Key Laboratory of Frontiers in Theoretical Physics —and its mission is to ensure its position as an international hub of theoretical science. Moreover, it is involved in theoretical physics and relevant interdisciplinary sciences, and offers a variety of academic programs, including postdoctoral fellowships, visitor programs, outreach programs, and an associate member system.

2.3.6 Tsinghua University Center for Quantum Information (清华大学量子信息中心)

This Center was established, primarily by Andrew Chi-Chih Yao, on January 6, 2011, and aims to construct a global platform for education and research on quantum information in China. It falls under the authority of the Institute for Interdisciplinary Information Sciences, Tsinghua University, and its main research focus is quantum computing and control theories, quantum computers and experiments, and quantum devices and quantum communication. It is also involved in key national projects such as the Complete Quantum Network in the National Key Basic R&D Program, the Ministry of Education's Tsinghua Quantum Information Center Construction Project, and MOST's Quantum Computing Key R&D project.

2.3.7 Institute for Interdisciplinary Information Sciences, Tsinghua University (清华大学交叉信息研究院)

This is China's first research and education unit that specializes in interdisciplinary informatics research. Like the abovementioned Tsinghua University Center for Quantum Information, it was founded primarily by Andrew Chi-Chih Yao in January 2011. It aims to construct an interdisciplinary informatics research institution of the highest standard in the world in China and foster innovative personnel with the ability to compete internationally. Its main research themes are quantum optics, quantum communication, superconducting quantum computing, practical quantum information research, quantum artificial intelligence, and topological condensed matter physics. The Tsinghua School Computer Science Laboratory (established 2005), the Tsinghua School AI Class (established 2019), and the Tsinghua School Quantum Information Class (established 2021) were all set up as hubs to foster human resources in the fields of computer science and AI and quantum information. Its research and education section also includes the Center for Quantum Information (CQI) and Intelligent FinTech Institute, while the section for industry-university collaborations has the Tsinghua-Nanjing Joint Research Center for Interdisciplinary Intelligence, the Tsinghua-Xi'an Joint Research Center for Interdisciplinary Information Sciences, the Tsinghua-Ant Financial Joint Research Laboratory for Digital FinTech, and the Tsinghua-Xi'an Joint Research Center for Financial Technology. Tsinghua University Center for Quantum Information was officially opened at the same time as this institute was established, with Professor Yao leading the Institute for Interdisciplinary Information Sciences, taking charge of several key national projects in the quantum informatics field, and raising the quantum information center to become a key advanced research base for quantum computing and quantum networks. As of July 2020, 407 people have graduated from the Tsinghua University Yao Class, and 355 of these have remained in research, while 52 entered major computing companies.[59]

2.3.8 Beijing Academy of Quantum Information Sciences (北京量子信息科学研究院)

XUE Qikun (薛其坤), President of the Academy, President of the Southern University of Science and Technology and CAS Academician, was involved in the founding of this Academy. It is a new type of research and development institution, jointly established in the capital city of Beijing on December 24, 2017, as the representative quantum research hub by Beijing City and multiple top academic institutions in the city such as Tsinghua University, Peking University and CAS. It stands at the forefront of global quantum physics and quantum information science and technology; to respond to national strategic needs in quantum information technology, it is integrating existing resources in Beijing in fields such as quantum materials science, quantum computing, quantum communication, quantum materials and devices, quantum precision measurement, constructing a comprehensive experiment/research and development platform for quantum information science technology, and gathering outstanding scientists and engineers and their innovative teams from around the world. It is made up of five research divisions (Quantum State of Matter, Quantum Computation, Quantum Communication, Quantum Materials and Devices, and Quantum Precision Measurement), two platforms that support each research division (Micro-nano Fabrication Platform and Synergetic Testing Platform), and a quantum engineering research center. The main research fields

[59] 澎湃 (2021)「清华成立量子信息班：姚期智任首席教授，今年首届招生 20 人」

are quantum state of matter, quantum computation, quantum communication, quantum materials and devices and quantum precision measurement, and the Academy is focusing on two experimental platforms to support this research. It is working on human exchange, not just with universities and Chinese research institutes but also with private companies such as Baidu.

2.3.9 International Center for Quantum Materials, Peking University (北京大学量子材料科学中心)

This Center was established in 2010 to research frontier issues in condensed matter physics and quantum materials science. It aims to foster research teams with international influence by adopting world-class technology, including introducing cutting-edge experimental facilities, to build academic foundations for fundamental research and promote the development of advanced technology based on quantum science. It is organized into six research divisions (Low temperature and quantum transport experiments, Spintronics and low-dimensional magnetism experiments, High-resolution spectroscopy experiments, AMO experiment and precision measurement, Theoretical condensed matter physics, and Computational physics), and has 17 experimental laboratories, a public supporting laboratory for physical property measurement, a public experiment platform for nanofab, and a helium center.

2.3.10 Shenzhen Institute for Quantum Science and Engineering (南方科学技術大学深圳量子科学工学研究院)

Xue Qikun is the President of both this Institute and the Beijing Academy of Quantum Information Sciences. This Institute's focus is on quantum information technology research and human resource development, with the particular involvement of YU Dapeng (俞 大 鹏), a leader of quantum materials research. It was established in the Southern University of Science and Technology (SUSTech) in January 2018 as one of the first three "Top Ten Fundamental Research Institutions" to handle quantum technology outlined in the National Key Development Strategy announced at the start of 2017. Its facilities and equipment are the responsibility of SUSTech, and decision-making is up to Shenzhen City's Board of Directors for Fundamental Research Institutions; both are supervised by the President. Importance is placed on four areas: quantum materials, quantum precision measurement, quantum computing, and quantum engineering.

2.3.11 Jinan Institute of Quantum Technology (済南量子技術研究院)

Jinan Institute of Quantum Technology, set up in May 2011, is under the jurisdiction of Jinan City in Shandong Province. It is mainly engaged in basic research on the fundamentals and applications of quantum science. It is responsible for providing technical support for converting quantum scientific research outcomes, organizing the construction of a public R&D platform for quantum science and technology and a test network for quantum confidential communication, and introducing quantum science and technology personnel within the province. This institute has taken up the position of secretariat of the National Technical Commission for Quantum Computing and Measurement Standardization, and is acknowledged as a provincial Postdoctoral Innovation Practice Base, Science Education Base, and New R&D Institution. It has established an academic committee that includes 15 CAS academicians and members of the Chinese Academy of Engineering, and has a total of 113 personnel (leading national and municipal scholars, excellent young scholars). This institute is working on multiple major research projects on the national, provincial, and city levels, including setting new world records in the field of quantum communication; it has applied for more than 100 national patents, and published more than 150 papers in famous international journals such as Nature and Physical Review Letters.

2.4 Notable companies

As of 2021, this report identified 46 companies connected to quantum research in China;[60] information on 10 of these companies is listed below, and is correct as of May 30, 2022.[61] These are subdivided into quantum communication (19), quantum computation (14), quantum measurement (3), encryption key communication (7), and other (3). While the State Grid Corporation of China, founded in 2002, is an electric power company under the direct jurisdiction of the Chinese government, it has apparently been engaged in quantum research since it was first established. There are many companies with connections to CAS; at first, these were set up in Beijing, Shandong Province, and Anhui Province, but they have increased dramatically in number since 2015 and have therefore also increased in other areas. Figure 2-11 shows examples of highly noteworthy companies, such as startups and those with a connection to CAS.[62]

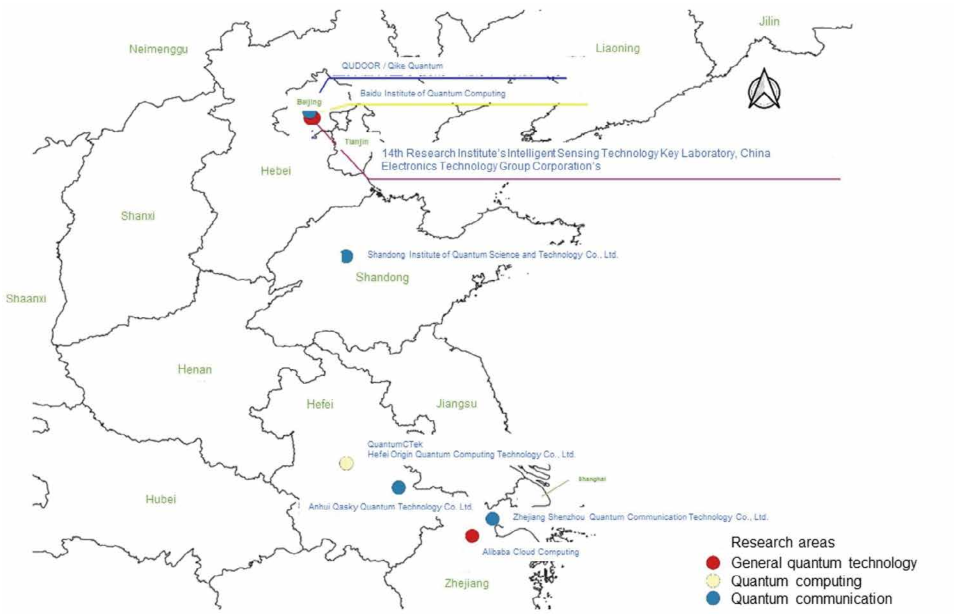


Figure 2-5: Locations of noteworthy companies

[60] 光子盒研究院 (2021)「国内量子科技公司全览 (2021 更新版)」。

[61] Taken from Center for Research and Development Strategy, Japan Science and Technology Agency (2022) 5.4 and 5.5.

[62] See note 22. Note that " 有限公司 " is short for " 有限责任公司 ," and are companies not permitted to be listed. " 股份有限公司 " is the same as a company limited in Japan, meaning it is listed. Thus " 有限公司 " and " 有限责任公司 " mean " 有限公司 ", and " 股份有限公司 " is "Co., Ltd."

2.4.1 Zhejiang Shenzhou Quantum Communication Technology Co., Ltd. (浙江神州量子通信技術有限公司)

Location	18F B3 1156 Gaoqiao Avenue, Gaoqiao Sub-district, Tongxiang City, Jiaxing, Zhejiang Province	Scale of company	Less than 50 people
Capital	85 million yuan	Date established	November 10, 2015
Legal representative	QIU Gaoyao (裘高尧)	No. of insured persons	14

This company has a history from before its establishment in its current form in 2015, issuing its first stock in quantum communications when JACK Ma's Alibaba Damo Academy focused on quantum technology. However, its performance worsened, and it was taken over by Hangzhou Dunyi Investment Association; it took on its current structure after that.[63] In terms of its business, it is involved in quantum communication backbones, constructing and managing websites, value-added communication projects, quantum communication technology, general quantum technology, the technological development of information systems technology, technological services, technology consultations, transferring technological outcomes, developing network communications security software and hardware products, computer system integration services, constructing and generally contracting for quantum communication engineering, quantum communication, classical communication, selling network security hardware and software systems, selling electronic products, and industrial design.

2.4.2 Anhui Qasky Quantum Technology Co. Ltd. (安徽問天量子科技株式会社)

Location	Yusheng Business Center, Eshan Road, High-Tech Industrial Development Zone, Wuhu City, Anhui Province	Scale of company	100-199 people
Capital	58.54 million yuan	Date established	July 15, 2009
Legal representative	HAN Zhengfu (韩正甫)	No. of insured persons	114

This company's research and development is led by Academician Guo Guangcan (University of Science and Technology of China). It is currently constructing an academic workstation, a quantum secure engineering technology and research center in Anhui Province, two R&D centers in Wuhu and Hefei, and a quantum information innovation platform; it has at least 180 employees. Of these, one is responsible for the science in the academic workstation, at least 90 serve as R&D staff at the R&D centers in Wuhu and Hefei, two are postdoctoral researchers, six have doctorates, and at least 34 have qualifications of master's level or higher.

[63] 「中国量子通信技术国际领先 预计普及性应用还需 5 年」毎日経済新聞、October 17, 2017.

2.4.3 State Grid Corporation of China（国家電網有限公司）

Location	86 West Changan Street, Xicheng District, Beijing City	Scale of company	900-999 people
Capital	829.5 billion yuan	Date established	December 29, 2002
Legal representative	XIN Baoan（辛保安）	No. of insured persons	968

This fully state-owned enterprise is run by the Chinese government. In 2021, it was ranked second in the Fortune Global 500. Over the past 20 years, it has continued to set records for the longest and safest mega-grid in the world, constructing several ultra-high-voltage power transmission projects and forming the world’s strongest power network in terms of transmission capacity and the largest transmission network in terms of transmission network connections for new energy. It invests in and manages key energy networks in nine countries and regions, including the Philippines, Brazil, Portugal, Australia, Italy, Greece, Oman, Chile, and China/Hong Kong. It has achieved A rank for 17 years running in the performance evaluations of the State-owned Assets Supervision and Administration Commission of the State Council, and a national sovereign rating from Standard & Poor's (S&P), Moody's, and Fitch, the three big international ranking institutions, for nine years running.

2.4.4 Alibaba Cloud Computing（阿里云計算有限公司）

Location	No. 12, Economic Plot, Zhuantang Science and Technology Park, Xihu District, Hangzhou City, Zhejiang Province	Scale of company	1,000-1,999 people
Capital	1 billion yuan	Date established	April 8, 2008
Legal representative	ZHANG Jianfeng（张建锋）	No. of insured persons	1,112

This company belongs to the Alibaba Group, one of the world’s largest e-commerce companies. It also provides comprehensive cloud computing services to sellers within its ecosystem and other third parties. On July 30, 2015, it announced it had signed up to joint research in the quantum field with CAS. Its new laboratory combines the technological advantages of classical computing algorithms, architecture, and cloud computing with CAS’ advantages in quantum computing and simulation, and quantum AI, aiming to explore next-generation super-high speed.

2.4.5 QuantumCTek (科大国盾量子技術有限公司) [64]

Location	F1, 3, 4, 5, 6, 7, D3 Block, Innovation Industrial Park No. 800, Wangjiang West Road, High-tech Industrial Development Zone, Hefei City, Anhui Province	Scale of company	—
Capital	80 million yuan	Date established	May 2009
Legal representative	Peng Chengzhi (彭承志)	No. of insured persons	232

This company is one of China's pioneers and leaders in commercialized quantum information technology (QIT), and is becoming one of the world's biggest manufacturers and providers of QIT-enabled ICT security products and services. Based on ongoing innovation and open collaboration in quantum science and technology, QuantumCTek is committed to providing a competitive QIT portfolio of quantum secure solutions in telecom infrastructure, enterprise networks, and cloud computing, as well as Big Data technology and services. Its quantum solutions, products, and services are used in government, finance, the energy industry, etc., ensuring the long-term quantum safety of numerous users. To date, the company has manufactured more than 1,000 quantum secure products and secured communication links longer than 6,000 km.

2.4.6 Shandong Institute of Quantum Science and Technology Co., Ltd. (山東量子科学技術研究院有限公司)

Location	7F, B block, Xinlang Street, 1768 Qilu Software Park Building, High-tech District, Jinan City, Shandong Province	Scale of company	50-99 people
Capital	70.49 million yuan	Date established	March 2, 2010
Legal representative	Zhao Yong (赵勇)	No. of insured persons	65

This institute is based on strategic cooperation between the government of Shandong Province and the University of Science and Technology of China. Its original quantum secure communications system and photoelectric device series products are widely used in governmental, financial, and political areas, and it has also expanded into other spheres, including electricity and transport, which have high needs for legal and information security. At present, it has established a corporate academic workstation in Shandong Province and a state engineering technological research center, and achieved "high-tech enterprise" and "software enterprise" status, as well as CMMI L4, quality control systems, information system integration, and three service levels. It has initiated a number of national "863" programs, key state-level scientific research projects, state-level strategic emerging industry projects, and

[64] This company is said to support initiatives for a quantum computer for the People's Liberation Army, and consequently was registered on the United States Department of Commerce's public entity list on November 24, 2021.

the construction of a science and technology innovation platform at state level, and has the most technology and products with independent intellectual property rights within the world of Chinese industry.

Relevant institutions

Ministry Of Science and Technology of the People's Republic of China, University of Science and Technology of China, Department of Science & Technology of Shandong Province, Shandong Academy of Information Communication Technology, Jinan University of Quantum Technology, University of Science and Technology of China National Shield Quantum Technology Co., Ltd.

2.4.7 Hefei Origin Quantum Computing Technology Co., Ltd. (合肥本源量子計算科技有限公司)

Location	6F Building E2, No. 2800, Innovation Industrial Park, Innovation Avenue, High-tech District, Hefei City	Scale of company	100-199 people
Capital	6.27 million yuan	Date established	September 11, 2017
Legal representative	ZHANG Hui (张辉)	No. of insured persons	100

This is a leading company in quantum computing in China. Its main office is located in the Hefei high-tech zone, and it has branch offices in Beijing, Shanghai, Chengdu, and Shenzhen. Hefei Origin Quantum Computing Technology Co., Ltd.'s technology originated in the Key Laboratory of Quantum Information, Chinese Academy of Sciences, and the company is focused on the research and development, popularization, and application of quantum computers. Its efforts are directed at quantum computer full stack development, as well as that of different software and hardware products, and it leads China's technological indicators. It has obtained over 400 intellectual property rights. In September 2020, it achieved its first target of going from scientific research on quantum computing to implementing engineering, releasing a domestic independently controllable superconducting quantum computing cloud platform and working toward its target of implementation in the quantum computing industry.

Relevant people

Guo Guangcan, Guo Guoping, Zhang Hui, KONG Weicheng（孔伟成）, ZHAO Yongjie（赵勇杰）, JIA Zhilong（贾志龙), CHEN Zhaoyun（陈昭昀）

2.4.8 Baidu Institute of Quantum Computing (百度量子計算研究所)

Location	Baidu Technology Park, 10 Beiquiwang East Road, Haidian District, Beijing City	Scale of company	—
Capital	—	Date established	March 8, 2018
Legal representative	—	No. of insured persons	—

In preparation for an age of quantum computing, this institute is engaged in wide-ranging growth, developing quantum technology, fostering quantum human resources, and pioneering new quantum businesses, as well as building a global research institution for quantum AI. It is also continuously integrating quantum computing and Baidu's core technology and business and exploring the quantum technology innovation business. Baidu Institute of Quantum Computing is currently part of the Baidu Research Institute and is focused on the applications of quantum software and information technology, particularly quantum AI, quantum algorithms, and quantum architecture. Baidu's quantum platform was designed to provide a comprehensive quantum infrastructure service, and aims to realize its "Quantum for All" vision by contributing to the development and prosperity of the quantum computing field through collaborations with universities and research institutions, holding and sponsoring top conferences, and strengthening associated industries.

At a conference for quantum developers held on August 25, 2022, Baidu released "Qianshi," the company's first superconducting quantum computer with a 10-qubit processor, and "Lianxi," a world-first all-platform quantum software-hardware solution.[65] They announced that this can also be used by external users, and that they are already designing a 36-qubit quantum chip. Moreover, at this conference, Pan Jianwei stated that quantum computing is still a long way from being practical and industrialized. During this process, the active participation and close cooperation of all aspects of government, industry, academia and research are required.

2.4.9 14th Research Institute's Intelligent Sensing Technology Key Laboratory, China Electronics Technology Group Corporation's (中国電子科学技術集団公司 第 14 研究所)[66]

Location	27 Wanshou Road, Haidian District, Beijing City	Scale of company	—
Capital	20 billion yuan	Date established	February 25, 2002
Legal representative	CHEN Zhaoxiong (陈肇雄)	No. of insured persons	199

[65] See the Baidu Institute of Quantum Computing, CCTV (hosting a quantum developer conference in Beijing), etc.

[66] It is no longer possible to access the 14th Research Institute's website, so this is an introduction to the China Electronics Technology Group Corporation (confirmed May 30, 2022).

This is a key nationally owned company directly managed by the central government. It is heavily involved in the domestic military electronic equipment and network information business, and is also said to be a group for national strategic science and technology. CETC has a relatively extensive science and technology innovation system in the field of electronics and information, and has overwhelming status in the field of military electronic equipment and network information; it has the important duties of supporting the independence and enhancement of science and technology, promoting the modernization of national defense, accelerating the development of the digital economy, and contributing to the daily lives of the people of China. It currently has 47 national research institutions, more than 500 companies and institutes (including 11 listed companies), over 200,000 employees (including 110,000 researchers), and 35 national key laboratories, research centers and innovation centers. It has been part of the Fortune Global 500 for many years, and was ranked 381st in 2020.

2.4.10 QUDOOR / Qike Quantum (国开启科量子技術(北京)有限公司)

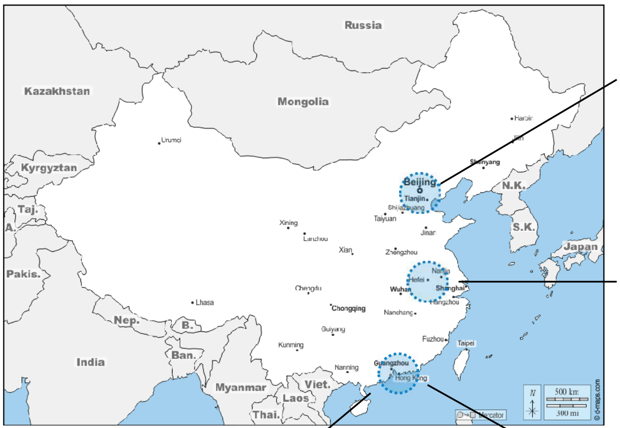
Location	1F 108-1 No. 5 building, East District, No. 10 Northwest Wangdong Road, Haidian District, Beijing	Scale of company	Less than 50 people
Capital	35 million yuan	Date established	April 14, 2016
Legal representative	CHEN Liuping (陈柳平)	No. of insured persons	26

This company is focused on the creation of quantum communication devices and the full-stack development of quantum computers using the excellent technology and rich product experience its technology team has accumulated over 20 years in the quantum information technology field. It is also China's first innovative technology company with both an accumulation of core technology for quantum computers and quantum communication and the ability to develop products.

In the field of quantum computers, QUDOOR began R&D on a distributed ion trap quantum computer in 2020. It is also involved in the R&D of different systems, including ion trap chips, a precision laser system, a qubit photoelectronic measuring and control system, a high-speed electric timing control system, quantum programming language, a quantum cloud, a quantum algorithm library, and quantum applications. In 2021, it launched AbaQ-1, China's first ion trap quantum computer; it is also consolidating the foundations for a 100-bit dispersed ion trap quantum computer with a quantum volume of over 100 million, to be completed in 2023, building cooperative relationships with top companies in fields such as Chinese domestic insurance, securities, the research and development of new medicines, and encryption/decryption, realizing ways of closely grouping industrial applications, and building a market ecology.

Currently, it is applying for/has received over 100 core patents, and this is expected to reach 150 within the year. It also possesses multiple examples of non-patented core technology, and is engaged in 10 cases of research work concerning national standards, industrial standards, and national standards.

Finally, venture companies that demonstrate their presence in the field of quantum computing include the abovementioned Origin Quantum and QUDOOR, as well as SpinQ (量旋科技) and Yuntao Quantum (云稻量子). An overview of these four companies is given in Figure 2-13.



https://d-maps.com/carte.php?num_car=11576

Qudoor / Qike Quantum
(启科量子/国开启科量子技术有限公司)
Established in April 2016. Headquarters: Beijing.
A quantum communication company based in Zhongguancun Science Park. It possesses core technology such as quantum key distribution and quantum random number generation. In 2020, it began researching and developing a distributed ion trap quantum computer, and turned its focus to full-stack development, including programming languages and cloud platforms. It expected to launch China's first ion trap quantum computer, AbaQ-1, in 2021[1].
[1] https://mmxx.news/ja/science/10a688451a3c62757e0b4f92649e03b1.html

Origin Quantum
(本源量子/合肥本源量子计算科技有限责任公司)
Established in September 2017. Headquarters: Hefei.
China's first quantum computer company. A spinoff of the CAS Key Laboratory of Quantum Information. It is engaged in the full-stack development of a quantum computer and expanding its cloud platform operating business. It has announced at least 10 types of quantum processor that use superconducting qubits, and reports over 100 companies using its cloud[2].
[2] https://36kr.jp/114294/

SpinQ (量旋科技/深圳量旋科技有限公司)
Established in August 2018. Headquarters: Shenzhen.
Develops desktop quantum computers for education and research. NMR method using permanent magnets of around 1 Tesla. Sells the first generation "SpinQ Gemini" (70×40×80 cm, 55 kg) with 2 qubits for 50,000 USD, and has reportedly finished shipping to institutions in China, Taiwan, and Canada. Has announced a plan to sell a new machine for less than 5,000 USD in the future.
[3] https://www.discovermagazine.com/technology/a-desktop-quantum-computer-for-just-usd5-000

Yuntao Quantum
(云韬量子/深圳市云韬量子科技有限公司)
Established in August 2018. Headquarters: Shenzhen.
This company is developing commercial applications for quantum computation[4]. In 2018, it released the Bayesforge Quantum AI Development Environment, and is promoting strategic cooperation between research and education institutions. Its main target is the development of chemicals through quantum-classical hybrid computation, and the optimization of financial risk. Tao Yin, its founder, obtained his doctorate from Goethe University Frankfurt. He was selected for Canada's quantum machine learning entrepreneur project.
[4] https://www.qtumist.com/post/9842

Figure 2-13: Chinese quantum computer startups

Source: Prepared by CRDS

2.5 Notable researchers

Based on the paper and patent data from Chapter 1, this section provides simple profiles for five noteworthy researchers selected after considering their position in China's quantum research community and other factors.

2.5.1 PAN Jianwei (潘建伟、潘建偉)

Professor/Head at the Division of Quantum Physics and Quantum Information, the University of Science and Technology of China, Chair and Director of the CAS Center for Excellence in Quantum Information and Quantum Physics, and Academician of CAS. Holds a doctorate in experimental physics (from the University of Vienna). He is mainly engaged in research concerning the verification of fundamental issues in quantum optics, quantum information, and quantum mechanics, and is known as the "Chinese Father of Quantum." He has achieved results in research on quantum communication, quantum computing, multiphoton entanglement manipulation, and more, and not just in China—he is an international pioneer who has led the most rapid development of experimental research in quantum information. The research on quantum invisibility that Professor Pan and his team released in 1999 was selected by the British journal Nature as one of its 21 famous physics papers of the century, alongside Roentgen's discovery of X-rays and Einstein's establishment of the theory of relativity. This work has been recognized in Nature as one of its "features of the year," by Science as a "Breakthrough of the Year," by the American Physical Society as some of the "The top physics stories of the year," and by the British Institute of Physics as some of the "Highlights of the year." Within China, it has been selected for "The Top Ten Annual Scientific and Technological Progresses in China." In 2001, he returned to China from Austria and established a research laboratory for quantum physics and quantum information in USTC, which was designated a key laboratory by CAS. Serves as the Executive Vice President of USTC since 2015, and Chair and Director of the CAS Center for Excellence in Quantum Information and Quantum Physics since 2016. In 2012 and 2014, he and his team constructed the world's largest quantum communication networks (a pilot quantum communication network in Hefei City and an experimental quantum communication network in Jinan), demonstrating the maturity of high-capacity urban quantum communication network technology, thus becoming involved in CAS' establishment of a center of excellence at the frontier of quantum information and quantum science and technology. His achievements to date have led to the Chinese government awarding him the State Natural Science Award First Prize, and he has also received the Military Science and Technology Progress Award First Prize, the Future Science Prize for Physical Sciences, the Outstanding Scientist Prize from the Hong Kong Qiu Shi Science and Technologies Foundation, the Heling Li Foundation Science and Technology Achievement Award, and the CAS Excellence Prize in Science and Technology.

2.5.2 XUE Qikun (薛其坤)

President of the Beijing Academy of Quantum Information Sciences, President of the Southern University of Science and Technology, and Academician of CAS. Obtained his doctorate at the Institute of Physics, CAS, in 1994. He is an internationally famous practical physicist, and at the end of 2012 he discovered the quantum anomalous Hall effect, a world first, using magnetic topological insulating film.

2.5.3 GUO Guangcan (郭光灿)

Director of the Key Laboratory of Quantum Information, CAS, Professor, and Academician of CAS. He has been engaged in quantum optics research since the 1980s and is a leading figure who has pioneered the theory and practice of quantum communication and computing in China. Head of the R&D team in Anhui Qasky Quantum Technology Co. Ltd. (introduced in 2.5.2), and member of Hefei Origin Quantum Computing Technology Co., Ltd.'s R&D group, with his laboratory serving as the source of its technology (see 2.5.7). He holds shares in both companies.

2.5.4 GUO Guoping (郭国平)

Deputy Director of the Key Laboratory of Quantum Information, CAS, Professor, and Vice President of the Institute of Microelectronics. Doctor of Physics (2005, University of Science and Technology of China), and is engaged in the practical development and application of quantum computers. He is a graduate of Guo Guangcan's laboratory.[67] He is a leading talent of the Youth Fund's Ten Thousand Talents Plan and a Changjiang Distinguished Professor. He is a member of Hefei Origin Quantum Computing Technology Co., Ltd.'s R&D group, and holds shares in the company.

2.5.5 YU Dapeng（俞大鹏）

Professor of the Southern University of Science and Technology, Dean of Shenzhen Institute for Quantum Science and Engineering, and Academician of CAS. Holds a doctorate in solid state physics (1993, Paris-Sud University, University of Paris-XI). He is a leading figure driving quantum materials research. He participated in the foundation of the Shenzhen Institute for Quantum Science and Engineering, in which around 200 million yuan of research funds was invested, and in January 2018, he was involved in the foundation of a 600 m^2 international first-rate center for quantum devices and quantum chip processing in Shenzhen, as well as research on quantum computing.

2.6 International cooperation and joint research

The report is not able to give any specific examples of international cooperation in the quantum field led by MOST or any other governmental institution, but international cooperation and international joint research with Chinese researchers is common. The most well-known example of this in the quantum field in China is Professor Yao, Dean of the Institute for Interdisciplinary Information Sciences, Tsinghua University, who constructed fundamental theories of computation and communication in America, and USTC's Professor Pan, who carried out quantum communications experiments at the University of Vienna. Professor Yao was engaged in research in America from 2010 until he became a Professor at Tsinghua University's Institute for Advanced Study (Center for Advanced Study; CASTU). In 2015, he renounced his American citizenship and became a national of the People's Republic of China, but as he is still a member of the American National Academy of Sciences, a fellow of the American Academy of Arts and Sciences, and a fellow of the American Association for the Advancement of Science, it is assumed that he is continuing international joint research. As for Professor Pan, in 1996, one year after he became an assistant professor at USTC, he received guidance from Anton Zeilinger of the University of Innsbruck in Austria. Zeilinger is a quantum physicist, and a pioneer of quantum scientific research, having published a paper on a quantum entanglement state known as a Greenberger-Horne-Zeilinger State[68] with Americans Daniel M. Greenberger and Michael A. Horne in 1989. Above all, he won the Nobel Prize in Physics 2022 for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science.[69]

This section focuses on international joint research in the research community and provides examples of the latest international joint research below.

[67] 中国科学院 (2022)「郭国平：做量子领域的“孤勇者”」
[68] Greenberger, D.M., Horne, M.A., and Zeilinger, A. (1989) Going beyond Bell's theorem. In *Bell's Theorem, Quantum Theory, and Conceptions of the Universe*, edited by M. Kafatos Dordrecht: Kluwer Academics, pp. 73-76.
[69] From The Nobel Prize in Physics 2022 Summary.

・In July 2020, WANG Lei (王雷) of the School of Physics, Nanjing University and the Department of Physics, Columbia University worked together to discover correlated electronic phases in twisted bilayer transition metal dichalcogenides (WSe_2), and paved the way for a new direction to explore insulating states caused by spin liquids and strong correlation.[70, 71]

・In March 2021, USTC's Professor Pan, ZHU Xiaobo (朱 晓 波), Chen, and their colleagues worked with Tsinghua University's MA Xiongfeng (马雄峰) and his colleagues, the University of Oxford, and others to carry out experimental exploration of five-qubit quantum error-correcting code with superconducting qubits.[72] They ensured average gate fidelities as high as 0.9993 for single-qubit gates and 0.986 for two-qubit gates through calibrations and optimizing target gate parameters. They also realized encoding and decoding of the logical state just by implementing single qubit rotation gates and double-qubit controlled-phase gates.[73]

・In April 2021, Professor Pan, Zhang of USTC and Fan Jing (范 靖) of the SUSTech worked with Roger Colbeck of the University of York and Tsinghua University's Ma Xiongfeng to achieve device-independent quantum randomness expansion for the first time in an international setting using different theoretical approaches, and established a firm foundation for the application of device-independent quantum randomness[74, 75, 76].

・In September 2021, Professor Pan and Zhang of USTC and their colleagues worked with Frank Wilczek of Massachusetts Institute of Technology and succeeded in creating intensity interferometers with color erasure using periodically poled lithium niobate waveguides developed in Jinan Institute of Quantum Technology, as well as verifying the system's high spatial resolution imaging capabilities.[77] It is hoped that this technology will be applied to astronomical observation, space remote sensing, the detection of space debris, and more.[78]

・In November 2021, Peng Xinhua (彭 新 华) of CAS' Key Laboratory of Microscale Magnetic Resonance and her colleagues worked with Dmitry Budker and his colleagues from the Helmholtz Institute, Germany to develop new ultra-sensitive quantum precision measuring technology.[79] When used in an experimental direct search for dark matter, this new technology increased the international historical high by at least five orders of

[70] 南京大学科学技术处 (2020)「物理学院王雷教授在双层转角过渡金属硫化物输运测量研究中取得重要进展」

[71] Wang, L., Shih, E.M., Ghiotto, A., Xian, L., Rhodes, D.A., Tan, C., Claassen, M., Kennes, D.M., Bai, Y., Kim, B., Watanabe, K., Taniguchi, T., Zhu, X., Hone, J., Rubio, A., Pasupathy, A.N., Dean, C.R.(2020) Correlated electronic phases in twisted bilayer transition metal dichalcogenides. *Nature Materials*, Volume 19, pp.861-866.

[72] 中国科学院 (2021)「【科技日报】中外科学家实现量子纠错"完美编码"」

[73] Ming G., Yuan, X., Wang, S., Wu, Y., Zhao, Y., Zha, C., Li, S., Zhang, Z., Zhao, Q., Liu, Y., Liang, F., Lin, J., Xu, Y., Deng, H., Rong, H., Lu, H., Benjamin, S.C., Peng, C.-Z., Ma, X., Chen, Y.-A., Zhu, X., and Pan, J.-W. (2021) Experimental exploration of five-qubit quantum error-correcting code with superconducting qubits. *National Science Review*, Volume 9, Issue 1, nwab011

[74] 中国科学技术大学 (2021)「中国科大实现设备无关量子随机性扩展实验」

[75] Liu, W.-Z., Li, M.-H., Ragy, S.H., Zhao, S.-R., Bai, B., Liu, Y., Brown, P., Zhang, J., Colbeck, R., Fan, J., Zhang, Q., Pan, J.-W.(2021) Device-independent randomness expansion against quantum side information. *Nature Physics*, Volume 17, pp.448-451.

[76] Li, M.-H., Zhang, X., Liu, W.-Z., Zhao, S.-R., Bai, B., Liu, Y., Zhao, Q., Peng, Y., Zhang, J., Zhang, Y., Munro, W.-J., Ma, X., Zhang, Q., Fan, J., and Pan, J.-W. (2021) Experimental Realization of Device-Independent Quantum Randomness Expansion. *Physical Review Letters*, Volume 126, 050603.

[77] 中国科学技术大学量子物理与量子信息研究部 (2021)「中国科大完成基于颜色擦除强度干涉的高空间分辨成像」

[78] Liu., L.-C., Qu, L.-Y., Wu, C., Cotler, J., Ma, F., Zheng, M.-Y., Xie, X.-P., Chen, Y.-A., Zhang, Q., Wilczek, F., Pan, J.-W. (2021) Improved Spatial Resolution Achieved by Chromatic Intensity Interferometry. *Physical Review Letters*, Volume 127, Issue 10, 103601.

[79] 中国科学技术大学物理学院 (2021)「我院彭新华研究组在量子精密测量和暗物质探测领域同时取得重大进展」

magnitude, pushing the boundaries of space astronomy for the first time.[80]

- In December 2021, Wang Jianwei (王　剑　威) of the School of Physics, Peking University worked with researchers from the University of Bristol and the Technical University of Denmark to show how quantum error-correction encodings can be implemented with resource-efficient photonic architectures to improve the performance of quantum algorithms[81, 82]. They also summarized the research priorities, funding support and outcomes of the quantum chip field in Asia, North America, Europe and Australia, and stated their hope that photonic quantum chips will completely integrate large-scale integrated photonic technology and quantum information technology, bringing about new changes in quantum computing, simulation, communication, and precision measurement.[83]

In November 2021, USTC, the Korea-China Science & Technology Cooperation Center (KOSTEC) and the Korea Institute for Advanced Study promoted exchange in the quantum information field in China and South Korea, and held the 2021 China-Korea Quantum Information Workshop to encourage the construction of a mutual international research cooperation platform. 2021 was the 30th year of diplomatic relations between China and South Korea, and both countries came together to promote student and human resource exchange and research cooperation, including building a platform for international cooperation, and to explore new development for innovation and integration.

China also formed an agreement concerning science and technology with Pakistan in 1976, which continues to this day. A China-Pakistan Technology Investment Conference was held in July 2022; in it, Javaid Iqbal of the Special Technology Zones Authority (STZA) stated that Pakistan's demographic advantage stood for a unique investment base for Chinese technology companies and research organizations, and both countries could enormously benefit by working together in R&D, especially in emerging technologies such as artificial intelligence, cloud and quantum computing, semi-conductors, Internet of things and smart device design and manufacturing.[84] In the 20th National Congress of the Chinese Communist Party, Moin ul Haque, Pakistani Ambassador to China, said that based on scientific research outcomes such as space technology and quantum computing, he is looking forward to continuing close cooperation with China that will accelerate the formation of a high-quality China-Pakistan economic corridor.[85] In a contribution to the Global Times, Prime Minister Shehbaz Sharif commented that he values China's rapid technological progress and is prepared to expand cooperation with China in emerging and smart technologies, including quantum computers, robots, AI, and Big Data.[86]

[80] Jiang M., Su H., Garcon, A., Peng, X., and Budker D. (2021) Search for axion-like dark matter with spin-based amplifiers. *Nature Physics*, Volume 17, pp.1402-1407.

[81] 北京大学人工微结构和介观物理国家重点实验室 (2021)「王剑威研究员和龚旗煌院士课题组与合作者在光量子计算芯片研究中取得重要进展」

[82] Vigliar, C., Paesani, S., Ding, Y., Adcock, J.C., Wang, J., Morley-Short, S., Bacco, D., Oxenløwe, L.K., Thompson, M.G., Rarity, J.G., Laing, A.(2021) Error-protected qubits in a silicon photonic chip. *Nature Physics*, Volume 17, pp.1137-1143.

[83] Pelucchi, E., Fagas, G., Aharonovich, Igor., Englund, D., Figueroa, Eden., Gong, Q., Hannes, H., Liu, J., Lu, C.Y., Matsuda, N., Pan, J.-W., Schreck, F., Sciarrino, F., Silberhorn, C., Wang, J., and Jöns, K.D. (2022) The potential and global outlook of integrated photonics for quantum technologies. *Nature Reviews Physics*, Volume 4, pp.194-208.

[84] Pakistan Special Technology Zones Authority News, "4500 Chinese tech companies attend China-Pakistan Technology Investment Conference hosted by STZA and Pakistan Embassy in Beijing." July 20, 2022.

[85] 新华社 (2022)「"中共二十大将推动中国向着民族复兴迈出坚实步伐"——专访巴基斯坦驻华大使莫因・哈克」新华社 ,

[86] 夏巴兹・谢里夫 (2022)「巴基斯坦总理谢里夫在《环球时报》撰文：巴中友谊——信任与爱始终不渝」环球时报 ,

2.7 Quantum innovation ecosystem

Although the status of different institutions, researchers and Chinese policies shown so far differ depending on the project, the communities centered on USTC and CAS have a significant influence on them. Above all, policies concerning science and technology are set out by the Chinese government (e.g. the State Council), but CAS is the institution that enacts policy proposals when policy decisions are made, so it is easy to imagine that their composition is driven by CAS. From this, China's quantum innovation ecosystem can be illustrated as follows (Figure 2-14).

Moreover, although each regional government has a large budget, they follow the policies issued by the central government, and demonstrate no significant features, so national and city-government level efforts remain those of MOST, the National Natural Science Foundation of China, and Hefei City. As there are numerous research institutions and universities, the Figure only uses those shown in 2.3; similarly, when it comes to companies it only uses those shown in 2.4.

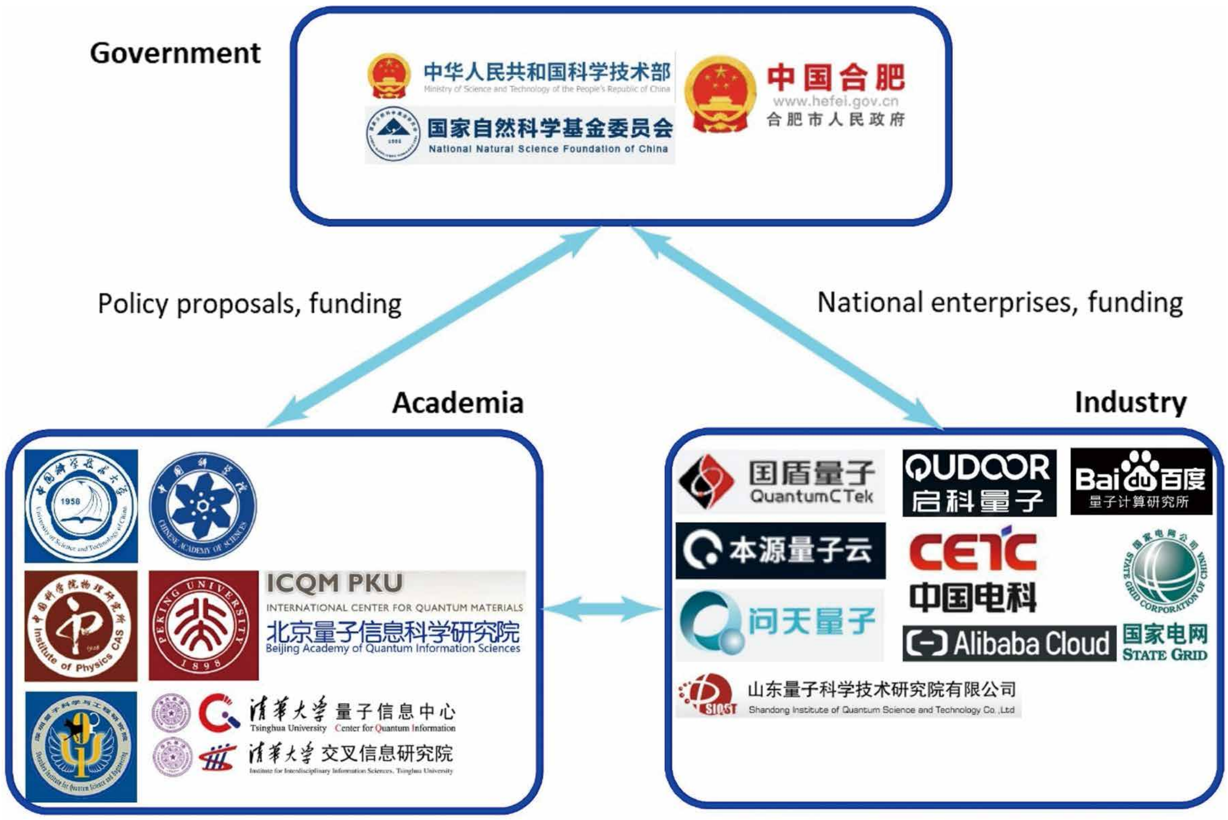


Figure 2-14: The quantum innovation ecosystem in China

Source: Prepared by APRC

3 Quantum technology trends in Japan

3.1 Quantum technology policy

While Japan's national policy on science and technology began with the Basic Act on Science and Technology in 1995, the first specific mention of "quantum" was the 2011 4th Science and Technology Basic Plan [1]. 2011 was the year in which Canada's D-Wave Systems announced the first analog computer for solving combinatorial optimization problems with quantum annealing, and a time when people's attention was beginning to turn toward the term "quantum" again. The 4th Science and Technology Basic Plan mentions optical and quantum technologies in the section describing the improvement and reinforcement of common infrastructure for science and technology. However, "quantum" as used here refers to large-scale quantum beam facilities such as SPring-8 and J-PARC (Japan Proton Accelerator Research Complex), rather than quantum computer science or quantum technology.

In 2016, the Cabinet Office approved the 5th Science and Technology Basic Plan, which sets out the aim of "realizing a world-leading 'super smart society' (Society 5.0)", and lists "light/quantum technology" as one of the "fundamental technologies that are Japan's strengths, which form the core of new value creation" [2]. In the following year of 2017, the Quantum Science and Technology Committee of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) announced the "New Measures for Promoting Quantum Science and Technology (Photonics and Quantum Technology)" [3] as a comprehensive strategy for the promotion of quantum technology, and a new research and development program called the Quantum Leap Flagship Program (Q-LEAP) was launched in its wake [4]. In addition, in 2018 the Strategic Innovation Promotion Program (SIP) "Photonics and Quantum Technology for Society 5.0" project also began [5].

In 2020, for the first time in the history of Japan's science and technology policies, a Quantum Technology and Innovation Strategy was formulated that encompassed quantum technology as a whole [6]. Until the creation of this policy, there had been no government-wide strategy for quantum technology, and instead various ministries and agencies had been formulating and implementing individual measures – MEXT for quantum computers and metrology, the Cabinet Office and the Ministry of Internal Affairs and Communications for quantum communications, and the Ministry of Economy, Trade and Industry (METI) for semiconductors.

The basic policy is ① the strategic development of quantum technology and innovation, ② hybridization and integrated promotion of quantum technology and existing (classical) technologies, and ③ integrating and strengthening ties between the Quantum Technology and Innovation Strategy, the AI Strategy, and the Bio (biotechnology) Strategy. The Quantum Technology and Innovation Strategy is part of the Japanese government's overall innovation strategy, and "quantum" has come to be recognized as a key area of science and technology for Japan to promote alongside AI and biotech [7]. The strategy sets forth three images of a future society: the realization of a revolution in productivity, a healthy and long-lived society, and the assurance of the safety and security of the nation and its people, and it also provides an outline of how quantum technologies will be utilized to achieve these ends.

The strategy for technological development sets quantum computers and quantum simulation, quantum metrology and sensing, quantum communications and cryptography, and quantum materials (quantum properties and materials) as the key technical fields. Research and development in each of these key fields is being supported based on specific technology roadmaps. The scope of technologies covered in this strategy is shown in the figure below. Quantum computing in particular includes a broad scope of methods, and while there is a focus on superconductivity, the current lack of a decisive technological advantage is duly reflected. This stance can also be seen in the concept for the Moonshot research and development program, “Realization of a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050” [8-9]. The roadmap calls for the demonstration of quantum supremacy (generally more than 50 qubits, by the mid-2020s), the demonstration of an NISQ (noisy-intermediate scale quantum) computer algorithm (100 to 1,000 qubits, by the end of the 2020s), and the demonstration of a fault-tolerant quantum computer (around 2040), which is consistent with various policies. Expectations are also high for areas that integrate quantum technology with related technologies, such as quantum AI technologies, quantum life technologies, and quantum security technologies. While the focus is on quantum technology, these efforts underline the importance of peripheral and fundamental technologies in order to realize quantum technology. Major research and development projects are summarized in Figure 3-1.

The international strategy consists of strategic development of international collaboration and ensuring and strengthening security trade control. The goal is to establish frameworks for bilateral and multilateral government-level cooperation with countries and regions with advanced research and technology within five years, and in fact, the governments of Japan and the United States jointly issued the Tokyo Statement on Quantum Cooperation in 2019 [10], in addition to discussions which are under way with the government of the EU through the Japan-EU Joint Meeting on Cooperation in Science and Technology. From the standpoint of national security, the strategy also calls for trade control of advanced technologies based on the Foreign Exchange and Foreign Trade Act in light of trends in various countries in Europe and the Americas. There is no mention of international collaboration with countries in Asia.

The establishment of Quantum Technology Innovation Hubs (QIHs) is set out as a strategy for industrial innovation. These are international hubs that work on everything from basic research to technical demonstrations, open innovation, intellectual property management, and human resources development. According to the strategy, these hubs will bring together researchers and engineers from Japan and overseas, and attract investment from companies and other entities. Eight hubs were launched in February 2021, and as described later two new hubs were established in April 2022, bringing the total to 10 QIHs [11]. The involvement of industry is also strongly urged, including the creation of consortia, support for the founding of startup companies, and the facilitation of investment, resulting in the establishment of the Quantum STrategic industry Alliance for Revolution (Q-STAR) based on the strategy. Various other active consortiums led by universities and companies include the Quantum ICT Forum, QPARC, the Quantum Innovation Initiative (QII) Consortium, the Quantum Software Consortium, and the Quantum Internet Task Force (Table 3-2) [12–17].

Strategies for intellectual property and international standardization include the promotion of securing and utilizing rights based on open and closed strategies and support for obtaining international standards. While the details of the strategy are scant, in actuality, many efforts are already under way in the field of quantum key distribution, such as the establishment of Recommendation Y.3800 (ITU-T [International Telecommunication Union - Telecommunication Standardization Sector]) [18], which reflects technical specifications based on research and development related to the Tokyo QKD Network (described in 3.2).

The strategy for human resources is described in considerably more detail, and includes the establishment of courses and majors at universities, the development of systematic educational programs, and collaboration and exchange of personnel between universities, research institutions, and companies. In addition to measures to support and strengthen “brain circulation,” which has a strong correlation to the international strategy and the industrial strategy, the strategy contains in-depth descriptions of the provision of learning opportunities at high schools and national institutes of technology in order to cultivate “quantum natives” with the knowledge and skills to use quantum technologies, among other efforts.

The Q-LEAP “Human resources development program” was launched based on the strategy, and has adopted four projects [4]. In addition, MEXT added a field-specific category for quantum technologies to its University Fellowship Foundation Program [19] (see Table 3-2). The National Institute of Information and Communications Technology (NICT)’s Quantum Camp program [20] also holds lectures and workshops in cooperation with universities and companies, steadily implementing the strategy. The Information-technology Promotion Agency (IPA) Exploratory IT Human Resources Project (MITOU Program) [21], which was launched in 2019, is also aligned with the strategy from the standpoint of developing quantum IT human resources.

The committee of experts that was organized to formulate this strategy was reorganized, and the Quantum Technology and Innovation Council [22] was formed to monitor trends and follow up on the implementation of the strategy. In fact, the new council was set up right away, and held meetings in April and October of 2021. A working group established under the council to review the strategy discussed matters such as clarification of the exit strategy, and the results were published in April 2022 as the Vision of Quantum Future Society [23]. This new national strategy supplements the Quantum Technology and Innovation Strategy, providing Japan with strategies for both research and development and for industry.

A central feature of the new strategy is that it illustrates how various quantum technologies can be applied in society (Table 3-3). This vision of the future shows how information and communication technologies and quantum technologies will be combined and used, for instance innovative computing services that combine supercomputers and quantum computers, or secure cloud services that connect quantum key distribution and cloud computing. Applications related to our daily lives, such as lifestyle services, safety and security, and healthcare are also proposed, and are well-timed in the sense of accountability for large-scale government investment in research and development. In October 2022, a working group for the practical application of quantum technologies was formed to discuss the initiatives necessary in order to achieve the vision that was presented.

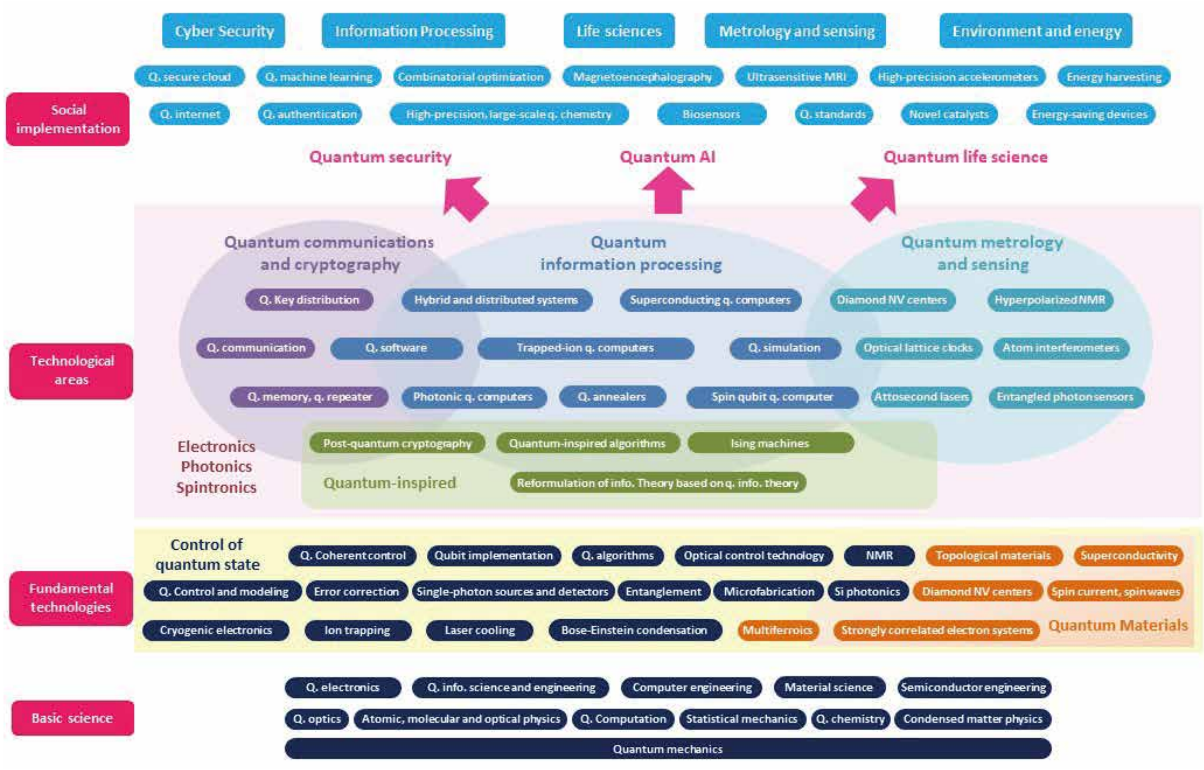


Figure 3-1: Scope of technologies covered in the Quantum Technology Innovation Strategy [6]

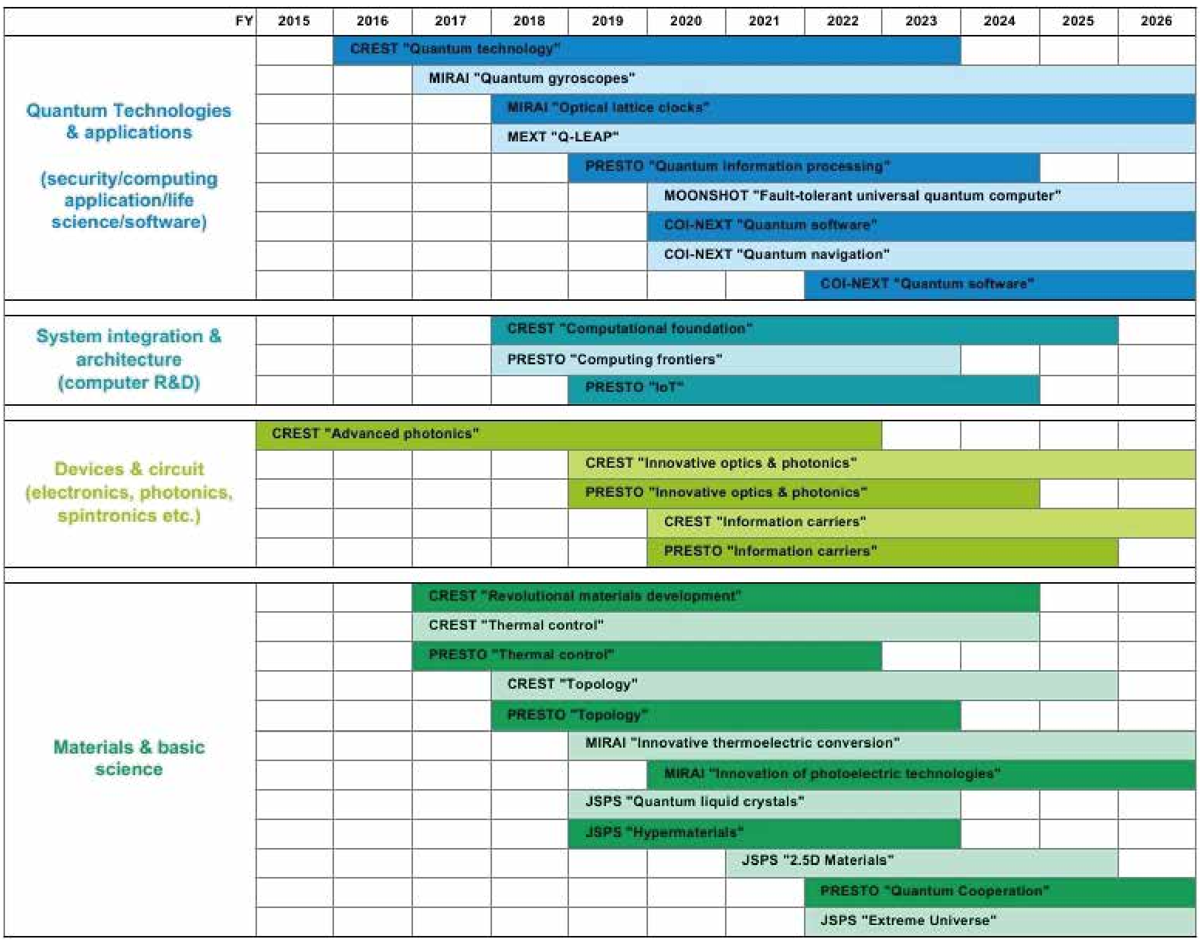


Figure 3-2: Major projects related to quantum technology

Table 3-1: Major quantum technology consortia

Consortium	Main purpose for establishment
Quantum ICT Forum [13]	Support for the healthy development of quantum information and communication technology (ICT)
Quantum STrategic industry Alliance for Revolution (Q-STAR) [12]	Creation of quantum-related industries and business
QPARC [14]	Seeking to be the first in the world to uncover practical applications for quantum computers
Quantum Innovation Initiative (QII) Consortium [15]	Realization of the world's first social implementation of quantum computers
Quantum Software Consortium [16]	Cultivating a place to support the development of quantum human resources, from the search for and creation of use cases to entrepreneurship
Quantum Internet Task Force [17]	Establishment and realization of quantum internet technologies and creation of an industry ecosystem

Table 3-2: Quantum technology fellowships [19]

Institution	Fellowship name
Tohoku University	Tohoku University Advanced Graduate School Doctoral Fellowship (quantum/spintronics area)
University of Tsukuba	Fellowship for human resources development in quantum fields in cooperation with the Tsukuba Science City hub for open innovation
Chiba University	Chiba University Fellowship program for quantum science
University of Tokyo	Quantum Science and Technology Fellowship
Nagoya University	Nagoya University Interdisciplinary Frontier Fellowship (quantum science area)
Kyoto University	Advanced Quantum Technology Fellowship for Future Creation
Osaka University	Osaka University Fellowship Quantum Leader Resources (QLEAR Fellowship)
Osaka City University	Nambu-Einstein Fellowship
Hiroshima University	Hiroshima University Graduate School Research Fellowship (quantum physics area)
Kyushu University	Kyushu University Leading Human Resources Development Fellowship Program (quantum science area)

Figure 3-3: Value created by quantum technology in the future society [23]

3.2 Quantum technology research and development

3.2.1 Research and development projects

The quantum information science research community in Japan can be traced back to the inception of the Quantum Computing Study Group in 1996. In 1998, the Quantum Information Technology Ad Hoc Technical Committee was established within the Institute of Electronics, Information, and Communication Engineers (IEICE) Electronics Society, and the first meeting of the Quantum Information Technology Research Group (QIT) was held the following year [24]. 2000 saw the start of the ERATO Imai Quantum Computation and Information project (research director: Hiroshi Imai) [25], with an international conference called EQIS (ERATO Conference on Quantum Information Science; now AQIS [Asian Quantum Information Science Conference]) held annually under the auspices of the project. In 2001, the JST exploratory research area program "quantum information science" [26] was conducted, which led to the CREST project "Creation of new technology aiming for the realization of quantum information processing systems" (Research Supervisor: Yoshihisa Yamamoto) [27] and the PRESTO project "Quantum and information" (Research Supervisor: Akio Hosoya) [28] being established as two new research areas (in 2003).

Near 2005, the "quantum winter" began as difficulty in scaling up quantum computers became widely recognized worldwide, and this awareness also spread among Japanese researchers. While the Japanese government had no quantum strategy at the time, a project called "Quantum cybernetics: Interdisciplinary research on quantum control and its application to quantum computation" (Project Manager [PM]: Jaw-Shen Tsai) was launched in 2009 as grant-in-aid for scientific research on innovative areas [29], followed by "Quantum Information Processing Project" under the Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST) (principal investigator: Yoshihisa Yamamoto)[30] which began in 2010, and as a result, there was an increase in national R&D investment in quantum technologies. At its outset, the FIRST project was part of an economic stimulus package, but it pursued research based on six themes, including quantum computers, quantum standards, and quantum communications, for which its focus was on laying the foundations for basic research and human resource development, in addition to nurturing young researchers through summer schools and student chapters. In 2010, the Tokyo QKD Network, a test-bed for quantum cryptography, was completed as an NICT-commissioned research project, and secure videoconferencing using QKD was demonstrated successfully in a world-first [31].

In the ImPACT Program project "Advanced Information Society Infrastructure Linking Quantum Artificial Brains in Quantum Network" (program manager: Yoshihisa Yamamoto), launched in 2014, instead of using a gate-based quantum computer, the researchers shifted course to a new analog method of computation that used quantum optical phenomena to skillfully solve combinatorial optimization problems [32]. The tendency to use Ising-model machines has continued since, with one domestic manufacturer after the next introducing similar types of computers. NEDO also launched a project in line with the current trend of AI chips (2016) [33]. Under the aforementioned ImPACT project, QKD research and development progressed steadily. The world's fastest QKD device was successfully developed, and the combination of QKD and secret-sharing has been developed for quantum secure cloud technology.

In 2016, MEXT announced its first quantum-related strategic objectives in 13 years, and the JST CREST project

”Creation of an innovative quantum technology platform based on the advanced control of quantum states” (Research Supervisor: Yasuhiko Arakawa) [34] and the PRESTO project “Quantum state control and functionalization” (Research Supervisor: Kohei Itoh) [35] were launched, along with the start of the ERATO Nakamura Macroscopic Quantum Machines Project (Research Supervisor: Yasunobu Nakamura) [36] . As for quantum metrology and quantum sensing, the JST Mirai Program projects “Development of high-performance gyroscopes with matter waves” (program manager: Mikio Kozuma) [37] and “Space-time information platform with a cloud of optical lattice clocks” (program manager: Hidetoshi Katori) [38] engaged in active research and development.

Under an R&D program called the Quantum Leap Flagship Program (Q-LEAP), large-scale projects called Flagship Projects have started running in the three technological areas of quantum information technology, quantum metrology and sensing, and next-generation laser (see Tables 3-3–3-6) [4]. Beginning in 2018, the SIP “Photonics and quantum technology for Society 5.0” project began research and development focused on the three themes of laser processing, photonic quantum communication, and photonic and electronic information processing [5]. In 2019, the JST PRESTO project “Technological foundation of advanced quantum computing and information processing” (Research Supervisor: Akihisa Tomita) [39] began, signifying the start of stepped-up research in the area of quantum software.

In the Cabinet Office’s Moonshot research and development program, the target set for Moonshot R&D Program Goal 6 is the “realization of a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050” (Program Director [PD]: Masahiro Kitagawa) [8]. The Moonshot Goal 6 program has adopted 12 Project Managers (PMs) who are carrying out long-term research and development to realize a fault-tolerant quantum computer (Table 3-7). In 2020, NEDO issued a public call for applicants for the development of high-efficiency, high-speed AI chips and next-generation computing technology development. As “quantum computing-related technologies” was mentioned in the public call, these efforts include the development of annealing machines and peripheral technologies [33]. In addition, the Quantum Software Research Hub, led by Osaka University [40] and the Quantum Navigation Innovation Hub, led by Tokyo Institute of Technology [41] were established through the JST Program on Open Innovation Platforms for Industry-academia Co-creation (COI-NEXT), positioning quantum technologies as a full-fledged, policy focus field (in 2020). In fiscal year 2022, the Sustainable AI Research Center through Co-creation by Quantum Software and HPC/Simulation Technology (Center of Innovation for Sustainable Quantum AI), led by the University of Tokyo, was also adopted as a COI-NEXT program [42].

To raise the level of development of basic quantum communications technologies, the Ministry of Internal Affairs and Communications initiated “Research and development for construction of a global quantum cryptography network” as a project under the direct supervision of the Japanese government [43]. With an investment of 1.41 billion yen (10.58 million USD[1 yen = 0.0075 USD, as of Apr 1, 2023]) in its first year, the project conducts research and development related to advanced QKD technology (for higher speed, longer distances, and improved environmental resistance), network management technology, and quantum relay technology through the participation of 12 organizations consisting of private-sector companies, universities, and national research institutes (Table 3-8).

In the area of quantum life science research, “Innovations medicine and life sciences through the application of quantum technology,” one of the aforementioned Q-LEAP Flagship Projects, was launched in 2020. This project plans to implement research and development relating to nanoscale biosensors, ultrasensitive MRI/NMR, and the clarification and imitation of quantum-theoretical life phenomena for a ten-year period. In addition, the JST PRESTO project “Creation of life science basis by using quantum technology” (Research Supervisor: Mitsutoshi Setou) [44] was initiated, for which pursuing research on diamond NV centers is one of the project themes.

Research and development related to quantum materials is being conducted extensively through the JST CREST project “Creation of core technology based on the topological materials science for innovative devices” (Research Supervisor: Masahito Ueda) [45] and the PRESTO project “Topological materials science for creation of innovative functions” (Research Supervisor: Shuichi Murakami) [46]. In 2022, MEXT announced the strategic goal of “creation of innovative quantum control technology through integrating quantum information and quantum materials,” and with the launch of the JST PRESTO project “Quantum Cooperation between Materials and Information” (Research Supervisor: Kensuke Kobayashi) [47], the creation of innovative quantum technology through the integration of quantum information science and quantum materials science is expected. The grant-in-aid for transformative research areas project “Extreme universe: a new paradigm for spacetime and matter from quantum information” (Head Investigator: Tadashi Takayanagi) [48], which began in 2022, will play a central role as a research project on fundamental physics using quantum information.

3.2.2 Quantum computing and quantum simulators

Research and development efforts for quantum computers continue to expand worldwide. In Japan, frameworks for collaboration between industry and academia centered around the Riken Center for Quantum Computing [49] are being developed based on the aforementioned Quantum Technology and Innovation Strategy [22].

Superconducting quantum bits (qubits) are one of the leading candidates among various systems for implementation of qubits and quantum gates, which are necessary in order to realize a gate-based quantum computer. Japan has a long history of research and development and high technological capabilities related to the fabrication and control of high-quality superconducting qubits [50], along with numerous researchers who are highly regarded internationally. The National Institute of Advanced Industrial Science and Technology (AIST) plays a central role in the fabrication and evaluation of superconducting quantum devices.

With regard to quantum software, such as control middleware and error-correction coding for quantum computers, the Osaka University Center for Quantum Information and Quantum Biology (QIQB) [51] is leading research and development efforts based on collaboration with Fujitsu, Nippon Telegraph and Telephone (NTT), and other companies. In 2022, a “hybrid quantum error reduction method” was proposed which combines quantum error correction and quantum error suppression [52]. Meanwhile, the Information Processing Society of Japan established the SIG on Quantum Software, which serves as a forum for exchange between various research areas, including quantum computer architecture, programming languages, quantum software development environments, and distributed quantum computation [53].

Table 3-3: Q-LEAP Adopted Research and Development Projects (Quantum Information Technology) [4]

R&D Project	Project Leader	Institute	Position
(Flagship Project) Research and development of superconducting quantum computers	Nakamura Yasunobu	Center for Emergent Matter Science, RIKEN	Team Leader
(Flagship Project) Development of quantum software by intelligent quantum system design and its applications	Fujii Keisuke	Center for Quantum Information and Quantum Biology (QIQB), Osaka University	Deputy Director, Professor
Development of cold-atom based quantum simulators by optical control with precisions on the attosecond temporal and nanometer spatial scales and their applications to quantum computing	Ohmori Kenji	Institute for Molecular Science, National Institutes of Natural Sciences	Professor and Department Chair
Multi-degree-of-freedom complex quantum simulator using cooled ions	Toyoda Kenji	Institute for Open and Transdisciplinary Research Initiatives, Osaka University	Specially Appointed Associate Professor
Architecture and applications for small to large scale quantum computation	Nemoto Kae	Principles of Informatics Research Division, National Institute of Informatics	Professor
Development of quantum software applications by fast classical simulator of quantum computers	Fujii Keisuke	Graduate School of Engineering Science, Osaka University	Professor
Large scale integration of silicon qubits to realize quantum computer	Mori Takahiro	Nanoelectronics Research Institute, National Institute of Advanced Industrial Science and Technology	Senior Researcher
Quantum software	Yamamoto Naoki	Faculty of Science and Technology, Keio University	Professor

Table 3-4: Q-LEAP Adopted Research and Development Projects (Quantum Metrology and Sensing) [4]

R&D Project	Project Leader	Institute	Position
(Flagship Project) Development of innovative sensor systems by highly sophisticated control of solid quantum sensors	Hatano Mutsuko	School of Engineering, Department of Electrical and Electronic Engineering, Tokyo Institute of Technology	Professor
（Flagship Project）Innovations medicine and life sciences through the application of quantum technology	Baba Yoshinobu	Institute for Quantum Life Science (iQLS), National Institutes for Quantum and Radiological Science and Technology (QST)	Director General
Establishment of earthquake early alert methods using high-sensitivity gravity gradiometer	Ando Masaki	Graduate School of Science, University of Tokyo	Associate professor
Development of photon-number-resolving quantum nano-photonics	Edamatsu Keiichi	Research Institute of Electrical Communication, Tohoku University	Professor
Development of quantum atomic magnetometer with dual quantum noise squeezing	Shibata Kosuke	Physics Division, Department of Science, Gakushuin University	Assistant professor
Development of spectroscopic techniques based on cutting-edge quantum optics toward elucidating functions of complex molecular systems	Shimizu Ryosuke	Graduate School of Informatics and Engineering, University of Electro-Communications	Associate professor
Research on quantum sensing devices using quantum entangled photons	Takeuchi Shigeki	Graduate School of Engineering, Kyoto University	Professor
Material science of complex defects for highly-sensitive quantum sensors	Teraji Tokuyuki	Research Center for Functional Materials, National Institute for Materials Science	Chief Researcher
Development of next-generation high-performance inertial quantum sensors	Nakagawa Ken’ichi	Institute for Laser Science, University of Electro-Communications	Professor

Table 3-5: Q-LEAP Adopted Research and Development Projects (Next Generation Laser) [4]

R&D Project	Project Leader	Institute	Position
(Flagship Project) Advanced Laser Innovation Center (ALICe)	Fujii Teruo (Acting: Professor Ishikawa Kenichi)	University of Tokyo	Executive Director/ Vice President
Development of attosecond light functions of strongly correlated quantum materials	Iwai Shinichiro	Graduate School of Science, Tohoku University	Professor
Developing guidelines on materials strengthening and toughening based on mechanism of atomic scale damaging under ultrashort pulsed laser processing	Sano Tomokazu	Graduate School of Engineering, Osaka University	Associate Professor
Operando measurements using advanced beams to study the mechanism of fine structure formation	Hashida Masaki	Kyoto University Institute for Chemical Research	Associate Professor
Research on basic technologies for a high-repetition attosecond pulse source driven by a free electron laser	Hajima Ryoichi	National Institutes for Quantum and Radiological Science and Technology-Quantum Beam Science Research Division	Senior Principal Researcher

Table 3-6: Q-LEAP Adopted Research and Development Projects (Human Resources Development Program) [4]

R&D Project	Project Leader	Institute	Position
Development of the standard program for quantum science and technology	Nemoto Kae	Principles of Informatics Research Division, National Institute of Informatics	Professor
Fostering quantum natives through practical research and development	Ohzeki Masayuki	Graduate School of Information Sciences, Tohoku University	Associate Professor
Quantum education for future technologies	Noguchi Atsushi	Graduate School of Arts and Sciences, University of Tokyo	Associate Professor
A hands-on program for fostering quantum-based thinkers among emerging engineers in various disciplines	Kishimoto Tetsuo	Graduate School of Informatics and Engineering, University of Electro-Communications	Associate Professor
Research on the commercialization of cultivating quantum transformation innovators	Choi Hee-won	JellyWare Inc.	Representative Director

Table 3-7: Moonshot Goal 6 Research and Development Projects

R&D Project	PM	Institute	Position
Research and development of theory and software for fault-tolerant quantum computers	Koashi Masato	Graduate School of Engineering,University of Tokyo	Professor
Development of quantum interfaces for building quantum computer networks	Kosaka Hideo	Quantum Information Research Center (Director), Faculty of Engineering, Yokohama National University	Professor
Fault-tolerant quantum computing with photonically interconnected ion traps	Takahashi Hiroki	Experimental Quantum Information Physics Unit, Okinawa Institute of Science and Technology Graduate University	Assistant Professor
Development of large-scale fault-tolerant universal optical quantum computers	Furusawa Akira	School of Engineering, University of Tokyo	Professor
Large-scale silicon quantum computer	Mizuno Hiroyuki	Center for Exploratory Research, R&D Group, Hitachi, Ltd.	Distinguished Researcher
Quantum cyberspace with networked quantum computers	Yamamoto Takashi	Graduate School of Engineering Science/Center for Quantum Information and Quantum Biology (Deputy Director), Osaka University	Professor
Development of integration technologies for superconducting quantum circuits	Yamamoto Tsuyoshi	System Platform Research Laboratories, NEC Corporation	Research Fellow
Large-scale quantum hardware based on nanofiber cavity QED	Aoki Takao	Faculty of Science and Engineering, Waseda University	Professor
Large-scale and high-coherence fault-tolerant quantum computer with dynamical atom arrays	Ohmori Kenji	Institute for Molecular Science, National Institutes of Natural Science	Professor/ Chairman

Table 3-8: QKD-related projects conducted as part of the Ministry of Internal Affairs and Communications project on research and development of priority ICT technologies [43]

R&D project	Representative research institutes	Principal investigator	Participating research institutes
Research and development for the construction of a global quantum cryptography network	Toshiba (corporation)	Katsube Yasuhiro	NEC (corporation), Mitsubishi Electric (corporation), Hamamatsu Photonics (corporation), Furukawa Electric (corporation), University of Tokyo, Hokkaido University, Yokohama National University, Gakushuin University, NICT (national research institute), AIST (national research institute), NIMS (national research institute),
Research and development of satellite quantum cryptography technology for the construction of a global quantum cryptography network	SKY Perfect JSAT (corporation)	Mamiya Atsushi	NICT (national research institute), Toshiba (corporation), NEC (corporation)

Table 3-9: Examples of industry-academia collaboration and joint research (quantum computing)

Company	University/Public Research Institution	Overview
Mitsubishi Chemical Corp., IBM Japan, JSR	Keio University	Excited state energy of organic TADF (thermally activated delayed fluorescence) emitters for OLED materials is calculated using a quantum computer. A new measurement scheme was devised to mitigate errors, resulting in a significant improvement in calculation accuracy [59, 60].
Mitsubishi UFJ Financial Group, Mizuho Financial Group	NICT, Keio University	Began efforts to evaluate the compromised period of cryptographic methods for which security is guaranteed by a discrete logarithm problem. World-first success in solving discrete logarithm problems by running Shor's algorithm on a quantum computer [61].
Fujitsu	Osaka University	The Fujitsu Quantum Computing Joint Research Division was established as a collaborative research program of the Center for Quantum Information and Quantum Biology (QIQB) of Osaka University. The Division will focus on the development of foundational technologies for fault-tolerant quantum computers [62].
NTT	Osaka University	Proposed a hybrid quantum error reduction technique, consisting of quantum error correction and quantum error suppression, which makes it possible to reduce the size of quantum computers required for practical applications by up to 80% [63].
NTT	University of Tokyo, AIST, Osaka University	Proposed a new framework to suppress both the effects of noise in the hardware and the errors inherent in the algorithm itself by preparing multiple quantum states affected by unknown noise sources in parallel and then interfered with each other [64].
NTT	Kyushu University, University of Tokyo	Proposed an architecture that significantly reduces the impact of burst errors, which are an obstacle in the development of fault-tolerant quantum computers, by changing error-correction strategies adaptively according to the error properties of quantum computers [65].

Table 3-10: Examples of Ising machine applications by companies

Company	Field/Research Problem	Overview
MELCO Investments, Fujitsu	Portfolio optimization	Fujitsu's Digital Annealer is used to optimize a portfolio containing a combination of several hundred stocks in about 10 minutes. Analysis results based on highly-accurate calculations can now be used in actual asset management operations [66].
Dharma Capital, Toshiba	High-frequency trading	The Simulated Bifurcation Machine™ was applied to high-frequency trading to verify the effectiveness of investment strategies based on optimal solutions presented by a quasi-quantum computer in a financial trading system [67].
NEC Fielding, NEC	Delivery planning optimization	A delivery planning system for maintenance parts utilizing the NEC Vector Annealing Service was fully implemented for maintenance parts delivery in the 23 central wards of Tokyo. This cut the time needed for formulating delivery plans from two hours a day to 12 minutes [68].
Fixstars Corporation, Sumitomo Corporation	Staff allocation optimization	Launched a service to optimize the allocation of workers in actual workplaces by linking SaaS, which performs real-time forecasting and actual management of logistics production volume based on employee skill data, to the Fixstars Amplify Ising machine [69].
Fujitsu, PeptiDream Inc.	Exploration of medium-molecular weight peptide conformations	Fujitsu's Digital Annealer and high-performance computing technology are used to identify stable conformations of a cyclic peptide, a drug candidate, within 12 hours and with high precision [70].
Toshiba Digital Solutions, Revorf	Prediction of allosteric regulation in proteins	The quantum-inspired optimization solver SQBM+ is used to achieve much improved accuracy in predicting allosteric regulation, the mechanism that realizes functional diversity in proteins by regulating their structure and activities. The application of the technology in computational drug discovery will be verified.
Sompo Holdings, Sompo Japan Insurance, Sompo Risk Management, Hitachi	Non-life insurance portfolio optimization	Complementary metal-oxide semiconductor (CMOS) annealing is applied to large-scale and complex non-life insurance portfolio optimization problems which are necessary for Sompo Japan at the working level. Practical use of CMOS annealing for non-life insurance underwriting has now begun [71].

Several projects are conducting research and development under the Moonshot Goal 6 program related to implementation systems other than superconductivity, such as silicon qubits and ion trapping [8]. For silicon qubits, a team at Riken has successfully developed the world's highest-fidelity silicon qubit [54]. While the performance of silicon qubits is still inferior when compared to that of superconducting qubits, rapid progress is expected in the integration of silicon qubits because existing semiconductor integration technologies can be applied to them. In addition to these areas, the development of optical quantum computers, which use a different method from gate-based ones in their approach to achieving fault tolerance, is under way [55].

Meanwhile, a quantum annealing machine that uses superconducting qubits and specializes in optimizing Ising problems is under development at the National Institute of Advanced Industrial Science and Technology (AIST) [56]. Activities are also under way to increase the practical utility of quantum simulation technology using cooled atoms, such as the successful high-speed generation and control of Rydberg orbital electrons that improve the flexibility of simulation [57].

Exploratory use cases of quantum computers have been built up at the Osaka University QIQB [51], the Keio University Quantum Computing Center [58] and other research centers in cooperation with many companies that use the computers for their business. Quantum computing technology has been applied in a wide range of fields, including finance, manufacturing, chemicals, transportation, and information. Mitsubishi UFJ Financial Group and Mizuho Financial Group in the financial sector, and JSR and Mitsubishi Chemical in the chemical sector were early adopters of gate-based quantum computers. As for the application of quantum computers to materials development, many companies are participating in QPARC, a consortium that provides lectures, training, and a software platform [14]. Information is also exchanged at the Quantum Innovation Initiative Consortium [15]. Specific examples of industry-academia collaboration and joint research on the use of quantum computers are compiled in Table 3-9. The development of applications using Ising machines that do not use the quantum nature of hardware is also being actively pursued, and many successful proof of concept experiments using real problems have been reported (Table 3-10).

3.2.3 Quantum communications

Quantum key distribution (QKD) began with the proposal of the BB84 protocol in 1984, and thanks to vigorous research, the theoretical basis was established by around 2010, and by around 2015 Toshiba and NEC had built a practical device with a clock rate in the 1 GHz range (decoy-state BB84 protocol) [72]. Research and development to establish a security theory that is viable even in the presence of imperfections in the device and to improve the clock rate is continuing. Research on quantum cryptographic communications is being actively pursued at Hokkaido University, the University of Tokyo, Nagoya University, Keio University, and Gakushuin University. Research on QKD networks and quantum secure applications is being conducted mainly by NICT as part of the SIP "Photonics and quantum technology for Society 5.0” project [5]. In 2022, the Tokyo QKD Network will be extended to Nomura Securities offices, as the use of QKD for the transmission of a large volume of financial transaction data with high confidentiality and low latency has been successfully verified in an experiment [73]. Various methods have been tested out to extend the key transmission distance, and currently the most common method is to relay keys through a trusted node. The Tokyo QKD Network was launched in 2010 as a quantum cryptography network test-bed, using part of the ultra-high-speed research and development network test-bed (JGN) operated by NICT. The project that developed the network was an international affair, with participants including NEC, Mitsubishi Electric, NTT, and Toshiba's Cambridge Research Laboratory, as well as ID Quantique and the University of Vienna [31]. Twin-field QKD, in which photons are transmitted from both ends and detected at a third point between them, is capable of sharing cryptographic keys over a distance of over 500 km, but there are still issues to be solved for practical use, such as phase synchronization between different light sources. As for satellite applications, a proof-of-principle experiment using China's QUESS (Mozi) satellite has been reported, and in Japan, NICT has successfully conducted a basic experiment on quantum communication using the microsatellite SOCRATES [74]. Sony, SKY Perfect JSAT, and other companies are also participating in research to demonstrate long-distance QKD using satellite communications. In recent years, research and development has been conducted not only to simply connect QKD devices at secure stations, but also to develop a platform for key provision, including key generation control, key management, and key supply. Specific examples of industry-academia collaboration and joint research, including efforts conducted through the Ministry of Internal Affairs and Communications project, are compiled in Table 3-11.

Continuous-variable (CV) QKD, which can be configured using only conventional coherent optical communications components and is thus highly compatible with existing technologies, is attracting attention as research with the potential to reduce the cost of QKD devices. It has also been demonstrated that it is possible to share fiber cores with optical communications, and implementation for practical use is expected in the future. However, it must be noted that unconditional security of CV-QKD, including implementation security, has not yet been proven.

The formation of quantum entanglements between distant nodes is an essential technology for long-distance quantum communications. The key to its realization is quantum relay technology, which converts quantum entanglements between neighboring nodes into quantum entanglement between distant nodes. In addition to fundamental devices such as quantum entanglement light sources and quantum memory, advanced control technologies such as frequency stabilization, quantum teleportation transfer operations, high-precision spatiotemporal synchronization, and optical fiber phase synchronization are also essential elements. A wide range of physical systems for quantum memory have been studied, including atoms, ions, diamond NV centers, and rare earth-doped crystals, but no physical system has yet met all the necessary performance requirements, such as lifetime and fidelity. Experimental research related to quantum relay technology has been actively conducted at Osaka University and Yokohama National University, and in 2020, LQUOM [75], a startup at Yokohama National University that develops quantum relay devices, was founded. In the all-photonics quantum method, which can be realized using only optical devices, a research group from Osaka University, NTT, and others succeeded in a proof-of-principle experiment in 2019 [76].

Just as the internet connects computers around the world, the concept of a "quantum internet" is also being considered, in which quantum computers, quantum sensors, and other quantum information processing devices are linked as nodes that form a quantum communication network for exchanging quantum data. In November 2018, the Quantum Internet Research Group (QIRG) was established under the Internet Research Task Force (IRTF), a sister organization of the Internet Engineering Task Force (IETF), with Keio University professor Rodney Van Meter serving as one of its chairs [77]. In addition to secure delivery of cryptographic keys, various applications are expected, including secure access to cloud quantum computers, the realization of distributed quantum computation, synchronization of optical lattice clocks, and construction of quantum sensor networks. In Japan, this area is being actively discussed by the Quantum Internet Task Force [17].

Table 3-11: Examples of industry-academia collaboration and joint research (quantum communications)

Company	University/Public Research Institute	Overview
Sony Computer Science Laboratories, SKY Perfect JSAT	Next Generation Space System Technology Research Association, University of Tokyo, NICT	Realization of basic technologies for highly confidential satellite communications to meet the growing demand for use of satellites and to enable the establishment of a secure satellite communications network.
Toshiba, NEC, Mitsubishi Electric, Hamamatsu Photonics, Furukawa Electric	University of Tokyo, Hokkaido University, Yokohama National University, Gakushuin University, NICT, AIST, NIMS	Establishment of basic technologies for the construction of a global-scale quantum cryptography network. This will contribute to the realization of an extremely robust and secure cyberspace.
SKY Perfect JSAT, Toshiba, NEC	NICT	Research and development of satellite quantum cryptography technology for the construction of a global quantum cryptography network.
NEC, Toshiba, ZenmuTech	NICT, Gakushuin University, University of Tokyo, Hokkaido University	Development of quantum secure cloud technologies by combining quantum cryptography, secret sharing, digital signature technology, and privacy-preserving computation. Establishment of secure data exchange infrastructure that can be applied to genome data, electronic medical records, etc. In 2019, highly confidential and highly-available transmission and storage of biometric data was achieved using quantum cryptography.
NTT	Osaka University, University of Toyama	Research and development to realize an all-photonic quantum network. In 2019, a proof-of-principle experiment of "all-photonics" quantum relay was successfully demonstrated.
Nomura Holdings, Nomura Securities, Toshiba, NEC	NICT	Successful verification of highly-confidential, low-latency transmission using quantum cryptography for a large volume of financial data.

3.2.4 Quantum metrology and sensing

Measurements and sensing are the very foundations of all science and technology. Quantum metrology and quantum sensing technology are used to measure external information extracted from the manipulation and transition of quantum states by exploiting the fact that quantum states are sensitive to external fields. Although highly-accurate measurements are expected, quantum sensors are used to measure classical information, and it is not easy to demonstrate the superiority of quantum sensors over conventional technologies. Table 3-12 compiles specific examples of industry-academia collaboration and joint research which are being conducted in Q-LEAP and other projects.

Since it was first proposed in 2001, the optical lattice clock has spread to more than 20 metrology research institutes in Europe, the Americas, and Asia, and by 2016 the original target of an 18-digit level of accuracy had been achieved, and the main focus of research and development has shifted to applications and practical implementation [78]. Creating optical lattice clock networks is important to ensure reproducibility and to share time information, and in Europe, optical fiber networks spanning thousands of kilometers are being developed to compare clocks among different national standards research institutes. In Japan, efforts are under way to redefine a "second" using optical lattice clocks, with NICT playing a central role in generating time standards with optical lattice clocks [79]. Another attention-getting application is the measurement of gravity potential by utilizing the change in the advance of a clock due to gravity. Aiming at geodetic applications such as measuring volcanic activity and crustal deformation, a portable optical lattice clock is being developed that can perform stably even outside the laboratory. In 2020, Riken, the University of Tokyo, and other research groups developed a portable optical lattice clock with 18-digit accuracy as part of the JST Mirai Program project “Space-time information platform with a cloud of optical lattice clocks,” and conducted experiments to verify general relativity using optical lattice clocks installed on the ground floor and observation deck of Tokyo Sky Tree [80]. The technology to make these clocks portable is expected to result in expanded geodetic application, such as bringing clocks to the actual sites to measure volcanic and tectonic activity. By utilizing the effect of the phase change of quantum interference in atomic waves in response to angular velocity, a gyroscope can be realized that detects the rotation of an interferometer with a high degree of sensitivity. Thermal atomic beam interferometry and laser-cooled atomic pulse interferometry are known approaches, but the performance of both types still falls short in comparison to conventional devices. While they share many basic technologies with optical lattice clocks and quantum simulators, quantum gyroscopes for navigation applications require performance in terms of acceleration tolerance and dynamic range. In Japan, the JST Mirai Program project “Development of high-performance gyroscopes with matter waves” is playing a central role in the active research and development of such devices [37].

Research and development of quantum sensors that use diamond NV centers has been conducted for more than two decades since the discovery of optically detected magnetic resonance. These sensors have been found to possess the potential to surpass conventional technologies in the measurement of magnetic and electric fields, temperature, pressure, pH, and other parameters [81]. Other expected applications include magnetoencephalography, magnetocardiography, intracellular measurement, biosensors for protein structure analysis, and detection of defects in metals. In addition to their use in sensor devices, diamond nanoparticles of a few nanometers in diameter are being used as probes for quantum measurement of biological phenomena and the intracellular environment. In 2019, a joint research group from QST and Kyoto University announced the successful fabrication of a 5-nanometer-size diamond nanoparticle quantum sensor [82]. Meanwhile, in the area of materials, Kyoto University, the University of Tsukuba, and the National Institute of Advanced Industrial Science and Technology (AIST) have made significant contributions to development.

Quantum entanglement sensing is a measurement technique that utilizes quantum entanglement of light or matter. A typical example is quantum entanglement microscopy, which enhances resolution by using quantum entangled light instead of laser light in differential interference microscopy [83]. The application of quantum optical coherence tomography (quantum OCT) as an imaging device is also known. In Japan, Hokkaido University reported in 2007 that a multiphoton entangled interference experiment had exceeded the standard quantum limit of phase measurement, and in 2013, a quantum entangled microscope based on the experiment was reported on. In addition, in 2016, the obtaining of a two-photon interference fringe corresponding to a world-record high resolution of 0.54 μm (in air) through quantum OCT using an ultra-broadband quantum entangled light source was reported [84]. The use of squeezed spin states and cold-atom systems have been proposed as methods to achieve sensing through the quantum entanglement of matter. Quantum metrology and sensing technologies using quantum entanglement are mainly in the basic research stage, and their applications are still awaiting development.

Another attractive quantum sensing technology is hyperpolarized MRI, which achieves ultra-sensitive measurement of stable isotope nuclei. In this type of imaging technology, highly sensitive MRI imaging is achieved by injecting hyperpolarized stable isotope nuclei into a specimen using an excitation device. In 2003, the dissolution dynamic nuclear polarization (d-DNP) method was developed, which makes water-soluble materials, for instance noble gases like He-3 and Xe-129, highly sensitive and then dissolves them in an aqueous solution. The d-DNP method succeeded in amplifying the Carbon-13 NMR signal 10,000-fold, and research aimed at safe molecular imaging diagnosis without exposure to radiation as an alternative to PET and other methods has been pursued worldwide [85]. In Japan, a research group at Osaka University developed a dynamic nuclear polarization method (triplet DNP) using the spin of electrons in the photo-excited triplet state, and in a world-first, succeeded in amplifying NMR signals more than 10,000 times while the sample was kept at room temperature [86]. While C-13 excitation systems manufactured by GE Healthcare in the US have been installed in more than 23 locations around the world and clinical trials involving several hundred patients are under way, no C-13 excitation systems that can be used for clinical research (in compliance with pharmaceutical manufacturing standards) have been installed in Japan, which has been pointed out as a critical delay [87].

Table 3-12: Examples of industry-academia collaboration and joint research (quantum sensing)

Company	University/Public Research Institute	Overview
Denso, Hitachi, Yazaki	Tokyo Institute of Technology	Diamond NV centers. Participating in the Q-LEAP Flagship Project in the quantum metrology and quantum area.
Murata Manufacturing, Shimadzu, Horiba, Nikon, Vision Development Co., NanoCarbon Institute Co., Thorlabs Japan	QST	Diamond NV centers. Participating in research on nanoscale biosensors for the Q-LEAP Flagship Project in the quantum life area. Responsible for developing probes and equipment.
Japan REDOX	Hokkaido University, University of Tokyo	Hyperpolarized MRIs. In collaboration with Hokkaido University and the University of Tokyo, the aim is to put a purely domestic C-13 excitation system on the market. Plan is to begin domestic sales of equipment for small animal imaging in fiscal 2021 (AMED advanced measurement).
JEOL RESONANCE, Toray Research Center, Taiyo Nippon Sanso	QST	Hyperpolarized MRIs. Participating in research on ultrasensitive MRI/NMR using quantum technology for the Q-LEAP Flagship Project in the quantum life area. Responsible for developing the hyperpolarized probe and equipment.
Shimadzu	Kyoto University, NICT	Quantum entangled light. In collaboration with Kyoto University and NICT (Q-LEAP), or with Kyoto University, Kyushu University, Hiroshima University, and Kitasato University (CREST [Quantum Technology]), developing quantum entanglement spectroscopy and establishing a hybrid quantum/classical optical tomography system. Shimadzu is mainly responsible for the development of optical elements.

The range of applications for hyperpolarized MRI has expanded from cancer diagnosis to evaluation of cardiac function, which has in turn led to the development of the new field of quantum life science. Along with the application of quantum sensing using diamond NV centers in the life science field, intensive research and development has been undertaken in the Q-LEAP Flagship Project “Innovations medicine and life sciences through the application of quantum technology” [4], and in 2022, the Institute for Quantum Life Science [88] was established in the National Institutes for Quantum Science and Technology (QST). The institute has been designated as one of the Quantum Technology Innovation Hubs, namely quantum life science and functionalization [11].

3.2.5 Quantum materials

In recent years, the field of “quantum materials,” which is an associative concept that spans various fields including condensed matter physics, quantum information science, and materials science, has been attracting attention [89]. The term had originally been introduced to emphasize novel physical properties in high-temperature superconductors and heavy fermion systems, but it is now transforming into an interdisciplinary field where knowledge of quantum information is utilized in order to understand physical phenomena, and from the opposite angle, new materials provide the stage for research in quantum information. The most prominent example of this fusion is the study of topological materials using the concept of entanglement [90].

Since the discovery of the transport properties of massless Dirac fermions in graphene, the role of spin-orbit interaction, a relativistic effect in matter, has attracted a great deal of attention, and fascinating quantum phenomena such as the spin Hall effect, spin-orbit torque, magnon chirality in magnetic materials, skyrmions, and Majorana fermions have been found on many occasions. In addition, new phenomena were discovered in van der Waals heterostructures of two-dimensional materials due to unique proximity effects not existing in the conventional materials, such as the quantum spin Hall effect caused by topological order in WTe2, spin-to-charge conversion in graphene/WS2 heterostructures, and superconductivity in twisted bilayer graphene. Theoretical predictions and experimental demonstrations of topological insulators, topological superconductors and the like have also been made. These new materials are characterized by topologically protected states (massless Dirac surface states) at the edge of two-dimensional materials and on the surface of three-dimensional materials, and have been experimentally confirmed in chalcogenide semimetals. Topology is a universal concept in condensed matter physics which has been shown to provide opportunities for new discoveries by linking seemingly unrelated groups of materials.

As for the theoretical aspect, following the discovery of the fractional quantum Hall effect, a new type of order (topological order) was found to exist in fractional quantum Hall states, for which the traditional approach to condensed matter, Landau’s symmetry breaking theory, was not suitable. Quantum information science has succeeded in introducing the concept of quantum entanglement, an example of pure quantum correlation, and recently it has been discovered that topological order in certain strongly correlated electron systems is one of the patterns of many-body quantum entanglement. In the language of quantum information science, the study of topological order and new quantum phases could be called the study of patterns of quantum entanglement. Non-trivial patterns are a treasure trove of new quantum phenomena such as fractional charge, fractional statistics, and gapless excitations in topologically ordered phases (spin liquid and fractional quantum Hall states) [91].

The new quantum systems offered by new quantum materials are expected to serve as platforms for various quantum technologies. One prominent example is the application of Majorana particles appearing in quantum spin liquids to topological quantum computers. Approaches that originate from materials science will become important in many aspects of problems that are difficult to solve through quantum technology alone, for example the effect of impurities on the performance of superconducting qubits. And as another example of the active exchange between these fields, there is a growing interest in the utilization of quantum technology in quantum materials research, such as the use of quantum machine learning algorithms to classify topologically ordered phases.

3.3 Notable research institutes and universities

Based on the Quantum Technology and Innovation Strategy (formulated in January 2020), eight international research sites, called Quantum Technology Innovation Hubs (QIHs), were established in various locations around Japan in February 2021 (Figure 3-4). The purpose of these hubs, centered around national research institutes and universities, is to bring together leading researchers and engineers from Japan and around the world, attract active investment from companies and other entities, and build frameworks for organic cooperation and collaboration among universities and companies. With Riken as the headquarters, each QIH works primarily on its respective research area. In addition, two new hubs were established in accordance with the Vision of Quantum Future Society (April 2022) for a total of 10 (as of October 2022).

3.3.1 Institute of Physical and Chemical Research (Riken)

The Riken Center for Quantum Computing (RQC; Director: Nakamura Yasunobu) was established within Riken to pursue research and development of quantum computers (in 2021). In order to realize a quantum computer, the RQC takes a full-stack approach that covers broad aspects of research and development, from hardware to software and from basic science to applications [49]. In addition to the main R&D targets, namely the development of superconducting qubits for qubit integration and quantum computer simulators that can be used together with supercomputers such as Fugaku, the Quantum Leap Flagship Program (Q-LEAP) Flagship Project “Research and development of superconducting quantum computers” (Project Leader: Nakamura Yasunobu) is working on the implementation of qubit systems for general-purpose quantum computers.

Research and development related to quantum technologies at Riken can be traced back to 2001, when the Single Quantum Dynamics Research Group (Group Director: Tonomura Akira) was established in the Riken Frontier Research System. The Macroscopic Quantum Coherence Team (Team Leader: Tsai Jaw-Shen) was later inaugurated within the group and pursued research in quantum information science, showing that Riken set its sights on quantum information processing from early on.

The targets of research and development at the RQC include optical quantum computers that use photons rather than superconducting systems, research on hardware relating to the use of various physical systems such as electron spins in semiconductor quantum dots and neutral vacuum-trapped atoms, along with software-related research and development which is under way such as quantum computing theory and quantum algorithms.

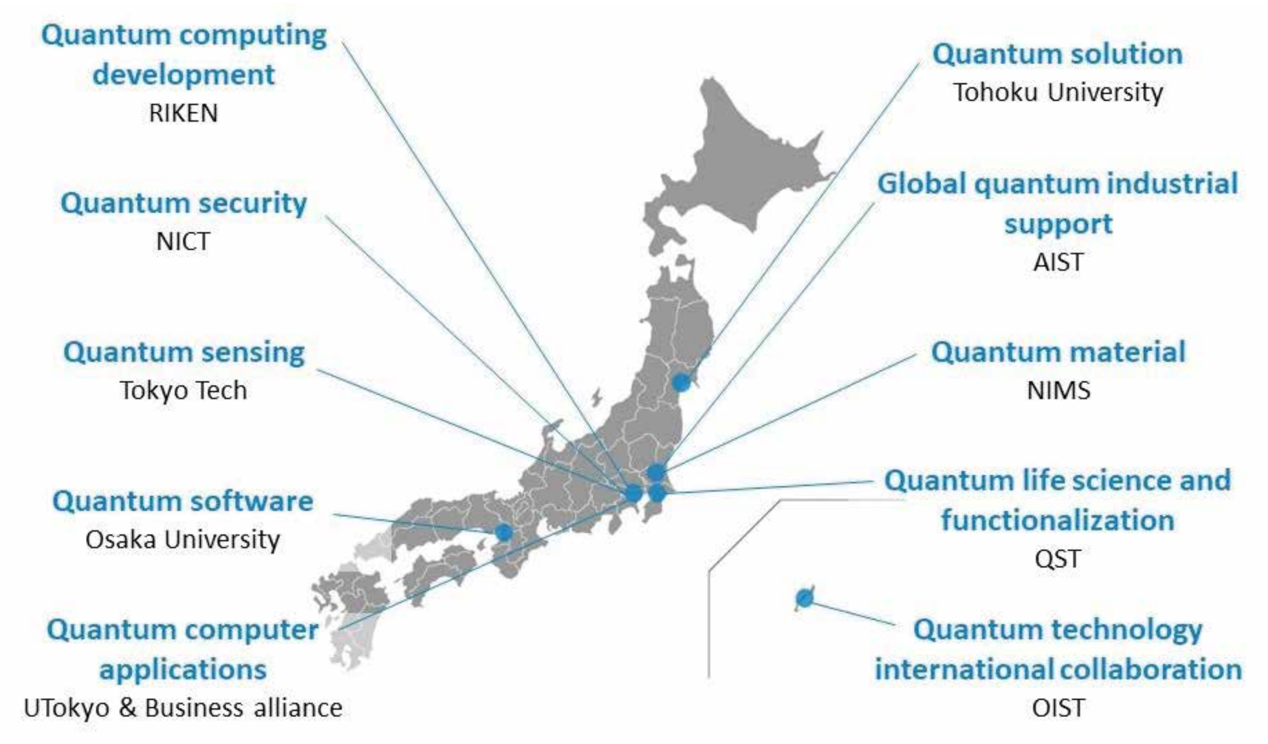


Figure 3-4: Quantum technology innovation hubs

Aside from the RQC, there are other research centers within Riken which are deeply involved in quantum technology, including the Riken Center for Emergent Matter Science (CEMS; Director: Tokura Yoshinori), which brings together top researchers working on quantum matter and quantum electronics [92] and the Riken Center for Computational Science (R-CCS; Director: Matsuoka Satoshi), which is engaged in the development and operation of the supercomputer Fugaku and research and development in the field of high-performance computing [93] .

3.3.2 National Institute of Advanced Industrial Science and Technology (AIST)

The National Institute of Advanced Industrial Science and Technology (AIST) is conducting research and development on quantum technologies at a quantum devices development hub with the provisional name Global Quantum Industrial Support Hub (Director: Yasuda Tetsuji), which is responsible for the design, manufacturing, mounting, integration, and evaluation of quantum devices [94]. In addition to the primary R&D theme of developing the quantum devices necessary for quantum computers, quantum annealing machines, quantum sensing, and quantum standards, the hub engages in research and development of integrated circuits to regulate these quantum technologies. R&D is also conducted on the provision of prototype services and the integration of technology across multiple layers.

AIST has three clean room facilities: Qufab (Superconducting Quantum Circuit Fabrication Facility), which fabricates superconducting circuits, COLOMODE (Communal Fabrication Line for Outstanding Modern Devices), which fabricates silicon qubit prototypes, and the Nano-Processing Facility (NPF). Since 2022, AIST has managed these three facilities in an integrated manner under the name “PoC Fab” [95]. For conventional semiconductor integrated circuits, AIST has the “Super Clean Room” (SCR) facility, where prototypes of devices and circuits on

300mm wafers can be fabricated. These shared facilities are also available to users who are not part of AIST. A cryogenic facility for quantum device characterization with a dilution refrigerator for evaluating superconducting circuits is also in operation, and a system is being developed to enable everything from prototyping to evaluation within AIST. In addition, the NEC-AIST Quantum Technology Cooperative Research Laboratory, established in 2019, is pursuing research and development for social implementation, focusing on quantum annealing and quantum sensing technologies.

3.3.3 University of Tokyo

Aiming to be the first in the world to achieve the social implementation of quantum computers, the University of Tokyo launched the Center for Quantum Computer Applications (Executive Director: Aihara Hiroaki), and is focused on promoting cooperation among industry, government, and academia and developing human resources. The University of Tokyo's efforts are wide-ranging, spanning research and development, industry-government-academia collaboration, and education.

With respect to research and development, based on an MoU concluded with IBM in December 2019, the University of Tokyo established the IBM-UTokyo Lab (Lab Director: Kawasaki Masashi), which pursues a variety of joint research and development from quantum computer hardware to software. In addition, the 2021 launch of the University of Tokyo-IBM Quantum Hardware Test Center, located on the Asano campus, represented Japan's first quantum systems test-bed [96].

The Quantum Innovation Initiative (QII) Consortium was established in order to facilitate the exchange of information and cooperation between industry, government, and academia, with the participation of Keio University, the Tokyo University of Agriculture and Technology, and Riken, in addition to 14 companies (as of October 2022) [15]. IBM also participates in the QII Consortium, and the "IBM Quantum- University of Tokyo Collaboration Center" was completed at the International Center for Elementary Particle Physics (ICEPP) on the Hongo campus, where participating members of the QII Consortium engaged in exchanges and held seminars related to IBM Quantum (in August 2021). This collaboration center is the second "IBM Q Network Hub" in Japan, following the facility opened at Keio University in May 2018. The Quantum Native Education Center [97] was also established with the ICEPP as the office in charge, and is involved with quantum-related education on a university-wide basis, including faculties of science, engineering, and information science, in order to cultivate the human resources who will play a leading role in quantum research in social implementation, industrial applications, and academic fields.

3.3.4 Osaka University

In April 2021, Osaka University reorganized the Quantum Information and Quantum Life Research Division, which had been established in the Institute for Open and Transdisciplinary Research Initiatives in July 2018, and launched the Osaka University Center for Quantum Information and Quantum Biology (QIQB) (Director: Kitagawa Masahiro) [51]. The QIQB consists of six research groups: Quantum Computing, Quantum Information Fusion, Quantum Information Devices, Quantum Communications and Security, Quantum Measurement and

Sensing, and Quantum Biology, promoting research in each field and transdisciplinary research among these fields as well as other academic fields. The center, as an international research hub for quantum innovations, promotes international academic exchanges with other research centers and is active in wide-ranging fields from human resources development to social implementation. The Quantum Leap Flagship Program (Q-LEAP) Flagship Project "Development of quantum software by intelligent quantum system design and its applications" (Project Leader: Fujii Keisuke) [4] is conducting research and development to identify areas where the quantum advantage emerges, to develop a methodology for extracting NISQ (noisy intermediate-scale quantum) device performance, and to establish quantum AI and its applications.

The Quantum Software Research Hub [40], which consists of 16 participating institutions represented by QIQB, was formed under the support of the JST COI-NEXT program, works to establish, implement and popularize a quantum software development platform, and is engaged in research and development aimed at using quantum software to resolve social issues. In addition, software and algorithms are being developed in anticipation of a future fault-tolerant quantum computer. As for industry-academia collaboration, the Quantum Software Consortium [16] provides opportunities for joint research and academic consultation.

Generous support for graduate students is a distinctive feature of quantum human resource development. At Osaka University, graduate students selected for the University Fellowship Foundation Program "Fellowship for Quantum Leader Resources (QLEAR Fellowship)" receive a stipend (equivalent to their living expenses) and a research grant to carry out activities related to the theme of their research [98]. This program is part of the MEXT University Fellowship Foundation Program for Science and Technology Innovation. In addition, for those seeking to enter doctoral programs in fields related to quantum software, support is provided through the QMeGa fellowship program, which is funded by the Quantum Software Research Hub.

3.3.5 National Institute of Information and Communications Technology (NICT)

In April 2021, the Quantum ICT Collaboration Center (Director: Sasaki Masahide) [99] was launched within the National Institution of Information and Communications Technology (NICT) with the aim of bringing new information security to society through quantum technology. The purpose of the Center is to provide an environment where a comprehensive approach to quantum ICT, from basic research to demonstration of technologies, open innovation, and development of human resources can be employed. In March 2022, a new building was completed on NICT's Koganei campus.

NICT has a long history of efforts related to quantum technologies, and in particular it was one of the first institutions in the world to focus on the potential of quantum communications and quantum cryptography [31]. The establishment of the Quantum Information Technology Laboratory in 2001 is considered NICT's starting point, and collaborative industry-government-academia projects related to quantum cryptography were launched at the same time. In 2010, the Tokyo QKD Network, a quantum cryptography network covering the Tokyo metropolitan area, was established and became the first such network to successfully demonstrate secure TV conferencing through quantum cryptography [100]. The technology developed through the Tokyo QKD Network has been adopted internationally by the standardization sector of the ITU-T [18].

The Advanced ICT Research Institute is also conducting a number of R&D projects which are closely related to quantum technology. In addition to QKD networks, the Quantum ICT Laboratory is actively engaged in research on basic proof-of-principle and device development necessary for quantum information and communications, such as trapped-ion optical lattice clocks and ultra-sensitive photon detection technology. In addition, the Superconductive ICT Device Laboratory is developing devices such as single-photon detectors that use a niobium-nitride (NbN) superconductor and integrated circuits that can operate at ultra-low power, and has published results such as the successful field demonstration of a photon detector system for quantum computers [101]. Meanwhile, the Cybersecurity Research Institute conducts research and development aimed at ensuring the security of next-generation cryptography, including assessing the security of post-quantum cryptography [102] and conducting experiments on solving discrete logarithm problems using actual quantum computers [61].

3.3.6 National Institutes for Quantum Science and Technology (QST)

The National Institutes for Quantum Science and Technology (QST) established the Institute for Quantum Life Science in April 2021 (Director General: Baba Yoshinobu) [88] to develop the field of quantum life science, initiated in order to establish a hub for quantum life science research, which integrates quantum technologies and life science. The Institute pursues collaborative efforts with various researchers in such fields as quantum biology, structural biology, quantum life informatics, and medicine, along with research and development on nanoscale quantum biosensors, ultrasensitive MRI, and the clarification and imitation of quantum-theoretical life phenomena conducted through the Quantum Leap Flagship Program (Q-LEAP) Flagship Project “Innovations medicine and life sciences through the application of quantum technology” (Project Leader: Baba Yoshinobu).

In 2022, the Quantum Life Science Research Hub was newly established, where various efforts are being undertaken to create a place where innovation can be generated through the integration of quantum technology and life science. In particular, the facility is working proactively to provide a research environment with open laboratories and corporate booths, to promote industry-government-academia collaboration by providing state-of-the-art basic technologies and facilities owned by QST, to manage intellectual property, and to develop human resources.

3.3.7 National Institute for Materials Science (NIMS)

The National Institute for Materials Science (NIMS) has established a quantum technology innovation hub for quantum materials by strengthening its research and development infrastructure. In particular, NIMS is leveraging its strengths in thin-film growth technology and single-crystal fabrication technology to conduct R&D on materials for quantum sensors, quantum cryptography and other technologies in collaboration with universities and research institutes.

The main focus areas of R&D at NIMS are the fabrication of single-crystal diamonds for quantum magnetic sensing for medical applications by realizing highly-sensitive magnetoencephalography, the development of materials for next-generation quantum entanglement light sources using quantum dots to achieve quantum cryptography over far longer distances, and the exploration of materials topology and development of innovative photonics quantum functions for optical and medical applications by realizing ultra-small lasers.

3.3.8 Tokyo Institute of Technology

The university established a Quantum Sensor Hub [103], aiming for the social implementation of quantum and quasi-quantum sensors that surpass the performance of classical sensors by a wide margin, using solids, atoms, and ions. The research and development being conducted can be broadly divided into two thematic areas, the Quantum Leap Flagship Program (Q-LEAP) Flagship Project “Development of innovative sensor systems by highly sophisticated control of solid quantum sensors” (Project Leader: Hatano Mutsuko), which focuses on the development and applications of ultra-sensitive quantum sensors for magnetic, temperature, and electric fields using diamond NV centers, and the JST COI-NEXT Program “Quantum Navigation Innovation Hub” [41], which focuses on the development of ultra-high precision inertial navigation equipment using quantum and quasi-quantum inertial sensors, and realization of near real-time spatial and continuous geoid measurements in cooperation with optical lattice clock and star tracker technology. The Quantum Computing Group (Head Investigator: Nishimori Hidetoshi), which was established in the International Research Frontiers Initiative (IRFI), conducts research on the fundamental theory of quantum computation, based on both quantum annealing and quantum circuits, and holds study sessions on the latest developments [104].

3.3.9 Keio University

Keio University faculty and students collaborate with researchers from IBM and other participating companies to develop quantum software, centered on the Keio University Quantum Computing Center (KQCC) [58], an IBM quantum network hub that provides access to IBM's “IBM Q” cloud of quantum computing machines. The KQCC has become a research hub for industry-academia collaboration in which participating companies from various industries tackle themes that range from finance, chemistry, machine learning, and optimization to cryptography. In 2021, a joint research project with Mitsubishi Chemical and JSR reported the calculation of the excited state energy of OLED (organic light-emitting diode) materials using a quantum computer [60]. Keio is also actively engaged in education and training, including the release of a free online course that teaches the key concepts of quantum computing [105].

Keio University’s Human Biology-Microbiome Quantum Research Center (Bio2Q) was chosen to be a part of the 2022 World Premier International Research Center Initiative (WPI), the first such center among private universities [106]. The Research Center plans to utilize artificial intelligence and quantum computers for high-speed analysis of data on intestinal microbiomes and internal organs. Meanwhile, Keio also participates in the JST COI-NEXT Program “Center of Innovation for Sustainable Quantum AI,” which conducts joint research with companies in a wide range of fields including drug discovery, materials, finance, and logistics, using the “Shin-Kawasaki Souzou no Mori (Shin-Kawasaki Creative Forest),” a joint development center for industry-academia-government collaboration, as a satellite hub [42].

3.3.10 Tohoku University

Basic research on quantum computing and its applications for combinatorial optimization and machine learning are being conducted in the Quantum Computing Joint Research Group, which was launched in 2020 [107]. In addition to basic research and joint research with companies on issues important to industry such as combinatorial optimization problems and machine learning, the Group also puts effort into enhancing quantum computing-related educational activities, such as lectures and class exercises.

Joint research with companies on quantum annealing is led by the Center for Quantum Annealing Research and Development (T-QARD) [108]. It was launched in 2017 as a quantum annealing lab, after which it was officially recognized as the current Center under the Graduate School of Information Science and Technology. A number of joint research projects are currently under way.

T-QARD plays an active role as an organization that bridges academia and business, having contributed to building a support system for quantum annealing research in Japan, for instance the partnership between Tohoku University and the Tokyo Institute of Technology for cooperation in research on quantum computing (concluded on July 18, 2018), as well as to the launch of two startups, Jij Inc. [109] and Sigma-i Co., Ltd. [110].

In August 2021, the Tohoku University Cyberscience Center started a simulated annealing usage service for both internal and external researchers and developers by pairing NEC's simulated annealing software with Tohoku University's supercomputer, AOBA [111].

3.4 Notable Companies

3.4.1 Toshiba Corporation

Toshiba is a pioneer in the field of high-performance quantum cryptography devices, with trailblazing technology and advanced expertise cultivated through more than 20 years of research and development related to quantum technologies.

Since Toshiba’s first research on quantum cryptographic key distribution (QKD) in 2003 at the Cambridge Research Laboratory, which is now one of Toshiba Europe Limited’s research and development facilities, the company has demonstrated a number of remarkable technologies: in 2004, it achieved key distribution over 100 km of optical fiber; in 2010, key distribution speeds exceeded 1 Mbps; in 2017, QKD speed successfully exceeded 10 Mbps second, and Toshiba achieved the fastest continuous quantum key distribution in today's QKD systems at 13.7 Mbps over a distance of 10 km of fiber. Technologies for high-speed detection of photon signals and high-speed signal post-processing of secret keys contributed significantly to these results.

Meanwhile, for longer distance QKD networks, Toshiba developed a new protocol called twin-field QKD and demonstrated the practicality of key distribution over optical fiber links up to 240 km in length. In the future, the link range will be able to be extended to 500 km or more, and QKD is expected to make it possible to protect sensitive data transmitted in inter-city optical networks.

Toshiba has succeeded in transmitting a very weak QKD signal and the currently widely-used 100 Gbps optical communication signals over the same fiber, using wavelengths optimized by wavelength-division multiplexing of the different optical signals (the normal optical signal and the QKD signal). The fact that QKD requires a dedicated fiber to transmit the very weak quantum signals has been an obstacle to its introduction. Toshiba's QKD system has demonstrated QKD systems operating at 200 Gbps bandwidth over more than 100 km of fiber, and in 2022, the QKD network was used to protect data sent and received through a blockchain application in the financial sector, demonstrating that encrypted communications are possible at transmission rates of up to 800 Gbps over distances of up to 100 km [112]. The experiment used Toshiba Digital Solutions' Multiplexed QKD system (which allows the quantum channel and the data communication channel to share the same optical fiber), and Ciena's Waveserver 5 platform, equipped with 800 Gbps optical-layer encryption and open APIs running over Ciena’s 6500 photonic solution. These results suggest that quantum optical communication technology can be integrated with high-bandwidth data communication infrastructure, and potential for a wide range of social implementation is expected.

Toshiba has also developed a quantum-inspired optimization calculation theory for solving combinatorial optimization problems, the "Simulated Bifurcation Algorithm (SB Algorithm)," and since March 2022, the company has been providing a quantum-inspired optimization solution called SQBM+ (simulated quantum-inspired bifurcation machine) [113]. SQBM+ is a software program that utilizes the SB Algorithm, which makes it possible to obtain highly accurate approximate solutions to complex and large-scale combinatorial optimization problems in a short time, using existing computers. The company aims to use this product to solve social problems in various domains such as finance, drug discovery, genetic engineering, logistics, and AI. SQBM+ is available on Azure Quantum and AWS Marketplace, and can be run on a trial basis for different purposes [114, 115].

3.4.2 NEC

NEC is actively engaged in research and development of hardware and software for transmitting and receiving photon signals, which are necessary for quantum cryptographic key distribution, as well as cryptographic key information processing and other areas. Research and development of QKD devices is mainly being conducted through participation in the Strategic Innovation Promotion Program (SIP) “Photonics and Quantum Technology for Society 5.0” [5] and the Ministry of Internal Affairs and Communications project “Research and development for the construction of a global quantum cryptography network” [43]. In addition, NEC is also proactively involved in ITU-T standardization activities, such as making proposals to international standardization organizations.

NEC develops not only devices for the BB84 protocol, which is a common QKD-based encryption system, but also devices for the CV-QKD protocol, which uses optical phase differences to transmit and share key information. This method transmits key information on a weak light wave with quantum properties, and detects eavesdropping using a weak light wave with quantum properties, which enables only secure keys to be shared as in the BB84 method. The advantage of CV-QKD is that existing optical fiber networks can be used as pathways for these optical transmissions, and NEC is engaged in joint research with Gakushuin University geared toward its practical application.

In addition, NEC is making efforts in various fields aimed at the social implementation of QKD. Through joint research with NICT, NEC has developed a secure authentication system that uses quantum cryptography to protect the transmission of data on characteristics obtained during facial recognition and stores the reference data for authentication using secret sharing [116]. NEC has implemented this system on the Tokyo QKD Network, which has been operated by NICT since 2010, and has also been used on a trial basis to manage the data servers for national teams of Japanese athletes belonging to various sports associations. In the medical field, NEC collaborated with NICT and ZenmuTech to implement a system at medical institutions in Tokyo that use NEC's electronic medical records system, in which sample data from electronic medical records compatible with SS-MIX standardized storage were encrypted using quantum keys supplied in real time from the Tokyo QKD Network. The system was verified to have backed up the data via a wide-area network using secret sharing technology [117]. It was also reported that, using this system, sample data from electronic medical records were successfully cross-referenced between this system and the Kochi Health Sciences Center in Kochi prefecture.

With regard to quantum computers, NEC has high technological capabilities, including the realization of the world's first solid-state qubit for gate-based quantum computers using superconducting circuits [118]. Following the demonstration of a single-qubit device in 1999, the demonstration of universal quantum computation in 2003, and the demonstration of high-precision qubit reading in 2008, NEC successfully demonstrated the operation of a superconducting parametron device in 2014 [119].

The technology for manufacturing and control of qubits that had been developed using the gate-based method has been transferred to quantum annealing, and the company is working to extend the retention time of quantum states, which is key to achieving higher speeds. The New Energy and Industrial Technology Development Organization (NEDO)-commissioned Project for Innovative AI Chip and Next-Generation Computing Technology Development [33] has been adopted by the Tokyo Institute of Technology, Waseda University, and Yokohama National University, and the "Development of Quantum Annealing Machine Using Superconducting Parametrons" project is under way [120]. NEC is also participating in the NEDO project "Integrated Research and Development of Quantum Computation and Ising Computation Systems" [56], which has expanded the scope of its research.

The quantum annealing machine is expected to provide a breakthrough in the rapid solution of combinatorial optimization problems. The challenge for its practical application is that it must achieve both "coherence time" (quantum superposition time) and "integration." NEC has continued to develop elemental technologies to realize a domestically-produced quantum annealing machine, and to date, has confirmed the operation of a superconducting parametron device quantum bit in a superconducting three-dimensional wired basic structure circuit that can operate at cryogenic temperatures. By applying this three-dimensional structure to superconducting circuits, NEC hopes to accelerate its research to increase the scale of circuits by integrating qubits while maintaining a long duration of coherence.

Regarding gate-based quantum computers, research and development for the realization of future general-purpose quantum computers is being conducted in the R&D project "Development of integration technologies for superconducting quantum circuits" [121], which is a project under Moonshot Goal 6, which aims for the "realization of a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050." In this project, the focus is on the development of elemental hardware technologies required for the high integration of superconducting qubits.

3.4.3 Fujitsu, Ltd.

Fujitsu engages in the research and development of quantum computing as a next-generation computing technology. The company's efforts cover all technological domains, from devices to basic software and applications, but it focuses in particular on software technologies such as error correction and quantum simulators. Since the final methodology for hardware has not yet been decided, Fujitsu conducts R&D through a system that pursues a wide range of possibilities, in cooperation with other research institutions globally.

Fujitsu conducts joint research on quantum hardware with Riken, and in April 2021, the Riken RQC-Fujitsu Collaboration Center was opened within the Riken Center for Quantum Computing [122]. At the center, the two organizations will conduct joint R&D geared toward the practical application of superconducting quantum computing by integrating Riken's ongoing work with advanced superconducting quantum computer technologies with Fujitsu's computing technologies and applied knowledge of these technologies based on a customer perspective. Riken and Fujitsu will develop hardware and software technologies that will enable large-scale, 1,000-qubit-class computing systems, as well as R&D of applications using actual devices, with the involvement of end users. As a hardware implementation method other than superconducting qubits, research and development of a method using the spins of diamond NV centers is being carried out in collaboration with the Delft University of Technology.

As for software, research on error mitigation technology using randomized compiling has been conducted in collaboration with Keysight Technologies. In addition, in October 2020, Fujitsu began joint research with Osaka University on quantum error correction technology for fault-tolerant quantum computers, and in October 2021, the Fujitsu Quantum Computing Joint Research Division was established at Osaka University [62]. Software development for quantum computation using logical qubits is also under way.

In the area of application development, Fujitsu has been actively engaged since early on in the development of simulators (software that simulates the operation of quantum computers), including the launch of collaborative efforts with QunaSys [123], a company with strengths in quantum chemical calculations. In March 2022, Fujitsu developed the world's fastest quantum simulator capable of handling 36-qubit quantum circuit systems, equipped with the same A64FX CPU that powers the Fugaku supercomputer [124]. The new simulator can execute the quantum simulator software "Qulacs" [125] in parallel at high speed, achieving approximately double the performance of other significant simulators in 36-qubit quantum operations. Fujitsu has announced plans to develop joint research using this simulator in various fields, such as materials, manufacturing, and finance, in order to accelerate the development of quantum applications. The company has decided to begin joint R&D with five companies including Fujifilm.

Having determined that the practical application of (gate-based) quantum computers will take time, Fujitsu developed the Digital Annealer, which is a new computing technology architecture specialized for optimization problems, and began providing the technology as a service in 2018 [126]. Various proprietary technologies have been introduced, including a separate input interface for cost and constraint terms, automatic adjustment of constraint coefficients, automatic adjustment of annealing temperature, and a speeding-up technology that reduces the search space based on the constraints. The Fujitsu Digital Annealer is already being used by a number of Japanese and international companies and is being applied to real-world problems in many fields including manufacturing, finance, and delivery planning [66, 70].

3.4.4 NTT

Recognizing that the time will come when classical computers are no longer able to handle the growth of network traffic, NTT has been engaged in research on quantum technology since the 1980s, primarily at its Basic Research Laboratories. Meanwhile, based on the understanding that at the moment, there is no technology that has been identified as the sure-fire way to realize a quantum computer, NTT has been working extensively on a variety of approaches, including spintronics, superconducting flux qubits, quantum dots, optical quantum circuits, and topological insulators. The company is also engaged in related research such as manipulation of single and entangled photons, quantum memory, quantum sensors, optical lattice clocks, and quantum networks, by sharing NTT's optical communication technology and its infrastructure [127].

Various efforts related to quantum cryptographic key distribution (QKD) are known about, including a scheme to double the distance achieved by QKD without quantum relay [128], a proposal for twin-field QKD [129], and a proof-of-principle experiment of all-optical quantum relay [76]. Moreover, NCC conducted a demonstration experiment in collaboration with the University of Tokyo and other institutions on ultra-high-precision frequency transmission technology, which is necessary for the realization of optical lattice clock networks. In this experiment, a fiber network of a total length of approximately 150 km was built that connected Riken (located in the city of Wako, Saitama prefecture), the University of Tokyo's Hongo campus (in Tokyo's Bunkyo ward), and the NTT Atsugi R&D Center (in the city of Atsugi, Kanagawa prefecture). The participating companies successfully demonstrated optical frequency transfer over a loop network with a total length of 240 km, achieving ultra-high-precision optical frequency transfer between remote locations with a transfer accuracy of 1 × 10 -18 [130]. These results show that it is possible to transmit the optical frequency possessed by the world's highest-performance optical lattice clock over a distance of more than 200 km using optical fiber while maintaining its performance.

In December 2021, the development in collaboration with the University of Tokyo and Riken of a light source module, a key technology for an optical quantum computer, was reported [76]. The light source module has an integrated structure with input and output optical fiber, with features including a small size, a high quantum noise compression ratio, and THz operation capability. It is expected to make it possible to develop rack-sized optical quantum computers using optical fiber and optical devices.

NTT is also engaged in research and development of quantum algorithms and quantum error correction software. In October 2022, a new quantum algorithm was proposed that shows a quantum advantage in problems using a function whose output has no “structure,” such as hash functions [131]. This is noteworthy as it represents the first quantum algorithm based on an essentially new idea in about 30 years since Shor’s factorization algorithm. As for quantum error correction, NTT has presented a hybrid quantum error reduction method that combines quantum error correction and quantum error suppression, which had been studied independently of each other up until now, thereby making it possible to reduce the number of required qubits by up to 80% compared to conventional methods [63]. This proposal is expected to reduce the resources required to solve real-world problems (the size of a quantum computer) and accelerate the timeframe for practical application. It is also expected to set the future direction for a new type of fault-tolerant quantum computer. Meanwhile, NTT has produced a variety of known results from joint research with universities and research institutes, including the proposal of a new framework to suppress computational errors while minimizing the burden on hardware [64] and an architecture proposal for a burst-error tolerant quantum computer [65].

NTT has set ambitious goals through the construction of the all-photonics network IOWN (Innovative Optical and Wireless Network) including the performance targets of enhancement of network energy efficiency (100-fold), enhancement of transmission capacity (125-fold), and reduction of end-to-end latency (1/200). Four important research themes for the realization of this all-photonics network are: high-capacity optical transmission system and device technology, photonics-electronics convergence technology, the optical technology-based Ising machine LASOLV, and an optical lattice clock network, and various new technologies are being developed [132]. LASOLV is expected to be used for light wavelength assignment problems in IOWN and high-load processing such as machine learning. In 2021, the IOWN Secure Optical Transport Network, which combines quantum key distribution and post-quantum cryptography with IOWN, was announced [133].

Although NTT has not submitted an algorithm for the post-quantum cryptography (PQC) standardization activities under way at the U.S. National Institute of Standards and Technology (NIST), it is helping with the standards selection process in the form of making proposals for methods to enhance security and evaluating security. In February 2022, NTT announced that it had devised and verified countermeasures for vulnerabilities associated with implementation which were discovered for eight of the nine public-key encryption candidates for NIST standards [134]. Physical safety in the implementation of PQC via software and hardware is an important factor in the technology's ability to become widespread and standardized, and is expected to be incorporated in its future standardization. While the NIST standardization only covers public-key encryption, NTT is also pursuing research on (post-quantum) symmetric-key encryption.

3.4.5 Hitachi, Ltd.

Hitachi has long focused on research and development based on its vision of contributing to society through technology. The company's specific achievements can be traced back to Japan's first electron microscope (1942) and Japan's first metal-oxide-semiconductor (MOS) transistor (1962), up to the demonstration of the Aharonov-Bohm effect using an electron holography microscope (1986). In recent years, Hitachi has been focusing on the development of digital solutions utilizing IoT in order to attain "Society 5.0."

In the area of quantum information technology, in addition to basic research with an eye to the future, the company is also conducting R&D aimed at integrating quantum information technology with existing technologies. Specific examples include the development of highly secure communication devices that apply quantum cryptography to classical technology, and CMOS (complementary metal-oxide-semiconductor) annealing machines that operate similarly to quantum annealing machines.

CMOS annealing refers to a type of computer that efficiently solves combinatorial optimization problems using hardware specialized for Ising-model computing. Since the first CMOS annealing machine was announced in 2015, Hitachi has developed multiple implementation methods. In 2021, a CMOS annealing technique for solving large-scale combinatorial optimization problems while reducing implementation volume was presented [135]. The CMOS annealing machine can be accessed through the Annealing Cloud Web, a cloud-based computation service operated by Fixstars Corporation [136].

Optimization solutions are also being developed that use the CMOS annealing machine, and Hitachi now offers a work shift optimization solution that creates optimal work shifts for tens or even hundreds of people [137]. In addition, it was reported in March 2022 that Sompo Japan would begin practical use of the system in its insurance underwriting operations [71]. In addition to collaborative efforts with other companies, the Hitachi Hokkaido University Laboratory (Hitachi Hokudai Lab) established at Hokkaido University is conducting research on elemental technologies and their applicability to social issues.

With regard to quantum computing technology, research on the fabrication of qubits on silicon has been conducted mainly at the Hitachi Cambridge Laboratory [138]. Meanwhile, the Moonshot Goal 6 research and development project “Large-scale silicon quantum computer” (PM: Mizuno Hiroyuki) is pursuing R&D of large-scale quantum computers using the silicon semiconductor technology that has been cultivated to date [139].

3.4.6 Mitsubishi Electric Corporation

Mitsubishi Electric is conducting research on the practical application of quantum key distribution (QKD). The company has improved the stability of quantum cryptography devices by developing a polarization compensation module that can automatically compensate for fluctuations in optical transmission lines, achieving stable operation of interferometers through high-precision temperature control, and developing a low-noise compact photon detector, along with conducting field tests of the aforementioned devices. In addition, Mitsubishi Electric has been actively proposing familiar applications, such as the development of one-time pad cell phone software that encrypts calls by sharing QKD encryption keys among cell phone handsets [140].

The company is working on a wide range of information security technologies, including not only encryption algorithms but also device and cloud security and cyberattack countermeasures, and in the area of post-quantum cryptography (PQC), basic research is being conducted focusing on lattice-based cryptography and homomorphic encryption, among the many PQC schemes. Homomorphic encryption is based on the computational difficulty of algebraic expressions that relate multiple elliptic curves, and is regarded as a highly unique technology which Mitsubishi Electric has been researching for over 20 years. The company is also working on incorporating PQC into communications protocols, and is developing a method to check the operation of cloud quantum computers to see if they are correctly utilizing quantum properties or not [141].

3.4.7 Startups

University-launched startups are expected to bring innovation to the economy and society based on the results of university research efforts. There are reportedly 3,306 startups in Japan launched by universities (as of October 2021).

Japanese quantum technology startups include Osaka University’s QunaSys, which develops software for quantum computers [123], Tohoku University’s Jij [109] and Sigma-i [110], which develop algorithms for quantum annealing and provide consulting services, and Quemix, a subsidiary of TerraSky Co., Ltd. that focuses on materials calculation services [143], along with other startups, mainly providing software services. Another software startup that is not university-based but had its technological origins in the Impulsing Paradigm Change through Disruptive Technologies Program (ImPACT) project "Advanced Information Society Infrastructure Linking Quantum

Artificial Brains in Quantum Network" [32] is blueqat [144], which has been highly active in recent years.

Recently, a number of hardware-related startups have also been launched. Leveraging the strengths of their respective technologies, Yokohama National University's LQUOM develops and provides quantum cryptography devices and quantum relay devices [75], Osaka University's QuEL is taking on the challenge of developing qubit control devices and middleware based on microwave engineering [145], and Waseda University-launched Nanofiber Quantum Technologies develops nanofiber QED resonators as its core technology [146].

The Ministry of Economy, Trade and Industry pointed out in a survey that the that the percentage of employees that doctoral-level personnel account for in startups classified as "research result ventures" or "technology transfer ventures" is higher than that of researchers in general companies. The quantum technology startups listed in this section are also proactively utilizing personnel with doctorates.

Table 3-13: Quantum startups launched by Japanese universities

Company	Founded in	Overview of business	Technology base
Jij Inc. [109]	November 2018	Development of quantum annealing and mathematical optimization algorithms, consulting services	Tohoku University
QunaSys [123]	February 2018	Development of software for quantum computers, provision of quantum chemical computation cloud services	Osaka University
Quemix [143]	June 2019	Development of software for quantum computers, materials calculation support, provision of materials calculation services	Tokyo Institute of Technology
Sigma-i Co., Ltd. [110]	April 2019	Development of quantum annealing services and products, consulting services	Tohoku University
LQUOM, Inc.	January 2020	Development of quantum communication systems, quantum relay devices, and related technologies for the realization of the quantum internet	Yokohama National University
QuEL, Inc. [145]	July 2021	Development, manufacturing, and sales of quantum computer controllers and middleware	Osaka University
Nanofiber Quantum Technologies [146]	April 2022	Research, development, design, manufacture, and sales of technologies, products, and services related to quantum science including quantum computers, quantum cryptography, and quantum communications	Waseda University

3.5 Notable researchers

In this section, based on the analysis of papers and patents contained in the CRDS report "International Trends in Quantum Technology as Seen in Papers and Patent Maps" [147], we have selected 10 researchers of note, taking into account the role they play in Japan's quantum research community, and have provided short personal profiles.

3.5.1 Quantum fundamental technology

Kitagawa Masahiro

Professor at the Graduate School of Engineering Science and the director of Center for Quantum Information and Quantum Biology, Osaka University. Received a BEng in 1981, MEng in 1983, and PhD in quantum physics in 1994 from Osaka University. Served as a research scientist at NTT Basic Research Laboratories from 1983 to 1993 and has been working on quantum optics and quantum information since 1985. Became a faculty member at Osaka University in 1993 and then Professor in 2003. Has served as Research Director on a number of JST/CREST Projects; Nuclear Spin Network Quantum Computers (1999–2005), Molecular Spin Quantum Computers (2005–2011), and Hypersensitive MRI/NMR by means of Room Temperature Hyperpolarization and Quantum Coding (2016–2022). His research interest covers quantum measurement and sensing, quantum communications, quantum computing and quantum biology. Serves as the program director of the Moonshot Goal 6 toward fault-tolerant universal quantum computers, the project leader of the Quantum Software Research Hub and as a member of the quantum innovation committee of the cabinet office since 2020. He is a co-founder of QunaSys Inc., a quantum software startup, and QuEL Inc., a quantum middleware startup. His paper on "Squeezed Spin States" was selected as Physical Review A 50th Anniversary Milestones. He is a life member of American Physical Society and a member of Physical Society of Japan.

Kohei M. Itoh

President of Keio University, Japan. Graduated from Keio University and received his M.S. and PhD in Engineering from the University of California, Berkeley. Joined Keio University as a faculty member in 1995 and became a full professor in 2007. Served as Dean of Faculty and Graduate School of Science and Technology of Keio University between 2017 and 2019, and as the Chair of Keio AI and Advanced Programming Consortium between 2018 and 2021. Main areas of research have been quantum computing, quantum sensing, and quantum physics, which led to more than 330 journal publications. One of the 210 Council Members of Science Council of Japan representing ~870,000 scholars in the country, proposing and advising academic and scientific policies in Japan and has served on numerous executive boards including the Physical Society of Japan and the Japan Society of Applied Physics. Leads the Program Director of Quantum Information Technology in the MEXT Quantum Leap Flagship Program for researchers representing the field. He is a recipient of the Japan IBM Prize (2006) and the JSPS (Japan Society for the Promotion of Science) Prize (2009). He is also a founder of the IBM Quantum Computer Network Hub at Keio University.

Furusawa Akira

Professor of Applied Physics at the School of Engineering, the University of Tokyo and the Deputy Director of the RIKEN Center for Quantum Computing. Received a MS degree in applied physics and PhD in physical chemistry from the University of Tokyo, Japan, in 1986 and 1991, respectively. His research interests cover the area of nonlinear optics, quantum optics, and quantum information science. Has authored more than 100 papers in leading technical journals and conferences, including the first realization of unconditional quantum teleportation, which was achieved in 1998 at California Institute of Technology as a visiting scientist at Professor Jeff Kimble's lab. Received the Ryogo Kubo Memorial Award in 2006, the JSPS prize in 2007, the Japan Academy Medal in 2007, the International Quantum Communication Award in 2008, the Toray Science and Technology prize in 2015, and the Medal with purple ribbon in 2016. He is a member of the Physical Society of Japan, the Japanese Society of Applied Physics, and OPTICA.

3.5.2 Quantum computing

Nakamura Yasunobu

He is a professor at the University of Tokyo's Research Center for Advanced Science and Technology (RCAST) and the Leader of the Superconducting Quantum Electronics Research Team at the Riken Center for Emergent Matter Science (CEMS). His area of expertise is quantum information science, especially experiments on superconducting quantum circuit systems and hybrid quantum systems. In 1992, he joined NEC. While continuing his research at the Fundamental Research Laboratories, he successfully developed the world's first superconducting quantum bit device, which is the heart of a quantum computer. After working as a visiting researcher at the Delft University of Technology, he became a principal researcher at NEC in 2005, a professor at the University of Tokyo's Center for Advanced Science and Technology in 2012, and a team leader at CEMS in 2014. Since 2016, he has served as the Research Supervisor for the ERATO Nakamura Macroscopic Quantum Machines Project, and since 2019 as the Project Leader for the Quantum Leap Flagship Program (Q-LEAP) [4] Flagship Project "Research and development of superconducting quantum computers." He has been appointed Director of the Riken Center for Quantum Computing, which opened in April 2021. He has received many awards including the Nishina Memorial Prize in 1999, the Leo Esaki Prize in 2014, and the Asahi Prize in 2021. In 2021, he was awarded the Micius Quantum Prize 2021.

Fujii Keisuke

Professor at the Graduate School of Engineering Science and the deputy director of the Center for Quantum Information and Quantum Biology, Osaka University. Received his PhD in Graduate School of Engineering, Kyoto University in 2011. Was a research scientist at the Graduate School of Engineering Science, Osaka University (2011–2013), a program-specific assistant professor at the Hakubi Center, Kyoto University (2013–2016), and an assistant professor at the Center for Photon Science, the University of Tokyo (2016–2017). Serves as a Project Leader in a Q-LEAP Project; Development of quantum software by intelligent quantum system design and its applications. His areas of expertise are quantum information and quantum computing, specifically, quantum error correction, error-tolerant quantum computing, measurement-based quantum computing, quantum computational complexity, and quantum machine learning. Serves as the Team Leader of Quantum Computing Theory Research

Team, RIKEN Quantum Computing Research Center, as a Visiting Professor at the Department of Applied Physics, Graduate School of Engineering, the University of Tokyo, as a program manager of the IPA MITOU target program, and a board member of the Quantum Research Institute, a general incorporated association for the spread of quantum technology. He is a technical advisor of a quantum software startup QunaSys Inc. In 2023, he was awarded the title of Osaka University Distinguished Professor.

Nemoto Kae

Professor at Okinawa Institute of Science and Technology Graduate University (OIST) and leads the Quantum Information Science and Technology Unit. Received a PhD degree in theoretical physics from Ochanomizu University, Tokyo, Japan, in 1996. Served as a Professor with the National Institute of Informatics (NII), Tokyo, where she has been a member of faculty since 2003. Before joining NII, she spent several years as a Postdoctoral Fellow with the University of Queensland and the University of Wales, U.K. Her current research interests include the implementation of quantum information devices, hybrid quantum systems, quantum networks, and complex systems. She has served as director of the Global Research Center for Quantum Information Science at the National Institute of Informatics, and co-director of the Japanese-French Laboratory for Informatics. In 2015, she was named as a Fellow of the American Physical Society (APS), after a nomination from the APS Division of Quantum Information, "for pioneering the theory for quantum optical implementations of quantum information processing and communication". She is also a Fellow of the Institute of Physics. Decorated as an Officer of the National Order of Merit of the French Republic in 2022.

3.5.3 Quantum communication

Sasaki Masahide

Director General of the NICT Quantum ICT Collaboration Center and a NICT Fellow. Specializes in quantum information and communication theory and demonstration experiments, integrated lightwave-photon control, photon detection technology, and quantum cryptography networks. Worked at NKK (Nippon Kokan K.K., now JFE Holdings) from 1992 to 1996, where he researched quantum devices. After working as a researcher at the Communications Research Laboratory of the Ministry of Posts and Telecommunications, he became the group leader of NICT’s Quantum Information Technology Group, Fundamental Research Division in April 2001. In 2003, he demonstrated that small-scale quantum computers can be incorporated into optical receiver circuits to enable quantum communication that breaks the “Shannon limit” of conventional theory and has since led a team in the demonstration and practical applications of quantum key distribution for over a decade. He has a track record of remarkable achievements in both the fundamentals and applications of quantum information communication, including leading an industry-academia-government collaborative project to significantly improve the performance of QKD devices and building a quantum cryptography network (the Tokyo QKD Network) in 2010 to realize fully secure video transmission for the first time in the world. He is also actively involved in activities to popularize quantum technologies, such as cooperating with companies to develop applications that completely conceal mobile communications for smartphones and drones and conducting demonstration tests in special zones for regional development.

Tomita Akihisa

Professor at the Faculty of Information Science and Technology, Hokkaido University since 2010. Received B.S. and M.S. degrees in physics and a PhD degree in electronics from the University of Tokyo in 1982, 1984 and 1998, respectively. Engaged in research on photonics from 1984 to 2000 and conducted research on quantum information technology from 1998 to 2010 both at NEC Corporation. He also led the group for quantum information experiments in Quantum Computation and Information Project, ERATO and SORST, JST, from 2000 to 2010. Since 2019 he is serving as President of the Quantum ICT Forum. His current research covers photonics for quantum information processing and quantum communication.

Koashi Masato

Professor at the Photon Science Center, the University of Tokyo. Received a PhD degree in physics from the University of Tokyo in 1995. Engaged in research on quantum optics and quantum information science from 1995 to 1999 at the NTT Basic Research Laboratory. Was an associate professor at the Graduate University for Advanced Studies, SOKENDAI (1999–2004), and the Graduate School of Engineering Science, Osaka University (2004–2011). Serves as Project Manager of the project "Research and Development of Theory and Software for Fault-tolerant Quantum Computers" on the Moonshot Goal 6 towards a fault-tolerant universal quantum computer program. His areas of expertise are quantum communication and quantum cryptography.

3.5.4 Quantum metrology and sensing

Katori Hidetoshi

Professor at the Department of Applied Physics, the University of Tokyo. Received a B. Eng. (1988), M. Eng. (1990) and D. Eng. (1994) in Applied Physics, The University of Tokyo. From 1994 to 1997, he worked at Max Planck Institute for Quantum Optics in Garching, Germany, as a visiting scientist. He joined the Engineering Research Institute at the University of Tokyo in 1999. Since then, he has been engaged in the precision measurements with ultracold atoms, in particular with "optical lattice clocks" that he proposed in 2001. Has been a Professor at the Department of Applied Physics, Graduate School of Engineering, the University of Tokyo since 2010 and a chief scientist at the Quantum Metrology Laboratory, RIKEN, since 2011. Served as a research director of the ERATO, "Katori Innovative Space-Time Project (2010–2016)," JST. Team Leader of the Space-Time Engineering Research Team in the RIKEN Center for Advanced Photonics, and Chief Scientist of the Quantum Metrology Laboratory in the RIKEN Cluster for Pioneering Research. Leads the JST-Mirai Program; Space-time information platform with a cloud of optical lattice clocks as a program manager since 2020. Recently, his group performed a measurement of gravitational redshift with two transportable strontium optical lattice clocks over nearly the entire height of the Tokyo Skytree, setting a new record for the best ground-based test of general relativity. He was awarded the first JSPS Prize, European Time and Frequency Award, and The Julius Springer Prize for Applied Physics in 2005, the IBM Japan Science Prize (2006), the Rabi Award (2008), the Asahi award (2012), the Nishina memorial award (2013), The Medal with Purple Ribbon (2014), the Japan Academy Award (2015) and the 2022 Breakthrough Prize in Fundamental Physics (2022).

Hatano Mutsuko

Professor at the Department of Electrical and Electronic Engineering, School of Engineering, Tokyo Institute of Technology. Received a D. Eng. from Keio University. Joined the Central Research Laboratory, Hitachi Ltd. Was a Visiting Researcher with the University of California at Berkeley from 1998 to 2000. In 2010, she joined the Department of Electrical and Electronic Engineering, Tokyo Institute of Technology, Tokyo, as a Professor. Her current research interests include the development of carbon-based devices for power electronics and quantum sensing applications. Leads the Quantum Leap Flagship Program (Q-LEAP) Flagship Project “Quantum Metrology and Sensing" as Project Leader since 2020. Served as President of the Japan Society of Applied Physics. She has been appointed the Executive Member of the Council for Science, Technology and Innovation.

Kozuma Mikio

Professor at the Institute of Innovative Research, Tokyo Institute of Technology. Received a D. Eng. from Tokyo Institute of Technology. Assistant professor at the Graduate School of Arts and Sciences, the University of Tokyo (1998–2001), and an associate professor at Tokyo Institute of Technology (2001–2013). Leads the JST-Mirai Program; Development of high-performance gyroscopes with matter waves as a program manager since 2017. Currently serves as a project leader at the Quantum Navigation Innovation Hub in the Program on Open Innovation Platforms for Industry-academia Co-creation (COI-NEXT). His areas of expertise are quantum optics, cold atoms, and quantum electronics.

3.5.5 Quantum materials

Tokura Yoshinori

Professor at the University of Tokyo and Director of the Center for Emergent Matter Science (CEMS) at RIKEN. Specializes in physics of strongly correlated electron systems and is known for his work in high-temperature superconductivity, Mott transition, colossal magnetoresistance, multiferroics, and magnetic skyrmions. He is a member of the Japan Academy, a Cultural Merit awardee, and an honorary fellow of the National Institute of Advanced Industrial Science and Technology (AIST). He is also a member of the Science Council of Japan and a foreign member of the Royal Swedish Academy of Sciences.

Obtained his PhD in engineering from the University of Tokyo in 1981. Became a lecturer at the Faculty of Engineering, the University of Tokyo in 1982, an associate professor at the Faculty of Science, the University of Tokyo in 1988, and a professor at the Graduate School of Science, the University of Tokyo in 1994. He moved to the Graduate School of Engineering, the University of Tokyo in 1999 and became the director of CEMS at RIKEN in 2013. Led the JST-ERATO “Tokura Spin Superstructure” project (2001–2007) and “Tokura Multiferroics” project (2006–2012) as Research Director. He also served as the Core-Researcher of the quantum science of strong correlation (QS2C) project in Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program). He has received many awards for his contributions to physics, such as the Nishina Memorial Prize (1990), the IBM Japan Science Prize (1990), the Bernd T. Matthias Prize (1991), the JPS Award for Academic Papers on Physics (1999), the Asahi Prize (2002), Medal with Purple Ribbon (2003), James C. MacGroddy Prize for New Materials (2005), IUPAP Magnetism Award and Néel Medal (2012), and the Person of Cultural Merit (2020).

Nagaosa Naoto

Deputy Director of the RIKEN Center for Emergent Matter Science (CEMS), Division Director, Strong Correlation Physics Division, RIKEN CEMS. Leads the Strong Correlation Theory Research Group, Strong Correlation Physics Division, RIKEN CEMS as the Group Director since 2013. Graduated from the Department of Applied physics, the University of Tokyo in 1980. From 1983 to 1986, he was a research associate in Institute for Solid State Physics, the University of Tokyo, and received a D. Sci from the same institute in 1986. From 1988 to 1990, worked as a visiting scientist at Department of Physics, Massachusetts Institute of Technology, before joining the Department of Applied Physics at the University of Tokyo where he is now a professor. From 2013 he has joint appointment as the Deputy Director of the RIKEN Center for Emergent Matter Science (CEMS). His research field is theoretical condensed-matter physics, especially involving the strong electron correlation, optical responses of solids, topological aspects of condensed matter, and superconductivity. He has received the Yukawa Prize, the Japan IBM Prize, the Nissan Science Prize, the Nishina Memorial Prize, the Fujihara Prize, and the Medal with Purple Ribbon. His research interests are condensed matter theory, strong electron correlation, magnetism, and superconductivity in solids, topological aspects of electronic systems.

Taniguchi Takashi

Fellow and Executive Vice President of the National Institute for Materials Science (NIMS). Serves as the Director of the International Center for Materials Nanoarchitectonics (MANA). Received his B.Sc. from Tokyo University of Agriculture and Technology in 1982 and earned his PhD in 1987 at Tokyo Institute of technology in materials science under K. Kondo and A.B. Sawaoka. Worked as a research associate at faculty of engineering at Tokyo Institute of Technology from 1987 to 1989. Moved to the National Institute for Research in Inorganic Materials (NIRIM) in 1989. After NIRIM unified into National Institute for Materials Science (NIMS) in 2001, he worked as a group leader of high-pressure research group. He was promoted to Fellow in 2018. His research area covers materials science under high pressure and high temperature, especially studies on diamond and boron nitride crystals as superhard and wideband gap materials. Was a former president of the Japan society of High Pressure Science and Technology. Since 2019, he is vice president of the International Association for the Advancement of High Pressure Science and Technology. His honors include the Thomson Reuters Research Frontier Award (2016), the Commendation for Science and Technology by the Ministry of Education, Culture, Sports Science and Technology, Japan (2017), The Japan Society of High Pressure Science and Technology Award, (2018), the CerSJ Awards for academic achievement in ceramic science and technology at The Ceram. Soc. Japan (2018), election as an Academician of World Academy of Ceramics (2019), Citation Laureate for 2022 by Clarivate (2022) and the James C. McGroddy Prize for New Materials (2023).

3.6 International collaboration and joint research

Quantum technology is recognized as an important foundational technology for the future of the world economy and society, as well as for national security. Major countries such as those in Europe, U.S., and China are strategically and actively pursuing research and development in this field, and international competition is intensifying. Japan formulated the Quantum Technology Innovation Strategy in January 2020, aiming to promote focused research and development, industrialization and commercialization based on Japan's strengths. In February 2021, Japan also launched the Quantum Technology Innovation Hub, which enhances collaboration among universities, research institutions, companies and the government.

International collaboration is highlighted in both the 2020 Strategy as well as the Vision. The former underlined the importance of partnering with Europe and the U.S. from an industrial and national security perspective and called for multi- and bi-lateral frameworks for quantum technology cooperation. The current status of international cooperation in quantum technology is continued collaboration on various projects and initiatives that support the advancement of quantum science and technology. Exchange of information and best practices and the fostering of dialogue and networking among researchers and stakeholders is also ongoing. Both sides seek to enhance cooperation and coordination in the global context of quantum research and innovation.

Japan and the United States have a strong and strategic partnership in innovation and technology, which includes cooperation on emerging technologies such as quantum information sciences. They have signed several agreements and launched various initiatives to support joint research and development, exchange of information and best practices, and the fostering of talent and entrepreneurship in quantum science and technology. Some examples are the Tokyo Statement on Quantum Cooperation, the Project Arrangement on Quantum Information Science, and the U.S.-Japan Competitiveness and Resilience Partnership. They also collaborate with other countries and regions to advance the global quantum research and innovation agenda.

The U.S. Embassy in Tokyo's acting deputy chief of mission and Japan's director-general for science, technology and innovation policy signed the Tokyo Statement on Quantum Cooperation in December 2019 to support continued collaboration in research and development to advance quantum information science and technology (QIST) for economic, societal, and security benefits [148]. The statement recognizes that QIST is a key area of science, technology, and innovation that has enabled transformative capabilities across multiple sectors, and that global research enterprise is the foundation of this progress. The statement also expresses the commitment of both countries to promote increased engagement through international conferences and events, support joint efforts to prepare the next generation of scientists and engineers, and foster a culture of openness and trust among researchers.

One example of international cooperation is the Project Arrangement (PA) on Quantum Information Science (QIS) signed between the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan and the Department of Energy (DOE) of the United States in June 2021. The PA aims to promote joint research on QIS topics such as quantum computing, quantum communication, quantum sensing, and quantum algorithms. Another example of international cooperation is the U.S.-Japan Competitiveness and Resilience (CoRe) Partnership announced in May 2021. The partnership includes cooperation on emerging technologies such as artificial intelligence (AI), biotechnology, quantum information sciences, and 6G networks [149].

Japan and Europe have a strong and long-standing partnership in science and technology, based on a cooperation agreement signed in 2009. Collaboration on various projects related to quantum science and technology, such as the Quantum Internet Alliance and the Quantum Flagship initiative, which aim to develop and exploit the potential of quantum technologies for communication, computing, and metrology is ongoing.

Japan and the European Union (EU) share a common commitment towards promoting scientific and technological research [150]. Bilateral collaboration in the field of science and technology is based on an overarching Science and

Technology Cooperation Agreement that was signed in 2009 and entered into force in 2011. Its key goals are to promote research excellence and increase growth and industrial competitiveness.

In October 2019, Japan and Europe co-organized an international symposium on quantum metrology and sensing, which showcased the state-of-the-art research and applications of quantum technologies for precision measurement and sensing. The symposium also fostered networking and collaboration opportunities among participants. In December 2019, Japan and Europe held a joint workshop on advanced quantum technology for future innovation, which brought together researchers and experts from both sides to exchange views and information on the latest developments and challenges in quantum science and technology.

The importance of international cooperation is clearly positioned in the Quantum Technology Innovation Strategy, and Japan is advancing joint research, information exchange, talent development and other activities with Europe, the U.S. and other regions. Japan is also actively involved in the construction of global rules and governance for quantum technology. Some of the challenges are to address ethical, social and legal issues arising from the development of quantum technology, and to ensure international standardization and interoperability. It is also necessary to verify whether the level and speed of research and development, industrialization and commercialization of quantum technology in Japan are sufficient compared to other countries.

International collaboration in quantum technology is important also from the perspective of talent development. Quantum technology requires a highly skilled and diverse workforce that can conduct cutting-edge research and development, as well as apply quantum technology to various business domains and sectors. However, there is a global shortage of quantum talent, and many countries are competing to attract and retain the best researchers and engineers.

International collaboration can help address this challenge by facilitating the exchange of knowledge, skills and best practices among quantum experts from different countries and regions. It can also foster the mobility and diversity of quantum talent, as well as create opportunities for education and training in quantum science and technology. International collaboration can also help build trust and cooperation among allied and partner nations that share common interests and values in quantum technology. It can enhance the security and resilience of quantum technology development and use, as well as promote the alignment of standards, norms and governance for quantum technology.

3.7 Quantum technology ecosystem

The quantum innovation ecosystem is summarized as follows based on the characteristics of Japan’s quantum policies and R&D community. Policies that had been siloed due to promotion by separate ministries and agencies have been unified under the Quantum Technology and Innovation Council since the formulation of the “Quantum Technology and Innovation Strategy” [22] by the Cabinet Office, and a system has been established that enables the planning and implementation of policies that look at diverse quantum technologies from a panoramic perspective.

Research and development is conducted mainly at the 10 Quantum Technology Innovation Hubs around Japan, with Riken providing the overall headquarters function for international collaboration and industry-academia cooperation. Research and development efforts at the QIHs are supported by large-scale projects under the direct control of government agencies, such as the Cabinet Office's Moonshot Research and Development Program [8] and Strategic Innovation Promotion Program (SIP) [5], MEXT’s Quantum Leap Flagship Program (Q-LEAP) [4], and the Ministry of Internal Affairs and Communications’ "Research and development for construction of a global quantum cryptography network" project [43], as well as projects undertaken by funding organizations, including the JST Mirai Program [37, 38], the JST Program on Open Innovation Platforms for Industry-academia Co-creation（COI-NEXT）[40–42], the NEDO “Project for Innovative AI Chip and Next-Generation Computing Technology Development” [33] and “Integrated Research and Development of Quantum Computation and Ising Computation Systems” [56].

In industrial circles, companies with quantum technologies are individually promoting social implementation, and industry-academia collaboration is also being enthusiastically promoted through participation in the above-mentioned projects. Active discussions are being held at consortiums on the development of applications for quantum technologies, and the content of these discussions contributes significantly to the government's strategic planning [23]. In addition to the government-led Quantum STrategic industry Alliance for Revolution (Q-STAR) [12], there are various active university- and industry-led consortia such as the Quantum ICT Forum, QPARC, the Quantum Innovation Initiative Council, the Quantum Software Consortium, and the Quantum Internet Task Force [13–17]. Startups have also been launched to tackle cutting-edge challenges that are difficult for universities and large companies to address, and they are playing an important role in the quantum ecosystem by improving the mobility of expert personnel and conducting joint research toward social implementation.

Japan's strategy is to build an infrastructure for quantum technology and implement it in society by leveraging its accumulated experience in research and development and integrating it with advanced technologies such as semiconductors and AI. The importance of engineering research and development of the fundamental technologies that make quantum technology possible has been pointed out [151], but the shortage of human resources to take on these tasks in the first place has been increasingly apparent. This is true not only in the quantum computer field, but also in the shortage of engineers involved in quantum information processing technology as a whole [152]. The training of human resources familiar with the rules of quantum information is key to the social impact of quantum technology, and future trends in human resource development, education, and training will be closely watched going forward. Close collaboration between the companies that need quantum ICT engineers and the universities and research institutions that can educate and train them is clearly necessary in the long run.

The success of various research and development projects also hinges on the enrichment and diversification of the players in the R&D community and their ability to function in various roles in the ecosystem. Therefore, it is necessary to adopt comprehensive measures oriented toward nurturing and stimulating activity in the ecosystem that is being established, rather than simply providing research funds through grants or establishing R&D hubs.

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4 Quantum technology trends in India

India's quantum technology policy began in 2017. Its research and development is centered on investment from the Department of Science and Technology (DST), led by public research institutions such as the Indian Space Research Organisation (ISRO), Defence Research and Development Organisation (DRDO), Raman Research Institute (RRI) and the Tata Institute of Fundamental Research (TIFR), as well as leading universities such as the Indian Institute of Science Education and Research (IISER), Pune, the Indian Institute of Science (IISc), and the Indian Institute of Technology Madras. In 2019, the government announced a National Mission in which it will invest 80 billion rupees (0.96 billion USD, when 1 rupee = 0.012 USD) over five years. In so doing, it aims to rapidly expand its research and development community through heavy investment similar to America and China to create a domestic industry for quantum technology as it works toward a "Self-reliant India."

4.1 Quantum technology policy

India is a late participant to the global competition of quantum technology development. Quantum technological development policy started in 2017 with the Quantum Enabled Science and Technology program (QuEST) by the Department of Science and Technology (DST). In 2019, the government placed quantum technology development as one of its great national missions so it could participate in the competition with countries with advanced quantum technology policies such as the U.S., the UK, and China; in its FY2020–2021 budget, it announced large-scale investment similar to that of America, Europe and Russia. India is now in a period of expansion in quantum technology development, as is evident from the high growth rate of the number of papers seen in Chapter 1.

In the past, as a state, India has set out four policy documents concerning medium- and long-term aims for science, technology and innovation. These are the S&T policies, Scientific Policy Resolution, 1958; the Technology Policy Statement, 1983; the Science and Technology Policy 2003; and the Science, Technology and Innovation Policy 2013 (STIP2013). However, there was no mention of quantum technology until STIP2013—it is referenced for the first time in two places in the policy document being prepared for the next period: Science, Technology and Innovation Policy 2020 (STIP2020).[1] First, it suggests that quantum technology is a disruptive emerging technology that will change society, the economy, and the environment, and brings up the quantum Internet of Things (IoT) as a field in which innovative strategy, development and governance is necessary, similar to blockchain and AI. Moreover, it proposes quantum frontier together with the deep ocean exploration and AI as fields that will pursue technological independence and domestic production through a large-scale national mission, working toward Prime Minister Narendra Modi's major goal of "Self-reliant India (Atmanirbhar Bharat Abhiyaan)." The specific measures for the former "quantum IoT" are unclear but concrete measures for the large-scale national mission for the latter "quantum frontier" are given.

The large-scale national mission involves the Prime Minister's Science, Technology and Innovation Advisory Council (PM-STIAC; organized by the Principal Scientific Adviser (PSA) who serve as an advisor to the prime

[1] DST, "Science Technology Innovation Policy 2020" (December 2022 draft version).

minister for science, technology and innovation) setting out nine fields[2] to promote national R&D of high importance[3]. Of these, four are also clearly specified in STIP2020: deep ocean exploration, national language translation, AI, and the quantum frontier; specific measures have been approved for these. Below is an overview of the policies concerning quantum technology research and development carried out by the Indian government to date, centered on the large-scale national mission in the quantum field.

4.1.1 The National Mission on Quantum Technologies and Applications (NMQTA)

Among the nine fields mentioned above, the large-scale national mission associated with the quantum frontier is called the National Mission on Quantum Technologies and Applications (NMQTA). In addition to DST, it is led by the India Space Research Organisation (ISRO), the Department of Atomic Energy (DAE), the Defence Research and Development Organisation (DRDO), and the Ministry of Electronics and Information Technology (MEITY). The country aims to develop wide-ranging quantum technology and to construct an infrastructure environment and personnel base that seeks excellence in the quantum technology research field, and in February 2020, the Indian government announced that its FY2020–2021 budget would assign 80 billion rupees (0.96 billion USD). However, in reality the global COVID-19 pandemic occurred after this, so the expenditure estimates for the expected budget do not stand.

There are no official policy documents for NMQTA—the Technology Information Forecasting and Assessment Council (TIFAC), which falls under DST, has created a draft concept note (draft from June 12, 2019)[4]. Here is an overview of NMQTA based on the draft concept note.

NMQTA's target activities are as follows:

① Fundamental research, technological development, and verification

NMQTA promotes research and development, including fundamental research, technological development, and translational research on a wide range of quantum technologies and related fields (e.g. quantum computers, quantum simulation, quantum materials and quantum devices, quantum communication, quantum sensors and quantum measurement). It seeks to verify quantum computers, quantum communication (optical fiber, free space), and quantum key distribution in particular. It also develops technology and prototypes connected to national priority matters and verifies relevant applications.

[2] The nine fields are: Translation of the national language, quantum frontier, AI, National Biodiversity Mission, electric vehicles, bioscience for human health, Waste to Wealth, deep-sea exploration, and AGNli (Accelerating Growth of New India's Innovations).

[3] PSA's Office, "The Prime Minister's Science, Technology and Innovation Advisory Council (PM-STIAC)." Last accessed: June 16, 2022.

[4] TIFAC, "DRAFT Concept Note National Mission on Quantum Technology & Applications (NM-QTA)."

② Establishing the Centre for Development of Quantum Technology (C-DOQ)

Establishing C-DOQ is the core of the NMQTA mission. It will function as a central hub, managing all NMQTA activities, and all missions will be carried out through this center. It will have five wings (technology development, translational research, application, operation, and commercialization), and aim to build collaborative and cooperative relationships with research organizations both in India and elsewhere, as well as to collaborate with the government, the world of industry, industrial associations, startup ecosystems, and regulatory bodies, and to realize product development on a global level.

③ Human resource development

NMQTA is to develop human resources in advanced areas of quantum technology, from university graduate student level to faculty level. The Observer Research Foundation, an Indian thinktank, has stated that "At present, there are just a few hundred researchers, industry professionals, academicians, and entrepreneurs in the quantum computing field of the country. Compared to China or the U.S., India lags far behind.[5]" As such, the development of human resources is a major challenge for India's quantum technology policy. To secure human resources with advanced skills in the rapidly growing field of quantum information science, NMQTA aims to foster approximately 25,000 people who can deal with software and hardware over five to seven years from its inception. A breakdown of these human resources is given in Table 4-1.

Table 4-1: Anticipated breakdown of human resources to be developed

Target	Percentage
Skilled and semi-skilled workers, including students (scientists, engineers)	48%
Undergraduate and post-graduate fellowships	40%
PhDs/postdoctoral researchers	8%
Core researchers in quantum technology and associated applications	4%

Source: TIFAC

④ International collaboration

India is making use of DST's existing bilateral cooperation frameworks to carry out international joint research and adopt international best practice. It aims to engage in more than 20 cases of international joint research, hold at least eight international conferences, and for the participation of at least 50 foreign experts.

⑤ Entrepreneurship, innovation and startup ecosystem development

With regard to applying research outcomes, NMQTA will support the world of industry, especially venture companies and small and medium-sized enterprises (SMEs). DST is collaborating with the Technological Development Board to foster entrepreneurs in quantum technology through consultations, education and training for entrepreneurship. It aims to carry out at least 12 industry-academia collaborative projects and at least 100 entrepreneurship consultations.

[5] Observer Research Foundation, "India's race to quantum supremacy." December 6, 2021.

80 billion rupees (0.96 billion USD) are currently allocated to the NMQTA's budget. They are to be invested by DST over the next five years; Table 4-2 below shows the specific expected distribution ratio.

Table 4-2: Expected distribution of NMQTA funding

Area	Distribution
C-DOQ	41%
Fundamental research, technological development, and verification	37%
Human resource development	9%
Innovation and startup ecosystem	9%
International joint research	3%
Mission management	1%

Source: TIFAC

The following are more concrete technological aims that India anticipates through NMQTA[6]:

① The development of a domestically produced quantum computer

・To build a 50-qubit quantum computer by 2026

② The commercialization of quantum solutions

・To sell small-scale devices such as quantum simulators and sensors

・Translating quantum key delivery systems into field deployable devices

③ The establishment of long-distance quantum communication

・To realize long-distance quantum communication, quantum key distribution over several hundred kilometers through satellites and fiber

4.1.2 Main funding programs before the National Mission

92% of quantum-related projects in India are supported by the government, and the remaining 8% are run by the startup community and independent not-for-profit organizations[7]. Before the start of NMQTA in February 2020, they were supported by several quantum-technology related programs. The following programs fall under DST[8]:

(1) Quantum Enabled Information Science and Technology program (QuEST)

This pioneering program for quantum technology was established in 2017, and aims to provide technological skills to enable India to create a quantum computer and communication systems within 10 years. It focuses on developing and implementing core quantum technology and on the fundamental development of human resources. In January 2019, during a meeting held in IIT Hyderabad, 51 projects were selected from around 130 proposals. The themes of the selected projects can be broadly broken down into the following four main categories:

[6] AVASANT, NASSCOM, "The Quantum Revolution in India Betting Big on Quantum Supremacy." February 2022.

[7] See note 6.

[8] In addition to DST, organizations such as ISRO, MEITY, and DRDO also provide funding.

① The development of quantum communication systems via quantum information technology using photonics devices

② Quantum computation through the diamond N-V center and NMR

③ Quantum information technology from ion trap/optical lattice devices

④ Quantum information technology from superconducting/qubit devices

At first, the program expected to spend two billion rupees (24 million USD) over three years, but the amount to be distributed shrunk and the distribution period increased, so based on the FY2020–2021 budget DST decided to spend 800 million rupees (0.96 billion USD) over the next three years. This was less than 50% of the initial plan.

In April 2022, the first symposium in India, organized by IIT Hyderabad's Centre of Quantum Science and Technology (CQST), was held by QuEST National Coordinator Arun K. Pati of the Harish-Chandra Research Institute (HRI) and QuEST Coordinator Apoorva Patel of the Indian Institute of Sciences (IISc).

The following are outcomes anticipated from the QuEST program.[9]

The development of core quantum technology

- The development and verification of an 8-qubit quantum computer, quantum communication (fiber, free space) and quantum encryption
- The development of quantum algorithms specific to applications
- The development of advanced mathematical quantum technology, algorithms and theories associated with quantum information systems

Human resources development

- The development of approximately 100 doctors of quantum engineering
- The development of 2,000 or so undergraduate and post-graduate students connected with the development of advanced algorithms and applications using quantum systems

The initial plan was that if outcomes were obtained from QuEST, DRDO, ISRO, and DAE would come together for Phase 2 and offer three billion rupees (36 million USD). However, based on the current situation, it is unclear whether this will happen.

(2) National Mission on Interdisciplinary Cyber Physical Systems (NM-ICPS)[10]

This mission began in 2018, with the aim of establishing 25 innovation hubs in Indian universities and research institutions to enable the country to create a foundation for cyber physical system (CPS) technology and a seamless ecosystem. Over five years, 36.6 billion rupees (around 439 million USD) have been spent. Similar to the Technology Fusion & Applications Research Program (TFAR) shown below, this is not a program that specifically supports quantum technology research, but it has set up famous quantum computer centers such as the I-Hub Quantum Technology Foundation (I-HUB) in the Indian Institute of Science Education and Research Pune (IISER Pune). The I-HUB aims to develop and apply quantum computers, quantum materials, atomic clocks, and quantum encryption communications; 13 groups from IISER Pune's Physics department are participating in this facility,

[9] See note 6.

[10] Science and Engineering Research Board, "National Mission on Interdisciplinary Cyber Physical Systems." Last accessed: June 16, 2022.

and collaboration with universities and laboratories in India and elsewhere is also going ahead. This encourages technological transfer and incubation, and human resource development, as well as technological development.

(3) Technology Fusion & Applications Research Program (TFAR) [11]

This program began in January 2020, supporting research on fusing emerging technologies such as quantum, the IoT, cyber security, and data science. Researchers and students are eligible for support, and as a whole, the program is expected to invest 2.5 billion rupees (30 million USD) over three years.

4.2 Quantum technology research and development

According to the paper and patent analysis in Chapter 1, in the last 10 years India has seen the publication of 5,958 relevant papers, the third highest after China and Japan, and the average growth rate for the number of papers is at the top with 26%, higher than that of China. Considering that Japan's growth rate is merely 2%, India is truly in a period of expansion for quantum research, and one can imagine that it comes after China in Asia. Looking at the number of papers by field in India shows that quantum materials (38%) and quantum computers (31%) have the most papers, followed by quantum fundamental technology (22%) and quantum encryption/communications (9%). Compared to other major countries and regions, the percentage of papers on quantum computers is high—this could be considered a characteristic. Looking at the changes in the number of papers every five years reveals that the percentage of papers in quantum materials was high until 2010, but since 2011, the number of papers in quantum computers and quantum encryption/communications has started to increase, and since 2016, both fields have grown significantly.

In other words, before 2017, when India began its quantum technology policy, Indian researchers, especially the noteworthy researchers mentioned in this paper, were independently carrying out research and development associated with quantum technology, and it is thought that quantum technology research has rapidly expanded in a wide range of fields with the start of the promotion of quantum technology in 2017.

The section below introduces the main research and development outcomes and trends since 2017 when India began its quantum technology policy. The fields that have become the core areas of research and development are: ① quantum computing, ② quantum communication and quantum satellites, and ③ quantum encryption. The Ministry of Electronics & Information Technology (MEITY) leads research and development in quantum computing, while ISRO does the same for quantum communications and quantum satellites, and DRDO leads quantum encryption; DST provides general wide-ranging support for all of these.

[11] DST Technology, "New programme to boost research in emerging technologies under single platform." Last accessed: June 16, 2022.

Table 4-3: Main research outcomes and trends in quantum computing

Implementation period/ Main organization	Overview
August 2019 C-DAC	The **Centre for Development of Advanced Computing (C-DAC)**, which is controlled by MEITY, **signed a cooperation agreement with the French company Atos for the global development of quantum computing, AI, and exascale computing.**[12] **A Quantum Computing Experience Centre was to be set up** in C-DAC, and Atos would support quantum education, including providing a Quantum Learning Machine.
January 2021 MEITY	To accelerate quantum computing-driven research and development, **MEITY established the Quantum Computing Applications Lab with Amazon Web Services (AWS).**[13] This provides the science, research, academic, and venture-company communities with free access to Amazon Braket, AWS' cloud quantum computer development environment. This was launched in March 2021.
March 2021 IISER Pune	Based on NM-ICP, DST and **13 research groups from IISER Pune established the I-Hub Quantum Technology Foundation for quantum research and development.**
May 2021 IBM	To develop human resources in the quantum technology field, **IBM announced that it will provide cloud access to its quantum computer system (IBM Q) for major Indian universities and research organizations**[14] as part the IBM Quantum Education program. IBM is providing access to IISER, IISc, IIT, the Indian Statistical Institute (ISI), Indraprastha Institute of Information Technology (IIIT), Tata Institute of Fundamental Research (TIFR), and the University of Calcutta. These facilities can access the IBM quantum system, quantum learning resources, and quantum tools via the IBM cloud, and use Qiskit (open source framework for quantum computing) to experience working and programming on a quantum computer.
July 2021 DIAT/C-DAC	**The Defence Institute of Advanced Technology (DIAT) and C-DAC signed an agreement concerning the joint development of a quantum computer.**
August 2021 MEITY	**MEITY announced India's first quantum computer simulation (QSim) toolkit,**[15] which enables researchers and students to engage in efficient quantum computing research. With MEITY's support, IISc, IIT Roorkee, and C-DAC have achieved outcomes from projects carried out together based on IBM's open source framework. A comparison of its characteristics to those of other simulators, including Google and IBM, shows that QSim enables simulations that include various types of errors that can occur in devices in reality.

[12] ProjectQ website, "India Races Toward Quantum Amid Kashmir Crisis." April 7, 2020.

[13] NNA, "MeitY ga AWS to Kyoryokushite Ryoshi Computer Kenkyu Shisetsu wo Setchisuru Keikaku" [MeitY plans to establish quantum computer research facility in cooperation with AWS]. January 21, 2021.

[14] INDIAai, "IBM to make quantum computers accessible to leading institutions for research & training." May 26, 2021.

[15] Science Portal Asia and Pacific, "Indo Hatsu no Ryoshi Computer Simulation no Toolkit Happyo" [India's first quantum computer simulation toolkit announced]. October 2021.

September 2021 IIT Delhi	**IIT Delhi established its Centre of Excellence on Quantum Technologies.**[16] This focuses on quantum computing, quantum communication, quantum sensing and measurement, and quantum materials and devices. In addition to designing and developing new quantum materials, the CoE is engaged in the modelling and technological development of a quantum processor, cryogenic controller and semiconducting qubits, and in research activities associated with CMOS and 2D materials.

Table 4-4: Main research outcomes and trends in quantum communication and quantum satellites

Implementation period/ Main organization	Overview
March 2021 ISRO	**On March 19, 2021, ISRO demonstrated free-space quantum communications over more than 300 m for the first time in India.**[17] It held a live video conference through QKD between two buildings in the Space Applications Centre (SAC). Lots of original technology was used for this, including a NAVIC (Navigation Indian Constellation) receiver, a satellite positioning system developed by ISRO for time synchronization between transmitting modules and receiving modules, and gimbal mechanism systems in place of a bulky large-aperture telescopes for optical alignment.
January 2022 DOS	**On January 27, 2022, the Department of Space (DOS) succeeded in demonstrating quantum communication using quantum entanglement over 300m free space and real-time cryptographic applications.**[18] Two key DOS laboratories in Ahmedabad worked with SAC and the Physical Research Laboratory to demonstrate real-time QKD, quantum-secure text, image transmission and quantum-assisted two-way video calling over a 300 m atmospheric channel using quantum entanglement. This experiment was carried out between two buildings 300 m apart in SAC in Ahmedabad. The researchers also carried out a quantum communication link experiment based on BBM92 protocol.
February 2022 DRDO	**DRDO and IIT Delhi succeeded in demonstrating QKD between two cities separated by more than 100 km for the first time in India.**[19] They succeeded in using commercial grade optical fiber to demonstrate a QKD link in two cities over 100 km apart, connecting Prayagraj and Vindhyachal in Uttar Pradesh. Through this achievement, India demonstrated military-level indigenous technology for secure key transfer.

[16] IIT Delhi, "IIT Delhi Establishes Centre of Excellence (CoE) on Quantum Technologies." September 27, 2021.

[17] ISRO, "ISRO makes breakthrough demonstration of free-space Quantum Key Distribution (QKD) over 300m." March 22, 2021.

[18] ISRO, "Department of Space demonstrates entanglement based quantum communication over 300m free space along with real time cryptographic applications." January 31, 2022.

[19] Government of India, Press Information Bureau, "DRDO and IIT Delhi scientists demonstrate Quantum Key Distribution between two cities 100 kilometres apart." February 23, 2022.

In addition, as continuous wavelengths are difficult to synchronize compared to pulsed sources when it comes to satellite communications, the Raman Research Institute is researching infrared communication with wavelengths of 800–900 nm, rare in teleportation. The aim is to develop a cost-effective way of detecting photons.

Table 4-5: Main research outcomes and trends in quantum encryption and quantum key distribution (QKD)

Implementation period/ Main organization	Overview
June 2020 Raman Research Institute (RRI)	The **Raman Research Institute (RRI) announced qkdSim, an end-to-end QKD simulation toolkit.**[20] This was developed jointly by Professor Urbasi Sinha' s team and the University of Calgary (Canada). This toolkit covers the different experimental imperfections in various devices and processes, and makes it possible to reproduce actual phenomena with high accuracy. It is one of the outcomes of the satellite quantum communication project led by ISRO.
December 2020 DRDO	**DRDO' s Young Scientist Laboratory for Quantum Technologies (DYSL-QT) developed a quantum random number generator (QRNG).**[21] It uses a fiber-optic branch path, and met the NIST international standards with a speed of 150 kbs.
December 2020 DRDO	**DRDO succeeded in QKD communication.**[22] It carried out a test between two laboratories, the Defence Research & Development Laboratory (DRDL) and the Research Centre Imarat (RCI), and demonstrated secure communication via QKD. The QKD technology was developed by two Indian laboratories associated with defense, the Centre for Artificial Intelligence & Robotics (CAIR) in Bengaluru and the DRDO Young Scientist Laboratories with Cognitive Technologies (DYSL-CT).
December 2021 Indian Army	With the support of the National Security Council Secretariat (NSCS), the **Indian Army has set up a Quantum Computing Lab and Artificial Intelligence Centre in the Military College of Telecommunication Engineering (MCTE) in Mhow, Madhya Pradesh.**[23] It is mainly promoting quantum key distribution, quantum communication, quantum computing, and post-quantum cryptography.
October 2021 C-DOT	The **Centre for Development of Telematics (C-DOT)**, a research institution belonging to India' s Ministry of Communication, **established a Quantum Communication Lab and unveiled its original quantum key distribution solution**, which can support a distance of more than 100 km via standard optical fiber.[24]

[20] Government of India, Press Information Bureau, "RRI comes up with simulation toolkit to ensure safety in secure quantum communication platforms." June 30, 2020.

[21] Government of India, Press Information Bureau, "DRDO Young Scientists Laboratory Develops Quantum based technology for Random Number Generation." December 29, 2020.

[22] Government of India, Press Information Bureau, "Quantum Communication between two DRDO Laboratories." December 9, 2020.

[23] INDIAai, "Indian Army sets up quantum computing lab and AI centre in MP." December 30, 2021.

[24] Government of India, Press Information Bureau, "Secretary Telecom Shri K. Rajaraman visits C-DOT; Inaugurates futuristic Quantum Communication Lab Indigenously developed Quantum Key Distribution (QKD) solution by C-DOT unveiled QKD) solution can support a distance of more than 100 kilometers on standard optical fiber Development of indigenous QKD solution is essential to address security threats of data posed by rapid advancement in Quantum Computing." October 10, 2021.

In addition to this, in July 2021, the Quantum Ecosystems Technology Council of India (QETCI) was founded as an NPO at the National Quantum Science and Technology Symposium held online by IIT Hyderabad, PSA and other organizations. QETCI aims to accelerate the quantum ecosystem in India by ensuring collaboration with various members of the quantum ecosystem that straddles the government, academia, industry, emerging companies, and investors. In August 2022, it launched the Quantum Science and Technology Hackathon 2022 in partnership with the Office of Principal Scientific Adviser, IEEE, AWS and Microsoft, with the goals of quantum ecosystem development, skill development, and solving the issues faced by people in quantum science and technology.

4.3 Notable research institutions and universities

While the funding needed for quantum research is invested through governmental support, the quantum research community has also diversified. RRI's Quantum Information and Computing Lab (QuIC) is one research group that became involved with optical quantum technology such as single photons and quantum entangled photons early on. This lab also focuses on areas such as quantum communication, quantum computation, quantum foundations, and quantum information processing. The Institute of Mathematical Sciences in Chennai and HRI are focusing their efforts on theoretical research in quantum information and quantum optics. Research institutions such as IISc, IISER Mohali, IIT Mumbai, and IIT Madras are engaged in research from both experimental and theoretical perspectives.

In Mumbai, the efforts of TIFR and IISER Pune are going into experimental research on qubits. TIFR in particular has a superconducting qubit experiment group led by Professor Vijayaraghavan. IISER Pune has a specialist experiment group researching NMR based qubits and ion trap systems. The Indian government has set up the I-HUB, a technological innovation hub for quantum technology, in IISER Pune. Including those not listed here, there are currently 40–50 universities engaged in quantum technology research.

The following shows noteworthy institutions by name in alphabetical order.

4.3.1 Harish-Chandra Research Institute (HRI)

This institution is located in Allahabad, Uttar Pradesh, specializing in research in math and theoretical physics. It has more than 30 faculty members, 80 graduate students and 30 postdoctoral fellows. It receives financial support from the Indian government's Department of Atomic Energy. Its Physics Group is made up of five subgroups: astrophysics, condensed matter physics, high energy physics, quantum information and computation, and string theory.

Notably, the Quantum Information and Computation (QIC) group led by Professor Ujjwal Sen and Aditi Sen De, who has the most papers and citations in India, is carrying out theoretical research on quantum information and computation, including quantum algorithms, quantum communication, quantum cryptography, and quantum entanglement theory. In recent years, it has worked on the interface between quantum information and many-body system physics, and quantum computers in ultra-cold gases or quantum optical systems.

Moreover, the Condensed Matter Group is conducting research on field theory techniques in condensed matter physics, quantum liquids, heavy fermions, mesoscopic systems, and quantum Monte Carlo methods for spintronics and electronic structure.

4.3.2 Indian Institute of Science (IISc)

In 2018, the Indian Institute of Science (IISc) in Bengaluru was acknowledged by the Indian government as an Institute of Eminence, and through its support launched the Quantum Technology Initiative in September 2020. It established the interdisciplinary Center for Excellence in Quantum Technology (CEQT) to simultaneously make use of the specialist knowledge of the Institute in the quantum technology field and to create technology that will yield economic benefits and social impact with the proactive involvement of the world of industry and strategic partners. Its diverse faculty work together to form India's second-largest quantum technology research and development group after the Indian Institute of Science Education and Research, Pune.[25]

CEQT, led by Professor Apoorva Patel, carries out research from both theoretical and experimental perspectives. Its experimental program focuses on superconducting qubit devices, single photon sources and detectors for quantum communication, integrated photonic quantum networks, and quantum sensors. The theoretical initiatives that support the experimental program include, in particular, quantum algorithms and simulations and post-quantum cryptography. Dr. Patel's team have the important role of developing QSim, a quantum computer simulation toolkit launched by MEITY in August 2021. IISc is ranked as the top Indian research institution in Nature Index.

4.3.3 Indian Institute of Science Education and Research, Pune (IISER Pune)

The Indian Institute of Science Education and Research, Pune (IISER Pune) is a research-intensive education and research institution founded in Pune in 2006. It offers 5-year master's programmes and PhD programmes. It has over 130 faculty members, more than 130 staff members, and more than 1,600 students of master's level or more. It offers PhD programmes for biology, chemistry, earth and climate sciences, humanities and social sciences, mathematics, and physics. Pune has long been a center of education and research, and is known as "India's Oxford". It is currently experiencing extraordinary development, especially in the IT industry, and hosts the headquarters of many IT-related companies.

IISER Pune carries out research in a variety of quantum technology fields, including quantum information, field theory, quantum materials, quantum optics, quantum control, and quantum chemistry; it possesses India's largest faculty connected with quantum technology.[26] In addition to theoretical groups for quantum chaos and quantum information, it also has experimental groups focused on researching both NMR-based quantum computation and ion-trap systems.

[25] QKRISHI, "Top Universities in Quantum Technologies in India." September 27, 2021.
[26] See note 25.

In April 2021, the I-HUB Quantum Technology Foundation (I-HUB) was founded at IISER Pune with support from DST, based on the NM-ICPS Program. I-HUB is a non-profit business belonging to IISER, and is mainly led by the faculty of its physics department; its goal is to develop quantum computers that can be used on a day-to-day basis and new quantum technology, and it aims to develop advanced computer systems and apply these for more familiar purposes, including precision sensors, navigation devices for global positioning systems, geological mapping, atomic clocks, encrypted communications, and new materials. Thirteen research groups from IISER Pune participate in I-HUB, and it intends to create a network with over 20 Indian research institutions and several foreign universities and research institutions. Project Director Umakant Rapol aims to develop a 10–30-qbit quantum computer within 5 years. I-HUB has been assigned 1.7 billion rupees (20.4 million USD) over five years, with approximately 800 million rupees (0.96 billion USD) given in 2021. It also provides support for technology transfer, incubation, and human resources development.[27]

4.3.4 Indian Institute of Technology Madras (IIT Madras)

IIT Madras has the third-most researchers of quantum technology in India,[28] with active quantum research in its Physics and Electrical Engineering departments. Its physics department carries out experiments, with emphasis on constructing a quantum memory and quantum sensors based on the diamond NV-center. On the other hand, the Electrical Engineering department has a group focusing on photonics-based quantum communication and quantum computational architecture, which has succeeded in demonstrating a QKD protocol using phase-encoded weak coherent pulses; this is expected to form the building blocks of a secure quantum communication network. On the theory front, IIT Madras has a large research group that covers various aspects of quantum computing and quantum information theory including quantum error correction, quantum entanglement, quantum chaos, and quantum metrology. The group also works on condensed matter theory and quantum optics, making it one of the most diverse groups in the country.[29] The Institute has also founded a new Centre of Excellence (the Centre for Quantum Information, Communication and Computing (CQuICC)) dedicated to quantum computation, quantum information theory, and quantum materials.

Professor Anil Probhakar of the Electrical Engineering department is one of the founders of the later-mentioned QKD startup, QNu Labs.

4.3.5 Raman Research Institute (RRI)

This research institute in Bengaluru was founded by C. V. Raman, winner of the Nobel Prize in Physics, in 1948. It was initially privately owned by C. V. Raman, but its funding is now provided by India's Department of Science and Technology (DST). It is split into four research areas: Astronomy and Astrophysics, Light and Matter Physics, Soft Condensed Matter, and Theoretical Physics.

[27] THE TIMES OF INDIA, "Quantum tech hub with 13 research groups at IISER." April 17, 2021.

[28] See note 25.

[29] DWHI NEW DELHI, "INDIA: MAKING STRIDES IN THE SECOND QUANTUM REVOLUTION." Last accessed: August 1, 2022

In 2012, the Quantum Information and Computing Laboratory (QuIC) launched by Professor Urbasi Sinha of the Light and Matter Physics Group carried out research focusing on optical quantum science and technology, becoming one of the first research labs in India to create a single-photon source in a quantum entanglement state and to establish ways of using them.[30] Its research fields include free space, fiber, quantum key distribution (QKD) through integrated photonics, quantum teleportation, experimental secure quantum communication including device-independent random number generation, photonic quantum computers, and research on the static and dynamic characteristics of quantum entanglement. In 2020, QuIC developed India's first free-space QKD protocol. It was also involved in the development of a complete end-to-end simulation toolkit called qkdSim.[31] In the same year, it succeeded in developing and experimentally demonstrating a new quantum state estimation protocol using quantum interference, one of its other major outcomes.[32]

The RRI is currently leading three key projects. A funding project started in 2017 with the Indian Space Research Organisation (ISRO) regarding India's first satellite long-distance quantum communication led to QuIC demonstrating quantum communication between two structures 50 m apart in February 2021, before ISRO verified quantum communication in free space over 300 m in March 2021. This experiment made use of quantum key distribution technology. In addition, RRI is implementing a project on fiber-based quantum communication, part of DST's QuEST program, and a project on quantum key distribution based on integrated photonics systems, which is part of the India-Trento Programme on Advanced Research (ITPAR) being carried out between India and Italy.

4.3.6 TATA Institute of Fundamental Research (TIFR)

TIFR is a national research center that falls under the umbrella of DAE, and an educational institute that awards master's degrees and doctorates. It was founded based on the ideas of Homi Bhabha with support from the Sir Dorabji Tata Trust in 1945.[33] TIFR carries out basic research in physics, chemistry, biology, mathematics, computer science, and the field of science education. It has campuses in Pune, Bengaluru, and Hyderabad, in addition to the main campus in Mumbai. Nature Index ranks it third among the research institutions in India.

The main research fields of its Quantum Measurement and Control Laboratory (QuMaC) led by Dr. R. Vijayaraghavan include quantum error correction, quantum simulation, the design of new qubits, quantum-limited parametric amplifiers, and quantum weak measurement. It receives funding from the QuEST program to carry out research to scale-up quantum processors using superconducting circuits. It is researching transmon qubits, and has recently developed a quantum processor in which three qubits all couple with each other, and clarified its properties.[34] It is currently cooperating with DRDO and major Indian IT service company Tata Consultancy

[30] See note 29.

[31] R. Chatterjee, K. Joarder, S. Chatterjee, B. C. Sanders and U. Sinha (2020) "qkdSim: An experimenter's simulation toolkit for QKD with imperfections, and its performance analysis with a demonstration of the B92 protocol using heralded photons," *Physical Review Applied* 14, 024036.

[32] S. N. Sahoo, S. Chakraborti, A. K. Pati, and U. Sinha (2020) "Quantum State Interferography," *Physical Review Letter* 125, 123601.

[33] Tata Institute of Fundamental Research, "History and Vision." Last accessed: June 10, 2022

[34] Tanay Roy, Sumeru Hazra, Suman Kundu, Madhavi Chand, Meghan P. Patankar, and R. Vijay "Programmable Superconducting Processor with Native Three-Qubit Gates," Physical Review Applied 14, 014072.

Services, which is engaged in the development of quantum algorithms, and is aiming to develop a 7-qubit processor.[35] It has already used broad funding support from NM-ICPS and DST to establish circuits that behave like artificial atoms, with the goal of building and controlling a quantum system.

4.4 Notable companies

India has seen many companies and startups begin to enter software and hardware development for quantum computing, in addition to globally famous high-tech companies such as IBM and Microsoft. These include Qulabs, India's first quantum computing startup; QpiAI tech, based in Bengaluru; QNu Labs, which is focusing on secure quantum encrypted products; Quantica Computacao, based in Chennai; BosonQ, Automatski, and Taqbit Labs, based in Bhilai; and QRDLab based in Kolkata. Various initiatives promoting research, education, and consulting in the quantum computing field are going ahead, and it is said that at least 15 startups are being launched in India.[36] This section provides details on five particularly noteworthy companies below.

4.4.1 QNu Labs

This is India's first startup focused on quantum encrypted products, established by IIT Madras. Professor Anil Probhakar of IIT Madras started this company in 2016, and is involved as a technical advisor. It has around 40 members, and is based in Bengaluru. QNu Labs provides a quantum security platform for random number generators, quantum key distribution devices, and key management. Its main targets are industries such as banking, communications, IT infrastructure, defense, and OEM (original equipment manufacturers), and it creates quantum technology to ensure the security of IoT devices, POS devices, and mobile devices. It has more than 15 client companies, and its expected revenue for 2022 is 2 million USD.

4.4.2 QpiAI

QpiAI was founded in 2019 by CEO Nagendra Nagaraja, who obtained his doctorate in machine learning and AI from Coventry University in the UK. It has over 10 client companies, and its predicted revenue for 2022 is 2 million USD. It has several associated companies, and is promoting technological innovation in several fields—not just quantum technology, but also AI, nanotechnology, superconductivity, materials, superconducting motors, and solid-state batteries/quantum batteries. QpiAI provides an AI modelling platform, an AI and quantum marketplace, and a quantum modelling platform that uses AI, as well as developing classical and quantum hybrid computer chips and offering solutions to various optimization problems. In May 2021, it held an AI/quantum certification program with IISc. Over 8,000 people registered, and around 300 attended the classes. In April 2022, it came to an agreement with QuantrolOx, a spinout startup from the University of Oxford with a base in Finland, to develop

[35] Analytics India Magazine, "India fast-tracks quantum research, joins hand with Finland." April 29, 2022.
[36] See note 6.

a testbed for a 25-qubit quantum computer and to provide quantum solutions for Europe, India and Asia.[37] It also plans to open a new office in Finland.

4.4.3 Qulabs.ai

This is India's first quantum computing startup. Established in 2017, it has bases in Hyderabad, Kolkata, and New Jersey, as well as joint research labs with IIT Hyderabad, IIT Kharagpur and IIT Roorkee. Its aim is to provide services such as quantum machine learning, quantum communication, quantum computation, quantum algorithms, and simulations. It has 25 researchers and an interdisciplinary group consisting of researchers and engineers from the IITs, ISI, and IISc. This startup has also set up the QuAcademy, which provides training, development, and bridge-building for new quantum technologies.

4.4.4 Automatski

This research and development company has bases in Los Angeles, New York, London, and Bengaluru. It carries out research in several fields, and quantum computing is one of these. It was founded in London in 2014, and set up a base in India in 2016. Its research concerns various forms of software and simulators associated with quantum computational modelling, including circuit model quantum computation, adiabatic quantum computation, and quantum annealing. In 2018, it released a 100,000+-qubit adiabatic quantum computer and annealing quantum computer.[38]

4.4.5 BosonQ Psi

This company was set up in Bhilai, Chhattisgarh in August 2020 by Abhishek Chopra and Rut Lineswala from Rutgers University's Aerospace Engineering course (in the U.S.). It aims to contribute to the fields of aerospace, automobiles, power generation, chemical production, polymer processing, oil exploration, medical research, meteorology, and astrophysics by developing world-class quantum software solutions for computational fluid dynamics, computational structural dynamics, computational heat transfer, multidisciplinary optimization, computational aeroacoustics, and more.

[37] Businesswireindia, "QpiAI and QuantrolOx Sign a MoU to Jointly Develop India's First 25-Qubit Quantum Computing Testbed and Offerings for the European and Indian Markets." April 13, 2022.

[38] Automatski, "QUANTUM COMPUTING." June 13, 2022.

4.5 Notable researchers

The noteworthy researchers here were selected with consideration for their position in the Indian quantum research community and research awards, based on the data on papers and patents in Chapter 1.

4.5.1 Urbasi Sinha

Proponent of the quantum national missions. Gained her doctorate through research on high-temperature superconductivity at the University of Cambridge, and after becoming a postdoctoral research fellow at the Institute for Quantum Computing in the University of Waterloo (Canada) in 2007, took up the position of Associate Professor of Light and Matter Physics at the Raman Research Institute in Bengaluru in 2012. Now leading the Quantum Information and Computing (QuIC) Laboratory, the first lab in India to focus on optical quantum science and technology, as a professor. Also an Associate Professor of the Centre for Quantum Information and Quantum Control, Toronto University and the Institute for Quantum Computing, University of Waterloo. Homi Bhabha Fellow from 2017 to 2019, and a Simons Emmy Noether Fellow at Canada's Perimeter Institute since 2020. In 2019, selected by Asian Scientist as one of the top 100 researchers in Asia.[39] leading India's first satellite quantum communication project, which is being carried out jointly with ISRO. Currently interested in the following themes: experimental quantum information, quantum computing, experimental research on quantum encryption, research on quantum entanglement, quantum key distribution using satellites for a quantum Internet, single-photon sources, polarization and entangled photon sources based on new degrees of freedom.

4.5.2 Rajamani Vijayaraghavan

Associate Professor of the Department of Condensed Matter Physics & Materials Science, Tata Institute of Fundamental Research (TIFR), and leading the Quantum Measurement and Control (QuMaC) Laboratory. Obtained his doctorate in applied physics at Yale University in 2008. After working as a doctoral researcher at the University of California, Berkeley, joined TIFR's superconducting qubits group in 2012. Researching transmon qubits, and recently developed a 3-qubit quantum processor and clarified its properties.[40]

4.5.3 Umakant Rapol

leading the atomic physics and quantum optics group as an Associate Professor of IISER Pune. Engaged in fundamental research using ultracold atoms and ions, and research on quantum technology. His current research is focused on using coherent quantum materials for quantum sensing, quantum simulation, and precision measurement. After obtaining his doctorate at IISc in Bengaluru in 2003, served as a visiting researcher at the École normale supérieure in Paris and the University of Innsbruck in Germany. Worked on research and development for

[39] Asian Scientist, "2019 Edition Of Asian Scientist 100 Announced." March 4, 2019.

[40] See note 34.

around four years at GE Research Bangalore, before taking up his current post in 2009. Also the Project Director of the I-HUB, the non-profit company set up in IISER Pune by DST through NM-ICPS.

4.5.4 Ujjwal Sen

leading researcher, top-ranked in terms of his number of papers and number of citations. Professor of the Quantum Information and Computation (QIC) Group, Physics Faculty, Harish-Chandra Research Institute. Specializing in quantum information computation and its interface with many-body physics, and researching quantum computation through interactions with quantum entanglement, quantum information, ultracold gases, condensed systems, and quantum optics. Worked at this institute in the Physics Faculty since July 2009, after receiving his doctorate in physics (Institute of Theoretical Physics and Astrophysics, University of Gdańsk in Poland).

4.5.5 Aditi Sen De

Researcher, the first woman to receive the Shanti Swarup Bhatnagar Prize for Science and Technology, awarded for outstanding research in India, in the field of physics in 2019, for her research on quantum information communication. Also ranked top in terms of the number of papers and number of citations. Studied physics with her husband Ujjwal Sen, Professor of the same Quantum Information and Computation (QIC) Group, at the University of Gdańsk in Poland, which was a global hub for quantum entanglement theory at the time, and obtained her doctorate in 2004. Moved to the Harish-Chandra Research Institute with Ujjwal Sen in 2009, and launched the QIC Group as a Professor of the Physics Faculty. Made great contributions to understanding quantum information and communication, especially computable quantum entanglement measurement and the formulization of a new density matrix recursive method. Her fields of interest include quantum channel theory, the security of quantum encryption, and the quantification of quantum correlation.

4.6 International cooperation and joint research

India's quantum research policy faces two major challenges: improving its R&D capabilities to ensure innovation, and creating infrastructure such as human resources and R&D environments. It is strongly promoting human resource development through various policies, and, meanwhile, is proactively encouraging international cooperation with technologically advanced countries to effectively improve its R&D capabilities in its limited research community. This section lists the specific status of cooperation with different countries in order of time, from oldest to newest.

(1) Italy

Phase 4 of the India-Trento Programme for Advanced Research (ITPAR), being carried out by DST and the University of Trento, is seeing the implementation of a QKD project (started in 2019) based on integrated photonics systems by Professor Sinha (RRI).[41]

(2) France

In August 2019, the governments of both countries agreed to technical cooperation in quantum and AI. The Quantum Computing Experience Centre was set up in the headquarters of C-DAC in Pune, and the French IT services company Atos provided a commercial Quantum Learning Machine as well as the relevant resources and training, supporting quantum education in India.[42]

(3) Israel

In 2019, DST and Israel's MOST called for applications for joint research projects on next gen solar energy and quantum devices (sensing, communication), and selected eight two-year projects. They are supporting each project with 40 million rupees (0.012 million USD),[43] [44].

Moreover, in April 2022, DRDO worked with IIT Delhi to hold a bilateral workshop with Israel, with the aim of creating a joint quantum technology roadmap and technological development plan for both countries with Israel's Directorate of Defense Research and Development (DDR&D). They discussed photonics-based quantum computing, sensing, encryption, quantum magnetometry, atomic clocks and free space quantum communication. Institutions such as IISc, TIFR, IIT Mumbai, IIT Madras, IIT Kanpur, IIT Kharagpur, IIT Tirupati, ISER, C-DAC, and C-DOT participated.[45]

(4) BRICS

The 2019 call for applications for the BRICS STI Framework Programme[46] saw photonic quantum technology as one theme, and a joint project ("Quantum Satellite and Fibre Communication") between the four countries of India, Russia, China, and South Africa was selected.[47] It plans to construct am intercontinental satellite quantum communication channel of over 10,000 km using optical fiber. India is responsible for modelling the quantum fiber communication.

(5) Australia

The 12.7-million ASD (around 8.51 million USD, when 1 ASD = 0.67 USD) Australia-India Cyber and Critical Technology Partnership (AICCTP) was established based on the Australia-India Comprehensive Strategic Partnership between each country's ministry for foreign affairs, agreed at a summit meeting in June 2020. The

[41] Professor Sinha's website, "Research."
[42] See note 12.
[43] DST, "Annual Report2020-2021."
[44] DST, "INDIAN-ISRAELI JOINT RESEARCH COOPERATION Call for Project Proposals 2020-2022."
[45] Government of India, Press Information Bureau "Indo-Israel bilateral workshop on Quantum Technologies concludes."
[46] DST, "2019 BRICS Calls for Proposals for Multilateral R&D."
[47] DST, "Provisional List of scientifically recommended Projects for BRICS CALL 2019 under BRICS STI Cooperation."

AICCTP is to be implemented between 2020 and 2024, with companies and researchers from both countries providing funding to carry out joint research on AI, quantum computing, promoted technologies such as robotics, and key technologies. It aims to contribute to the formation of a global technological environment that conforms with the vision common to both countries—of an open, free and rule-based Indo-Pacific region. Two calls for applications have taken place so far, and when it comes to projects concerning quantum technology, the following have been selected: a project on the development of ethical frameworks and best practice for emerging quantum technologies, by the University of Sydney and ORF for round 1 (February 2021), and a project by Victoria University with the Gujarat National Law University, "Cross Border Data Flows Between Australia and India - understanding the legal, policy and ethical standards for data, cyber security, AI, quantum and new technologies" for round 2 (January 2021). The third round is expected to take place in September 2022.[48]

(6) Russia

IIT has 23 colleges across India, including IIT Madras and IIT Mumbai, which lead quantum technology research in India. The IIT Alumni Council has the world's largest network of graduates, made up of the graduates from these 23 colleges, and signed an MOU with Lomonosov Moscow State University (MSU) in Russia and RUSSOFT, Russia's association of software developer companies, in August 2020, to receive key technology transfer, with the aim of building the world's largest and fastest hybrid quantum computer in India. Russia's state-run businesses, the IP owners, are expected to transfer key modules such as cryogenic technology, encryption technology, and modularized cloud management technology to the IIT Alumni Council.[49]

(7) EU

At the India-EU summit meeting in May 2021, the EU and India agreed the early operationalization of the Joint Task Force on Artificial Intelligence and further expansion of technological cooperation, especially concerning on quantum and high performance computing.[50] Moreover, the India-EU summit meeting held in April 2022 ensured the launch of the India-EU Trade and Technology Council. This is a strategic mechanism to deepen mutual cooperation and tackle common problems in trade, technology, and security due to the changes in the geopolitical environment. It is not clearly stated in the joint release,[51] but India hopes that, on top of 5G and AI, discussions will move ahead with this framework for quantum computers.[52]

(8) Finland

At a virtual summit held between government leaders from Finland and India in March 2021, quantum technology and quantum computers were noted to be a field in which stronger bilateral cooperation is anticipated. In April 2022, both governments agreed to establish an Indo-Finnish Virtual Network Centre on Quantum Computing, and will create a mechanism to connect the research institutions and companies within each country, led by India's

[48] Department of Foreign Affairs and Trade, "Australia-India Cyber and Critical Technology Partnership Grants." April 22, 2022.
[49] Adda247「IIT Alumni Council signs MOU with Russia for building Quantum Computers」August 28, 2020.
[50] Council of the European Union, "Joint Statement EU-India Leaders' Meeting." May 8, 2021.
[51] European Commission press release, "EU-India: Joint press release on launching the Trade and Technology Council." April 25, 2022.
[52] Hindustan Times, "India, EU launch new body to tackle challenges in trade, tech," April 25, 2022.

DST and the Ministry of Economic Affairs and Employment of Finland. IIT Madras, IISER Pune, and C-DAC are expected to participate. Product-orientated research collaboration will be implemented through industry and academia.[53]

(9) Japan

When it comes to the relationship between Japan and India, the Japan-India Joint Summit Statement "Partnership for a Peaceful, Stable and Prosperous Post-COVID World"[54] created during Japanese Prime Minister Fumio Kishida's visit to India in March 2022 included quantum communication as a field to promote collaboration between the two countries.

With this, the seventh meeting of the Japan-India Joint Working Group based on the Japan-India ICT Comprehensive Cooperation Framework, held online in May 2022, discussed 5G/Beyond 5G, and submarine cable systems, as well as strengthening the cooperative relationship regarding quantum communication. Moreover, in April 2022, Fujitsu Limited established a base in Bengaluru, with the aim of gaining outstanding human resources from India and accelerating R&D, especially the development of AI and quantum software.

(10) Canada

On May 19, 2022, Canada and India held the seventh India-Canada Joint Science and Technology Cooperation Committee meeting in Ottawa, where they renewed two MOUs signed by DST with the Natural Sciences and Engineering Research Council of Canada (NSERC) and the National Research Council Canada (NRC) respectively. The key fields here include the National Missions, quantum computers, artificial intelligence (AI), and cyber-physical systems, and it is hoped that this will encourage joint research between the two countries.[55]

(11) U.S.

On May 24, 2022, when the Quad Leaders' Summit meeting took place in Tokyo, Prime Minister Modi engaged in bilateral discussion with American President Joe Biden regarding the launch of the India-U.S. initiative on Critical and Emerging Technology (iCET). iCET, which is jointly led by the National Security Council Secretariat in India and the U.S. National Security Council, focuses on AI, 5G/6G, and biotechnology as well as quantum computers, and is excepted to further collaboration between the governments, academia and industries of the two countries.[56]

[53] Government of India, Press Information Bureau, "Visiting Finland Minister of Economic Affairs Mika Lintila meets Union Minister of State (Independent Charge) Science & Technology, Dr Jitendra Singh: The two Ministers announce the decision to establish an Indo-Finnish Virtual Network Centre on Quantum Computing." April 18, 2022.

[54] Ministry of Foreign Affairs, Japan-India Summit Joint Statement, "Partnership for a Peaceful, Stable and Prosperous Post-COVID World." March 19, 2022.

[55] Government of India, Press Information Bureau, "Renewed MoUs articulate new strategic direction for Indo-Canada S&T co-operation" May 23, 2022.

[56] Ministry of External Affairs of India, "Prime Ministers meeting with President of the United States of America." May 24, 2022.

4.7 Quantum innovation ecosystem

Rapid increase can be observed in the number of organizations involved in the quantum innovation ecosystem in India; it is said this includes governmental organizations (10–15), universities (40–50), service providers (15–20), and startups (15–20).[57] Figure 4-1 shows the main organizations mentioned in this chapter.

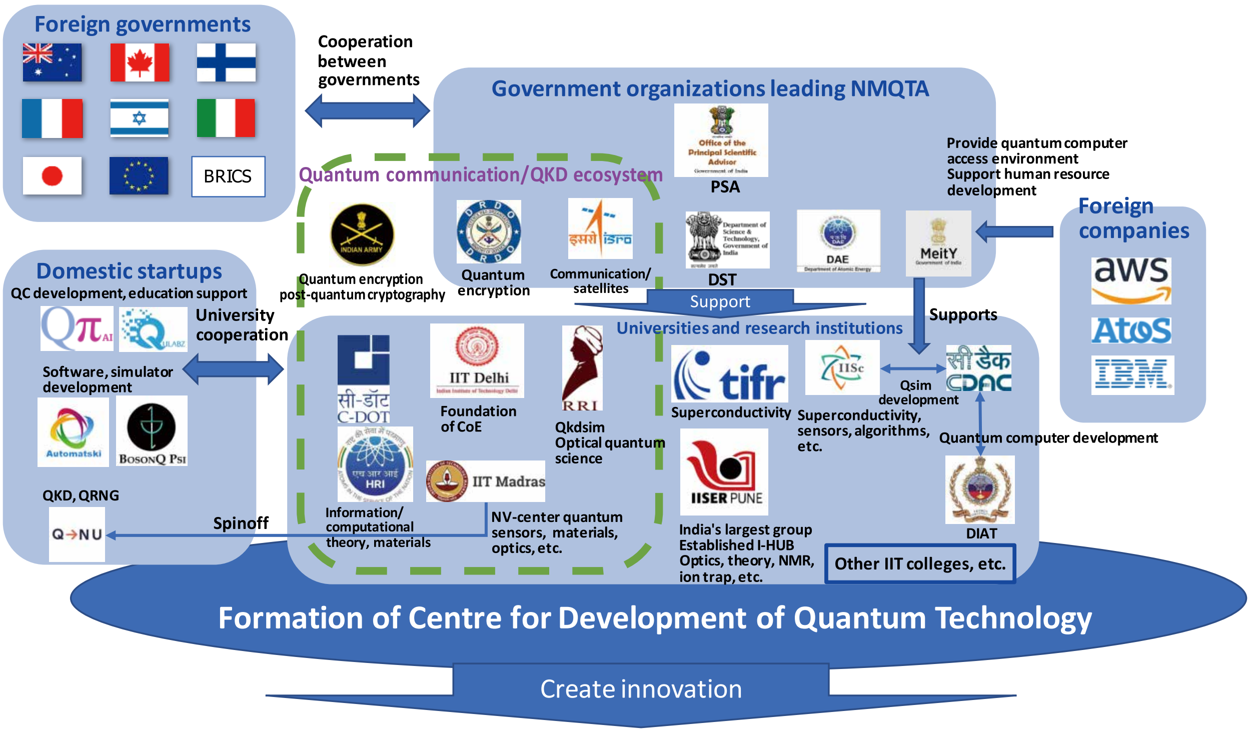


Figure 4-1: India's quantum innovation ecosystem

Source: Prepared by APRC

[57] See note 6.

5 Quantum technology trends in Australia

Through its universities, Australia has been conducting extensive high-level basic research since the beginning of the 1990s, and has built the foundations for quantum technologies. Centres of Excellence (CoEs) specializing in quantum technology began being built in 2011, with this focus, including in applied research, intensifying over the years. A number of university-funded startups have also launched. With support from CSIRO, companies are developing and endeavoring to commercialize services and equipment that will serve as industrial infrastructure. The government is also providing ongoing and substantive support at all levels. A national quantum strategy is currently being drafted by the federal government.

5.1 Quantum technology policy

Since the emergence of the second generation of quantum technologies in the 1990s, Australia has played an important role in advancing these technologies. According to Roberson and White, the basic research for these technologies has followed mainly two paths: quantum optics research led by professors Hans Bachor of Australian National University and Gerard Milburn of the University of Queensland (and Australian National University prior to that), and condensed matter physics research spearheaded by Professor Robert Clerk of the University of New South Wales.[1] At the beginning of the 1990s, both the National Magnet Laboratory and Semiconductor Nano Fabrication Facility were established as quantum technology research institutes.

Although there was at first no interaction between quantum engineering and condensed matter physics, the end of the 20th century saw that Bruce Kane (then a postdoctoral researcher at the University of New South Wales) wrote a paper on silicon-based quantum computing while the aforementioned James Milburn et al. proposed theories on quantum computing that utilized linear optics. This led to the establishment of the Australian Research Council Special Research Centre for Quantum Computer Technology (CQCT).

This accumulation of basic research is thought to have underpinned the commercialization of today's applied research and technologies, and could be said to have been a factor behind Australia's becoming a world leader in research and development capabilities.

2003 saw the launch of Centres of Excellence (CoEs) as a funding program led by the Australian Research Council (ARC), and these CoEs became centers for research and development in key fields.[2] In quantum physics, Milburn's laboratory received 24.5 million AUD (approxmately 1.67 million USD at a rate of 1 AUD = approximately 0.68 USD) for the ARC Centre of Excellence for Engineered Quantum Systems, launched in 2011. This funding concluded in 2018. This prompted the development of one more CoE in 2014 and five more in 2017, all of which are currently engaged in research and contributing to the modern picture of quantum physics.

1 Roberson, T.M. and White, A.G. (2019) "Charting the Australian quantum landscape," *Quantum Science and Technology*, 4, 020505. Professors' affiliations may have since changed.

2 Australia "ARC Centres of Excellence."

In the latter half of the 2010s, as quantum markets rapidly matured, Australia hammered out a quantum strategy out of a growing fear that it would fall behind the competition unless it redoubled its efforts in quantum research and development. Part of this national innovation strategy, the 2015 National Innovation and Science Agenda stated that it would establish the Cyber Security Growth Centre, which would build silicon quantum circuits through 26 million AUD (approx. 17.7 million USD) in funding.[3] The Cyber Security Growth Centre was rebranded as "AustCyber"[4] in 2017 as part of Australia's industrial growth strategy, and over 230 companies and experts now work to achieve its mission.

In recent years, related government organizations have released a series of roadmaps that have guided their efforts to strengthen Australia's quantum capabilities, with the federal government providing core support.

In May 2020, the Commonwealth Scientific and Industrial Research Organization (CSIRO) announced "Growing Australia's Quantum Technology Industry," a roadmap for industrializing quantum technologies. According to the "2040 Vision for Australia's Quantum Technology Industry" laid out in the roadmap, Australia expects the global market for quantum technologies to grow roughly 400% over 18 years beginning in 2012, and to be worth 86 billion AUD (58.5 billion USD) by 2040. CSIRO notes that quantum sensing/measurement (metrology), quantum computing, and quantum communications could be utilized in four fields of industry, namely healthcare, defense, natural resources, and financial services.

Recognizing that Australia has made some of the world's greatest research achievements over the past 20 years in the field of quantum technology, the CSIRO roadmap seeks to defend that position and compete to industrialize quantum technologies amid a rapid maturing of this field. This was followed by the establishment of a platform within CSIRO (see below) in 2021. On the other hand, the roadmap also points to ongoing issues to be addressed in formulating a growth strategy, including the balance between technical support and the pursuit of business opportunities, the balance between basic research and applied research, methods of industry-academia cooperation, and response to societal issues.

Quantum technologies are heavily emphasized in the roadmap, even more than other technologies. On November 17, 2021, then Prime Minister Scott Morrison announced the Blueprint for Critical Technologies, which outlined nine technologies of focus for the Australian government, quantum technologies being among them.[5] A plan to invest 111 million AUD (75.5 million USD) to commercialize and utilize these technologies was also announced. To help provide domestic companies with access to new markets and investors, the government established a quantum investment hub with 70 million AUD (47.6 million USD) in funding. The hub promotes strategic partnerships with like-minded countries and coordinates initiatives with industry and government. It also plans to attract further private investment in the course of formulating the National Quantum Strategy.

[3] Australian Federal Government, "National Innovation and Science Agenda," 2015.

[4] See the website of the Australian Federal Government for an overview and the website of Australia's Department of Industry, Science and Resources for details.

[5] The main technologies of focus pertain to critical minerals extraction and processing; advanced communications (including 5G and 60); artificial intelligence; cyber security technologies; genomics and genetic engineering; novel antibiotics, antivirals, and vaccines; low emission alternative fuels; quantum technologies; and autonomous vehicles, drones, and swarming and collaborative robotics.

In terms of security applications, Australia's Department of Defence released the 2016 Defence White Paper in which it pointed to the possibility of deploying quantum computing toward innovative weapon production and supersonic weapons, directed energy weapons, unmanned systems, etc., as well as the development of new weapons over the next 20 years (p.52, 2.43). The Defence Science and Technology Strategy 2030 makes mention of plans to use quantum technologies for position navigation and timing (PNT) in conflict scenarios[6]. The Australian Army also released its own quantum technology roadmap in April 2021.

Regarding the use of quantum technologies for infrastructure development, the 2021 National Research Infrastructure Roadmap National Infrastructure, released by Australia's Department of Education, Skills and Employment on April 7, 2022, cites the necessity of high-performance computing (HPC), exascale computing, quantum computing, big data, and non-commercial cloud services (such as Nectar Research Cloud, AARNet CloudStor) as technical infrastructure that will be necessary in the future.

Australia has had no systematic national strategy for the past 30 years[7], and this remains the case as of the timing of this report, however, these technologies are expected to contribute to social safety and prosperity by delivering their benefits to society[8]. This prompted the federal government to release the National Quantum Strategy Issues Paper, for which it conducted public hearings from April 6 to June 3, 2022, and compile opinions from a broad swath of stakeholders from industry, academia, and government[9]. A national Quantum strategy is currently being formulated under the leadership of Chief Scientist Dr. Cathy Foley[10], and it was announced on September 23, 2022 that the National Quantum Advisory Committee would be established and staffed by 15 experts from industry, academia, and government who were well-versed in areas such as research and development, commercialization, investment, supply chains, and national security[11].

5.2 Quantum technology research and development

The analysis of quantum technology-related research papers and patents in Chapter 1 shows that Australia ranks fourth among Asia-Pacific region nations for research papers (4,223 papers) and third for patents. The largest category among these is basic quantum technologies at 41%, followed by quantum computing at 25% (Figure

[6] For further context behind the necessity of the PNT, see the website of Australia's Department of Defence. To summarize Australia's stance on PNT, "[Australia] needs to have systems for commanding and ordering without communications being intercepted or obstructed in the event that global navigation satellite systems (GNSS) become degraded or inoperable" suggests that Australia sees a need to deploy and utilize quantum encryption and communications systems that are virtually impossible to crack.

[7] Canadian Institute for Advanced Research (CIFAR) *A Quantum Revolution - Report on Global Policies for Quantum Technology,* April 2021.

[8] There is also mention of "future expectations" in the conclusion of Roberson and White's discussion quoted in Note 1.

[9] Department of Industry, Science and Resources (DISER, at the time of publication) *National Quantum Strategy Issues Paper*, April 2022. News For news articles, see also "Australian Government Formulating a 'National Quantum Strategy' for Quantum Technology Growth," Science Portal Oceania. No date has been announced for when a strategy incorporating the results of these public hearings will be released.

[10] Department of Industry, Science and Resources, "Australian's Vision for Quantum," April 2022.

[11] "Australian Government Establishes National Quantum Advisory Committee," *Science Portal Oceania*, November 1, 2022.

1-8). Furthermore, according to a statement released by the Australian federal government,[12] Australian National University and University of Technology Sydney ranked sixth and 15th, respectively, in the world for research achievements in the field of quantum computing. For venture capital investment, Australia ranks sixth behind the U.S., Canada, and the UK.

A considerable amount of the basic research that has been done by Australian universities and research institutes began in the 1990s. The prioritization of and joint research into quantum technologies began in 2011 by CoE with funding from the ARC. Particularly well-funded is the ARC CoE for Quantum Computation and Communication Technology (CQC^2T), which aims to design and build silicon-based quantum computers and has been the institution receiving the most attention in Australia since it was founded as CQCT in 1999. These CoEs encourage collaboration among participating universities, which has led to many important achievements in different quantum technology fields. The ARC CoE for Engineered Quantum Systems, which has been in operation from 2017 through 2024, has achieved groundbreaking research results with a number of quantum technologies that fall under the umbrella of quantum machines. In August 2018, four of these CoEs came together to hold a large conference where a variety of stakeholders from industry, academia, and government discussed the future of quantum technologies in Australia.

The following are key individual research findings made in recent years.

・Important steps to achieving silicon quantum bits[13]

In 2010, Andrea Morello of CQC^2T succeeded in achieving a single-shot, time-resolved readout of electron spins in silicon. This was achieved by placing a phosphorus donor near a charge-detection device known as a single-electron transistor that is fully compatible with current microelectronic technology. This single-shot spin readout with a high fidelity that Morello's team demonstrated opens the way to developing the next generation of quantum computing and spintronics devices using silicon. These research results were published in Nature.

・Flip-flop qubits[14]

In February 2018, researchers at the University of New South Wales invented a radically new architecture for quantum computing based on “flip-flop qubits.” Their results, published in Nature Communications, did not require the precise placement of atoms that was required in other approaches, and enabled the scaling up of silicon quantum processors. The key achievement here was enabling qubits, the basic unit of information in a quantum computer, to remain coupled even when placed hundreds of nanometers apart.

[12] Australia Critical Technologies Policy Coordination Office, “Quantum Computers,” November, 2021. The statistics for research paper and patent numbers appear to come from some outside source, and the overall framework for the data is presumed to be the result of analyses done based on “Principles and Framework for Research Impacts,” which is published by the ARC.

[13] Mollello, A. et al. (2010) “Single-shot readout of an electron spin in silicon,” *Nature*, 467, pp.687–691.

[14] University of New South Wales University of New South Wales Basic Quantum Technology Laboratory Press Release “Flip-flop qubits: radical new quantum computing design invented,” February 15, 2022.

・Better than 99% accuracy in silicon-based quantum processors[15]

Researchers at the University of New South Wales Sydney announced on January 20, 2022 that they had demonstrated the ability to reduce the quantum computing error rate to less than 1%, paving the way to achieving silicon-based quantum devices that could be produced using existing semiconductor technologies. Their results, published in Nature, were even featured on the cover. Silicon-based semiconductor spin qubits are stable enough to hold quantum data for long periods and can use existing cutting-edge semiconductor fabrication technologies, giving them the potential to be a foundational part of highly reliable quantum computers.

・Development of the world's first lunchbox-sized quantum computer that can function at room temperature[16]

Quantum Brilliance, a spinoff company of Australian National University (ANU), became the first in the world to develop a room-temperature quantum computer so small that it can fit inside a lunchbox. Quantum Brilliance's quantum computers are not only unprecedentedly small, they can also function at room temperature rather than needing ultra-low temperature environments such as those inside dilution refrigerators or vacuum chambers, which gives them the potential to solve the problem of information storage.

・Discovery of a method for reducing transistor energy usage by 10x or more[17]

At the 2021 International Electron Devices Meeting, held in San Francisco from December 11 to 15, 2021, a Team of Researchers from the University of Wollongong announced that they had discovered the possibility of greatly reducing the amount of energy used by electronic devices and processors by using transistors with negative capacitance. Topological insulators, which conduct electricity on their boundaries but are insulating in their interiors, are attracting attention as a new quantum material to replace silicon. A research team with the ARC Centre of Excellence in Future Low-Energy Electronics Technologies (FLEET) discovered that, by combining a transistor that uses topological insulators with ferroelectric material functioning as a capacitor with a negative capacitance, they could achieve low-voltage switching and thereby reduce energy usage by greater than a factor of 10.

・University of Sydney and startup company identify quantum computer error factors using AI[18]

On August 2, 2021, the University of Sydney and quantum technology startup Q-CTRL jointly developed a revolutionary technology for identifying quantum computer error factors using machine learning on August 2, 2021. Their results were published in Physical Review Letters. This technology allows for identifying performance degrading factors with unprecedented accuracy, enabling quantum computers to be developed in less time. A drawback of quantum computers is their susceptibility to environmental noise, which can adversely impact performance. A research team led by the University of Sydney professor and Q-CTRL CEO Michael Biercuk focused on these errors caused by noise. In addition, using an ion trap and superconductive quantum computing hardware, they developed a technology for detecting tiny deviations from the conditions necessary for executing quantum algorithms. To accurately identify the factors behind measure deviations, the Q-CTRL research team developed a method for processing measurement results using its own machine learning algorithms. In addition,

[15] University of New South Wales, "Quantum computing in silicon hits 99 per cent accuracy," January 20, 2022.
[16] Australia Government, "World-first quantum computers that can fit inside a lunchbox," September 3, 2021.
[17] University of Wollongong, "Research discovery could reduce computing' s unsustainable energy use," December 20, 2021.
[18] University of Sydney, "Q-CTRL unveils machine learning technique to pinpoint quantum errors," August 2, 2021.

using the company's existing quantum control technologies, they made it possible to easily distinguish between actual noise and "phantom artifacts" that occur during measurement.

5.3 Notable research institutes and universities

Almost every major university in Australia has quantum technology-related curriculum and laboratories. As discussed above, six ARC CoEs[19] selected by and launched with funding from the ARC encourage collaboration among participating universities, which has generally resulted in important research findings in the field of quantum technologies. Numerous research institutes and universities outside of the ARC CoEs are also setting up their own research centers and education facilities to carry out distinctive quantum technology research and education.[20] The amount and quality of this research and education approaches that of China, which has been discussed in Chapter 2 of this report, as well as the U.S. and European nations, despite the lead they have had in the field of quantum technologies.

The following pages present information on Australia's largest research organization, CSIRO, as well as six CoEs focused on quantum technologies, followed by universities that have research labs or departments specializing in quantum technologies.

Table 5-2: CoEs and their main areas of quantum technology research

ARC CoE	Year Started	Managing University	Main Areas of Research
ARC CoE for Quantum Computation and Communication Technology (CQC^2T)	2017	University of New South Wales	Light quantum computation Silicon quantum computation Quantum communications Quantum data processing Architecture algorithms Scale-up engineering
ARC CoE for Engineered Quantum Systems (EQUS)	2017	University of Queensland	Quantum materials Quantum diagnostics and imaging Quantum engines and quantum measuring instruments
ARC CoE in Future Low-Electronics Technologies (FLEET)	2017	Monash University	Topological materials Exciton superfluidity Optical metamorphic materials Materials with quantum-level thinness Nanodevice fabrication
ARC CoE	Year Started	Managing University	Main Areas of Research

[19] Every three years (2011, 2014, 2017, and 2020), ARC chooses institutions from a variety of research fields to be CoEs and provides them with grants for a fixed period of generally seven years. Detailed information such as the amount of donations that each CoE receives was obtained from the website of the Australian Research Council's Centre of Excellence.

[20] Basic data about individual universities was obtained from JST/CRDS "Report on Trends in Science and Technology Innovation - Australia (2016)".

ARC CoE in Exciton Science	2017	University of Melbourne	Quantum/classical mechanical exciton theory and modeling Spectroscopy Design and production of materials and devices for solar cell, lighting, security, and exciton control
ARC CoE for Gravitaitonal wAve Discovery (OzGrav)	2017	Swinburne University of Technology	Quantum squeezing in gravitational wave astronomy Collection of gravitational wave data from black holes and neutron stars Putting gravitational wave detection to use in physical probes of celestial bodies
ARC CoE for Nanoscale BioPhotonics	2014	University of Adelaide	Advanced sensing tools that use photons Improving the imaging of ecosystems and other dynamic biological systems Discovering chemical substances, nano materials, and fiber-based photoreaction tools

Source: Prepared by APRC based on various data

5.3.1 Quantum Technologies Future Science Platform - CSIRO

Established by CSIRO in 2021. Its founding director is Jim Rabeau (formerly a professor at the University of Sydney, now Deputy Director for Industry, Innovation and Commercialization at the University of Sydney Nano Institute). With a focus on quantum sensing, quantum communications, and quantum computers, researchers in this program develop various applications in line with the government's "Modern Manufacturing Priorities," along with developing quantum technologies for agricultural and environmental applications.

5.3.2 ARC CoE for quantum Computation and Communication Technology (CQC²T)

A CoE that makes important research achievements in quantum computing. It concentrates on developing technologies for global quantum computing information networks (ultrafast quantum computing, absolutely secure quantum communications, and distributed quantum information processing). It was founded in 2011 with significant funding from the Australian Research Counsil (ARC), DEVCOM ARL (U.S.), the Semiconductor Research Corporation, Australia's Department of Defense, the government of New South Wales, and participating organizations in Australia. According to one ARC report, the CoE received 24.5 million AUD (16.7 million USD) in its first phase of operations.[21] Headquartered at the University of New South Wales (UNSW), CQC²T comprises more than 200 researchers from Australian National University, the University of Melbourne, Griffith University, the University of Queensland, UNSW Canberra, and the University of Sydney, and operates 19 coordinated programs along with nine collaborative work packages.

[21] From Table 3 in the ARC's 2011 Annual Report on Centres of Excellence

Launched as an engineering college, UNSW is a research organization that was involved in the 2000 founding of the Special Research Centre for Quantum Computer Technology, the predecessor of ARC's CoEs. The University of Queensland, University of Melbourne, Griffith University, UNSW Canberra, Macquarie University, and the University of Sydney also participate in the CQC2T, whose primary fields of research are semiconductor microfabrication facilities, crystal growth, ion injection, interface analysis, laser physics, strong magnetic fields, and low-temperature environments.

5.3.3 ARC CoE for Engineered Quantum Systems (EQUS)

Established in 2017, EQUS has received 31.9 million AUD (21.7 million USD, for seven years beginning in 2017) from the ARC. It is focused on engineering applications for Quantum technologies, with a mission to build quantum machines that will bring the benefits of quantum states to the real world. EQUS addresses the most difficult quantum state research problems that exist at the boundary between basic physics and engineering. It also works with its partners in industry and develops its scientific discoveries into practical apps and devices, while conducting cutting-edge research and developing the next generation of scientists possessed of a rich entrepreneurial spirit. The University of Queensland, University of Sydney, Macquarie University, the University of Western Australia, and Australian National University collaborate with EQUS.

The University of Queensland directs EQUS and is a research organization that hosts[22] the CQC^{2}T node. For quantum physics, it is ranked 1st in Australia and 60th in the world.[23] The most recent Excellence in Research Australia assessment gave quantum physics at the University of Queensland the maximum rating of “5: well above world standard.” Quite a number of staff are also ARC researchers.

5.3.4 ARC CoE in Future Low-Electronics Technologies (FLEET)

Established on June 12, 2018. It has received 23 million AUD (15.6 million USD, for seven years beginning in 2014) from the ARC. It is led by a vision to integrate disparate scientific threads, namely topological states of matter, atomically thin materials, cold atomic gases, and ultrafast laser science, into a coherent whole, tied together by the vision of using dissipationless conduction in novel quantum systems to reduce the energy used in computing. Monash University, UNSW Sydney, Australian National University, RMIT, and the Swinburne University of Technology, University of Queensland, and University of Wollongong collaborate with FLEET.

Hosting research organization Monash University has nine campuses, including some outside the country (in China, India, Italy, and Malaysia) and offers more courses than any other university in Australia. The university's Monash Quantum Information Science organization conducts research on quantum computers, both theories and technologies, on subjects that include memory, control, geometry, processes, and noise.[24]

[22] University of Queensland See the Quantum Technology Laboratory at the University of Queensland.

[23] See the quantum and particle physics ranking. Edurank ranks 14,134 universities in 183 companies across 246 subjects based on proprietary metrics.

[24] The organization's website stopped being updated in 2019.

5.3.5 ARC CoE in Exciton Science

Established in 2014, the ARC CoE in Exciton Science has received 23 million AUD (16.7 million USD, for seven years beginning in 2014) from the ARC. In collaboration with international partners, it aims to manipulate the way light energy is absorbed, transported, and transformed in advanced molecular materials, and to discover new ways to source and use energy. To find innovative solutions for renewable energy, it collaborates with industry on projects that include solar energy conversion, energy-efficient lighting and displays, and security labeling and optical sensor platforms for defense. Headed up by Paul Malvaney of the University of Melbourne, it collaborates with Monash University, RMIT, the University of New South Wales, and the University of Sydney.

CQC²T Deputy Director Lloyd Hollenberg and Professor David Jamieson serve as program managers for the University of Melbourne's team. The University of Melbourne currently runs two programs through the CoE. a quantum processor development program led by Professor Hollenberg and a direct ion injection program led by Professor Jamieson.

At the CQC²T's Melbourne node, located in the David Caro Building at the University of Melbourne, there is a clean room facility with a deterministic ion beam, along with a materials processing and manufacturing laboratory, a quantum sensing laboratory with a confocal microscope, and other well-equipped laboratories. The University of Melbourne is also collaborating with the IBM Q Network[25] as an initial member.

5.3.6 ARC CoE for Gravitational wAve Discovery（OzGrav）

Established in 2017, the ARC CoE for Gravitational Wave Discovery has received 31.3 million AUD (21.3 million USD, for seven years beginning in 2014) from the ARC. Swinburne University of Technology With the Swinburne University of Technology as its hosting research organization, it is headquartered at the University of Western Australia's Department of Physics. The CoE's mission is to capitalize on the historic first detections of gravitational waves to understand the extreme physics of black holes and warped spacetime, and thereby promote a more widespread understanding of astrophysics. It is also developing tools to make measurements in space, including the Square Kilometer Array[26] and next-generation gravitational wave detection systems. CoE Director Matthew Bales was selected to be a Research Fellow at the Australia Academy of Science in 2022.

5.3.7 ARC CoE for Nanoscale BioPhotonics（CNBP）

Led by the University of Adelaide, this CoE collaborates with Macquarie University and RMIT. It has received 23 million AUD (15.6 million USD, for seven years beginning in 2014) from the ARC. This CoE develops fundamental science in the area of monitoring basic body chemistry such as noninvasive optical monitoring to identify signatures of biological processes. It bridges the knowledge gap between scientists and engineers developing new bioimaging and biosensing methods and the end users in the life sciences and medicine.

[25] The IBM Q Network is a collaboration of leading Fortune 500 companies, academic institutions, and universities working to explore quantum applications for business and science. It provides organizations with quantum expertise and resources, and cloud-based access to the most advanced universal quantum computing systems and technology stack available.

[26] A radio telescope with a total collecting area of one square kilometer.

The University of Adelaide, which leads research at this CoE, excels in research involving agriculture, environmental science, health science, mining and energy, optical engineering, and advanced measurement. The university's Quantum Materials Strategy, launched on December 1, 2021, establishes the following goals. (1) Establish world-class research capability with a focus on the most advanced basic research and new applied quantum materials research; (2) become a trusted partner of industry and the Department of Defence; (3) be ranked in the top five universities globally specializing in quantum materials; (4) create an educated workforce for future industry, defence, and academic environments.[27]

5.3.8 Australia National University (ANU)

Australia National University was founded in 1946 as Australia's only public university. It amalgamated with Canberra University College in 1960, increasing its number of colleges, and is now a university with seven colleges, namely the ANU College of Arts & Social Sciences; Asia & the Pacific; Business & Economics; Engineering, Computing and Cybernetics; Health & Medicine; Law; and Science. Brian Schmidt, winner of the 2011 Nobel Prize in physics, serves as Vice Chancellor. ANU counts six Nobel laureates among its faculty and graduates, and is more engaged in research than other universities. It ranked 27th for QS World University Rankings 2022.

Partnered with four of the six ARC CoEs, ANU conducts more quantum research than any other university in the country, from basic research to technological application. It also excels in transferring its technologies to related startup companies.

5.3.9 Quantum Control Laboratory, University of Sydney（QCL）

The University of Sydney is Australia's oldest university, founded in 1850. This prestigious university has produced numerous politicians and prominent cultural figures that include Australia's first and 25th Prime Ministers, Edmund Barton and John Howard. It has eight campuses in Sydney and ranked 38th for QS World University Rankings 2022. Its pursuits are wide-ranging and include basic research, quantum information science, and technology development.

The university's Quantum Science Group is involved in quantum information (ion trap computing), quantum simulation for chemistry and materials, quantum sensing and metrology, and quantum control engineering. It hosts a global research node of the Microsoft Station Q network (led by Professor Reilly) and has led to the formation of Australia's first quantum-tech startup, Q-CTRL (founded and led by Professor Biercuk). Through a multi-year partnership with Microsoft, the University of Sydney received 150 million AUD that it used to build the Sydney Nanoscience Hub, a space and platform for quantum research in Australia.[28]

[27] University of Adelaide, "Quantum materials for a better world," December 2021.
[28] University of Sydney Microsoft – Quantum Computing Research, 2017.

5.3.10 Pawsey Supercomputing Research Centre, The University of Western Australia

Founded in 1911 Founded in 1911, the University of Western Australia has considerable research capabilities and a number of highly cited researchers that is behind only the University of Melbourne, Monash University, and the University of Queensland. With support from the Western Australian and federal governments, iVEC was reestablished as the Pawsey Supercomputing Research Centre (Pawsey), the name in honor of Joseph Pawsey, the "father of radio astronomy." The Quantum Computing Innovation Hub is conducting research aimed at leveraging Australia's business opportunities in high-speed computing.

Pawsey ran a pilot program for this hub in the first half of 2022 and plans to have machines directly tested by about 30 juniors majoring in quantum computing at the University of Western Australia. Through this pilot program, the students will explore how best to use quantum computers and make hardware easier to use over the long term. This hub has two quantum computers: the 2-qubit SpinQ Gemini and the 3-qubit Triangulum. Both of these are able to function at room temperature and have full quantum control design capabilities.

5.3.11 Centre for Quantum Software and Information, University of Technology Sydney

The University of Technology Sydney is conducting research aimed at developing software and an information processing platform necessary for future quantum technologies. With a focus on quantum software and information technology methodologies and functions, it is developing new applications for these technologies. Its research objectives consist of the following six key research programs: (1) quantum algorithms and complexity; (2) AI applications of quantum computing; intermediate quantum computing and architectures; (4) quantum programming and verification; (5) quantum information theory and security; (6) quantum experiments and hardware. The university also has a startup company community consisting of numerous students with entrepreneurial ideas. Working with the Sydney Quantum Academy, a human resource development platform offering doctoral degree scholarship student programs, the university aims to recruit and develop outstanding students who can contribute to a quantum innovation ecosystem in Sydney.

5.3.12 Centre for Quantum Dynamics, Griffith University

Established in 2003, the Centre for Quantum Dynamics comprises a theory group and laboratory, and is characterized by a powerful collaboration among its researchers. Its cutting-edge research encompasses areas such as ultrafast quantum processes, quantum computing, quantum networks, quantum metrology, quantum foundations, and quantum biophysics. Additionally, the Centre also hosts a node of the Australian Research Council’s CQC^2T and is home to the Australian Attosecond Science Facility, the only laboratory in Australia where atoms, molecules, and materials can be probed on sub-femtosecond timescales.[29]

[29] See Griffith University's Centre for Quantum Dynamics.

5.3.13 Macquarie Centre for Quantum Engineering, Macquarie University (MQCQE)

MQCQE aims to focus on investigating and utilizing more complex aspects of quantum science such as quantum entanglement, superposition, and quantum interference, to probe the quantum nature of reality in a deeper fashion, and to begin to engineer the quantum world to provide new types of functions which may be impossible using the classical laws of science. Its research domains include quantum sensors, quantum simulations, and quantum computers.[30]

5.3.14 Research Hub for Diamond Quantum Materials, Royal Melbourne Institute of Technology (RMIT)

Established on April 21, 2022, the MQCQE was jointly established at the RMIT by La Trobe University and Quantum Brilliance, a German-Australian quantum computing company that researches and develops diamond-based quantum computers and is headquartered in Canberra. It aims to usher in the next generation of quantum computing with a foundation in world-class expertise and resources in diamond material science.[31] RMIT is one node of ARC's CoE for Quantum Computation and Communication Technology (CQC^{2}T), and is a QuRMIT[32] group engaged in quantum metrology and information research.

5.4 Notable companies

Many professors at Australian universities are engaging in entrepreneurial pursuits with a focus on quantum computing technologies. Q-CTRL is of particular international renown in this field.

Australian quantum startups have even been attracting attention among investors in recent years. In December 2021, quantum cyber security startup QuintessenceLabs announced that it had raised 25 million AUD (17 million USD) in a Series B round that was led by CSIRO venture capital fund Main Sequence. Then in August 2021, Quantum Brilliance raised 13 million AUD (8.8 million USD) in seed funding with support from, once again, Main Sequence.[33] In November 2021, The Quantum Terminal was established as part of Tech Central, a startup hub in Sydney, with funding from New South Wales.[34] Two companies are also part of Tech Central, in addition to the Sydney Quantum Academy (discussed in 4.3 .11): Q-CTRL and Quantum Brilliance.

In addition to grants from the government, large tech companies are also investing in Australia's quantum technology pursuits. Global software giant Microsoft has invested many tens of millions of dollars in EQUS at the University of Sydney. Meanwhile, Australian financial institutions and telecommunications companies are supporting silicon quantum computing companies working on the development or commercialization of quantum computers of the world's more than 70 quantum-related spinoff companies and startup companies, five are

[30] The Macquarie Centre for Quantum Engineering (MQCQE)

[31] "New hub to make diamond-based quantum computers." After the hub was launched, a special website for the hub was also launched.

[32] Website of the QuRMIT (Ker-Mit) research group

[33] "Australia ramps up quantum computing focus with $70 million commercialisation hub," *Startup Daily*, November 17, 2021.

[34] From a New South Wales press release

headquartered in Australia. Roberson and White's self-evaluation quoted in section 5.1 ("as a result of the immense support for this field in Australia, there is a clear scientific legacy") seems accurate.[35]

Table 4-3 presents a breakdown by state and field of the 14 Australian quantum-related companies described in the CSIRO roadmap. Numbers in black circles indicate the number of companies in that state and, as the image shows, companies are particularly numerous in Australian Capital Territory and New South Wales with four and five companies, respectively. With the view that these 14 companies are noteworthy, this section provides an overview of their businesses and top products in alphabetical order.

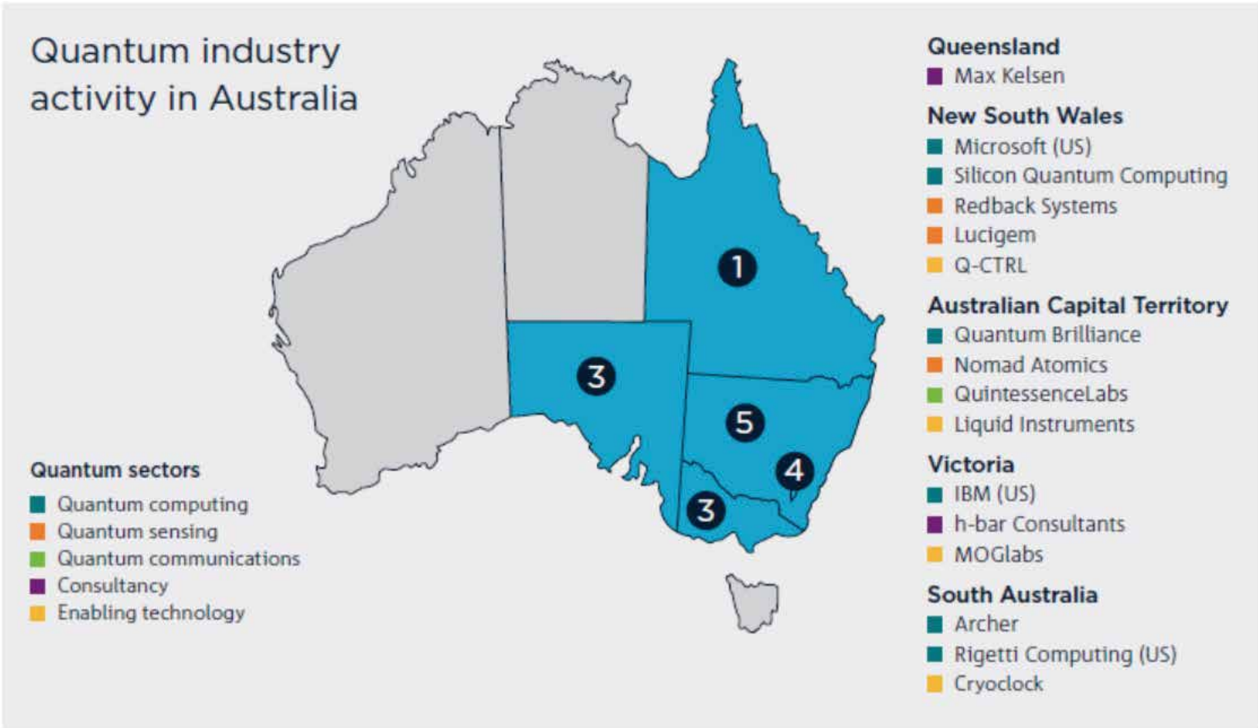


Figure 5-1: Quantum-related companies in Australia

Source: Diagram on pg. 10 of the CSIRO roadmap

5.4.1 Archer

Archer provides materials that enable quantum information processing. It has CQ qubits, processors, and chips patented in Australia, Asia, EU, and the U.S., and provides solutions to enable these products to be embedded into socially mainstream electronic devices. It has a knowledge hub at University of Technology Sydney and also a center in Adelaide.

5.4.2 QuantX Labs

Founded as CryoClock in 2016, QuantX Labs was later renamed to its current name. Its flagship products include the C-ROC quantum clock and Cryoclock, and it primarily develops ultra-precise timing and frequency solutions with potential application in PNT and location information systems. Its ultra-pure sapphire crystals can generate

35 Same as Note 1.

signals 1,000 times purer than any other commercial system currently available. In addition, using ultra low-noise synthesis technologies, it has developed a research system that can generate any frequency from the HF band to the X band.

5.4.3 H-bar consultants

Founded by world-renowned experts in quantum physics and quantum technologies, H-bar consultants is a consulting firm specializing in quantum technologies. Simon David, a senior lecturer at the University of Technology Sydney, is a cofounder and Managing Director.

5.4.4 Liquid Instruments

Liquid Instruments develops and sells a range of customizable hardware for experimental measurement and control. Serving as CEO is Daniel Shaddock, an ANU professor specializing in quantum metrology.

5.4.5 LuciGem

Founded in November 2019, LuciGem develops and sells fluorescent nanodiamonds for use in quantum engineering, life science, and biomedical applications. James Rabeau, Director of the CSIRO's Quantum Technologies Future Science Platform, is a cofounder and CEO.

5.4.6 Max Kelsen

Max Kelsoen is a company that provides machine learning and AI solutions and computing consulting services. Headquartered in Brisbane, it has received numerous tech awards from global American companies such as AWS, Deloitte, and Domino's.

5.4.7 MOGlabs

MOGlabs was founded in 2007 by Robert Scholten, a researcher with the University of Melbourne. The company sells and provides variable wavelength lasers, laser electronics, optical amplifiers, radiofrequency synthesizers, laser wavelength measurement devices and other such high-performance laser technologies essential for research organizations involved with quantum technologies. It is a collaborator with ARC's CoE EQUS.

5.4.8 Nomad Atomics

Nomad Atomics is a company that produces compact quantum sensors designed for use in the field. It provides quantum control solutions for reducing decoherence.

5.4.9 Quantum Brilliance

Quantum Brilliance is an Australian National University spinoff launched by ANU postdoctoral researchers and instructors in October 2019. It develops quantum computers powered by diamonds to achieve high-performance machines that can operate in ambient conditions with simple controls. As mentioned in section 4.2 ("Trends in research and development"), the company recently succeeded in making these machines smaller.

5.4.10 QuintessenceLabs

Founded in 2008 in Canberra, QuintessenceLabs manufactures and sells products that include the Trusted Security Foundation (TSF) 400, a quantum cyber security product that includes a random number generator that can operate at a speed of one gigabit per second. It has won numerous awards such as the BIG Innovation Award 2022 from the Business Intelligence Group and the winter of the American Chemical Society's award for the quantum computing category in 2021.

5.4.11 Redback Systems

Founded in 2019, Redback Systems develops and sells the RS40k, a single-mode fiber-Fed echelle spectrometer for high-resolution, broadband imaging. Founded in 2019, Redback Systems develops and sells the RS40k, a single-mode fiber-Fed echelle spectrometer for high-resolution, broadband imaging. In addition to providing spectral solutions to meet the needs of customers working with a wide range of wavelength regions, from ultraviolet to near infrared, it also develops software for detailed spectral analysis.

5.4.12 Rigetti computing (U.S., previously QxBranch)

Former IBM quantum computing researcher Chad Rigetti is a cofounder and CEO. Headquartered in the U.S., the company's Australia branch focuses on developing quantum computer applications.

5.4.13 Silicon Quantum Computing

Silicon Quantum Computing is a joint venture company formed by the Australian federal government, the government of New South Wales, the University of New South Wales, the Commonwealth Bank of Australia, and Telstra. The company's founder and CEO, Michelle Simmons, is also a director at CQC2T. It plans to build a silicon-based quantum computer in 2023, and is currently developing a 10-cubit quantum integrated circuit prototype. Based on development achievements made at CQC²T, the company has produced qubits at the atomic level, developed a technology for achieving the fastest two-qubit gate in silicon, and as created numerous technological breakthroughs that include low-noise devices and the fastest fidelity qubits in a solid state. It was initially funded with 83 million AUD (56.4 million USD).

5.4.14 Q-CTRL

Founded in 2017 by University of Sydney physicist Michael J. Biercuk, Q-CTRL provides solutions for enhancing quantum hardware stability. The company's quantum-scale sensing technologies, developed using technologies to characterize and control quantum errors in quantum computers, can improve performance by up to 500x in real-world environments.

5.5 Notable researchers

Based on research and patent data presented in Chapter 1, the following noteworthy researchers have been selected for mention in this paper in light of such factors as their position in Australia's quantum research community and the research awards that they have received.

5.5.1 Andrew S. Dzurak

Expert in silicon-based quantum computing and nano electronics. Professor at the Faculty of Science, University of New South Wales and an ARC Laureate Fellow, he is engaged in the development of quantum processor chips built using silicon CMOS technologies. Has served as the director of the NSW node of the Australian National Fabrication Facility (ANFF) since 2006. This network was built to enable university-based laboratories to provide state-of-the-art production facilities to researchers and members of industry. He is also a member on the Sydney Quantum Academy's Executive Board and Technical Advisory Committee which, with access to the research and educational resources of four universities in Sydney, promote and support the development of quantum economics. His main fields of research are quantum computing, nano-fabrication technology, silicon nano-electronics, single-electron devices, and metrology. He has published more than 20 papers in Science and Nature since 2010, six of which include theoretical 1- and 2-qubit quantum computations for silicon devices. He has published more than 200 scientific papers in total, and is a co-inventor in 13 patent families. Received the Australian Eureka Prize for Scientific Research in 2011 and the New South Wales Science and Engineering award for Excellence in Engineering and Information and Communications Technologies in 2012.

5.5.2 Gerard Milburn

Professor emeritus at the University of Queensland. Professor emeritus at the University of Queensland who conducts research in the fields of quantum information theory, quantum foundations, quantum optics, quantum control, and quantum measurement theory. After receiving his PhD in theoretical physics from the University of Waikato in 1982, he researched squeezed states of light along with nondestructive quantum measurement. Fellow at the Australia Academy of Science, and American Physical Society.

5.5.3 Michelle Simmons AO

Director of the CQC^{2}T and a laureate fellow at the Australian Research Council (ARC). She has pioneered the development of proprietary technologies that power atomic-scale, silicon-based electronic devices such as the world's smallest transistor, the narrowest conducting wires, 3D atomic-scale electronics, and the first 2-qubit gate using qubits at the atomic level. Founder and CEO of Silicon Quantum Computing, she stands at the forefront of silicon-based quantum computer development.

5.5.4 Peter Turner

CEO of the Sydney Quantum Academy and holds an Honorary Professorship in the Department of Physics and Astronomy, Macquarie University. A member of the Macquarie University Research Centre for Quantum Engineering. After completing his MSc and PhD in Physics at the University of Toronto, he finished an Alberta Ingenuity Fellowship at the Institute for Quantum Information Science at the University of Calgary, and held an Assistant Professorship in Physics at the University of Tokyo. As Director of the Quantum Engineering Centre for Doctoral Training at the University of Bristol, he established arguably the world's first program aimed directly at preparing graduates for the nascent quantum technology industry. In addition to delivering novel graduate training, during his directorship he also oversaw engagement with government and industry partners. Professor Turner has an extensive research track record with over 15.5 million AUD (10.5 million USD) awarded in competitive funding from the UK, the U.S., Japan, and Canada.

5.5.5 Lloyd Hollenberg

Professor at the University of Melbourne, he received his PhD in physics from the same institution in 1989. He later became a special researcher with the Japan Society for the Promotion of Science and completed a JSPS Fellowship at the KEK accelerator laboratory in Tsukuba, Japan. After his postdoctoral period, he returned to the School of Physics to take up a research and teaching position. Lloyd's early work in mathematical physics and lattice gauge theory was a natural starting point for his interest in quantum computing. Since 2001, Lloyd has been a driving force for the silicon quantum computer vision, providing theoretical underpinnings from device physics to quantum error correction and scale-up. He is an internationally known proponent of quantum technology having made contributions in both theoretical quantum computing and experimental implementations of quantum sensing using spin qubits in semiconductors. Lloyd has published more than 250 papers in refereed journals, including prestigious journals such as Science, Nature, Nature Physics, Nature Nanotechnology, Nature Materials, and Physical Review Letters. He was ranked sixth in the world for contributions to quantum computing in the 2001–2010 Thomson Reuters census. Under his ARC Laureate Fellowship (2013–2018) he developed quantum sensing and imaging technology that crosses the nano-bio divide. Lloyd has served on the Australian Research Council's College of Experts and was Chair of the Physics, Chemistry and Geosciences panel in 2008.

5.6 International collaboration and joint research

Recent years have seen Australia put renewed effort into international collaboration. At the beginning of the 21st century, Australia had already accomplished world-class foundational research in quantum technology. However, according to a report by the Australian Strategic Policy Institute (ASPI), technological investment in Australia fell behind that of other advanced nations in the 2010s (ASPI estimated public investment in quantum research in each country at over 13 billion USD in China, 3.15 billion USD in Germany, 2.6 billion USD in France, 2.6 billion USD in the U.S., 1.3 billion in Japan, and 3.3 billion USD in Australia [all figures were converted to USD]). The report also suggests that Australia has experienced a brain drain, where a large number of key people have left to work for organizations in other countries. The report mentions five individuals as examples of researchers who have been poached by research institutes or companies in the U.S., China, or Taiwan, including Silicon Valley startup PsiQuantum co-founders Jeremy O'Brien and Terry Rudolph, and Min-Hsiu Hsieh, who is now with Foxconn in Taiwan.[36] The report says the reasons for this are major efforts by China to attract people in the field of quantum technology, and that Australia views itself as having fallen behind the global quantum technology competition.[37]

In September 2021, a regional security framework known as AUKUS was formed among the U.S., the UK, and Australia. This new partnership suggests that there is a need to safeguard important, sensitive technologies through proper international cooperation.

In light of the circumstances described above, Australia is currently exploring several cooperative frameworks with other countries.

As for inter-governmental cooperation with the U.S., Australia's Department of Home Affairs released a joint statement on November 17, 2021, regarding cooperation in quantum science and technology.[38] With the goal of promoting partnerships and enabling cooperation between the U.S. and Australia, a joint statement aims to: “cooperate on achieving practical applications of quantum technologies that would be of mutual benefit to both nations,” “promote joint research, development, and usage of quantum technologies, underpinned by shared principles of research integrity,” “build a trusted global quantum marketplace and secure supply chain,” and “protect sensitive technologies for which there are national security implications.” Australian government will conduct Quantum Policy Dialogue as a means to advance this cooperative agenda. Co-chaired by representatives from each country, regular meetings of the Dialogue will be conducted by senior government officials involved in quantum technologies. In these meetings, participants will exchange information, identify practical initiatives, and review

[36] Brennen, G., Devitt, S., Roberson, T. and Rohde, P. (2021) *An Australian strategy for the quantum revolution*, Policy Brief Report No. 43, Canberra: Australian Strategic Policy Institute, p.14.

[37] Jackett, J. “Realising Australia’s quantum potential,” Analysis, Australian Institute of International Affairs, December 15, 2021. A similar assessment is also made in the ASPI report cited in footnote 32. According to author Jennifer Jackett, "it is possible that this includes projects that involve, for example, solutions for location, navigation, and timing in environments where GPS performance is degraded or nullified."

[38] Department of Industry, Science and Resources, Australian Government. “Australia signs quantum technology cooperation agreement with United States.” An abridged translation of the U.S. statement below was also referenced. Center for Research and Development Strategy (CRDS), “Australia and the U.S. Announce a Joint Statement on Quantum Science and Technology Cooperation,” February 21, 2022.

cooperation under the joint statement. It also calls for convening additional working-level meetings to advance specific topics under the joint statement.

Furthermore, as a platform to promote joint research, Australia and India established the Australia-India Strategic Research Fund (AISRF)[39] in 2006, and have been putting out calls for research projects every year since. For the most recent round of calls, the Round 14, AISRF plans to receive funding of roughly 5.2 million AUD (3.54 million USD) in fields that include quantum technologies, key minerals, and infectious prevention and control. Of this, one million AUD (0.68 million USD) has been allocated to Australian National University for "quantum-enhanced atomic gravimetry for improved sensing capabilities."

As for cooperation with other nations, on April 7, Australia's Minister for Science and Technology announced priority collaboration areas and identified partners for the first year of the strategic element of the Global Science and Technology Diplomacy Fund (GSTDF)[40]. This fund is expected to facilitate joint research with Japan, the UK, France, Spain, and the U.S. in the field of artificial intelligence and quantum computing.

[39] "Guidelines for Round Ten 2016," released by India's Ministry of Science & Technology, was referenced for the overview of the AISRF. See this media release by Minister for Science and Technology Melissa Price for details concerning Round 14.

[40] "Australian Government Announces Priority Collaboration Areas and Identifies Partners for International Joint Research in Science and Technology," May 11, 2022.

5.7 Quantum innovation ecosystem

Australia has an extensive quantum technology ecosystem, and there is strong engagement between academia and industry. Through Centres of Excellence such as the CQC²T and EQUS, the government supports joint research between academia and industry. Two new CoEs were established in 2017 as five-year plans specializing in quantum technology: Future Low-Energy Electronics Technologies (FLEET) at Monash University and Exciton Science at the University of Melbourne. These CoEs connect multiple universities in Australia and create a strong network among researchers, and there are also numerous venture companies that have been spun off or that collaborate with these universities.

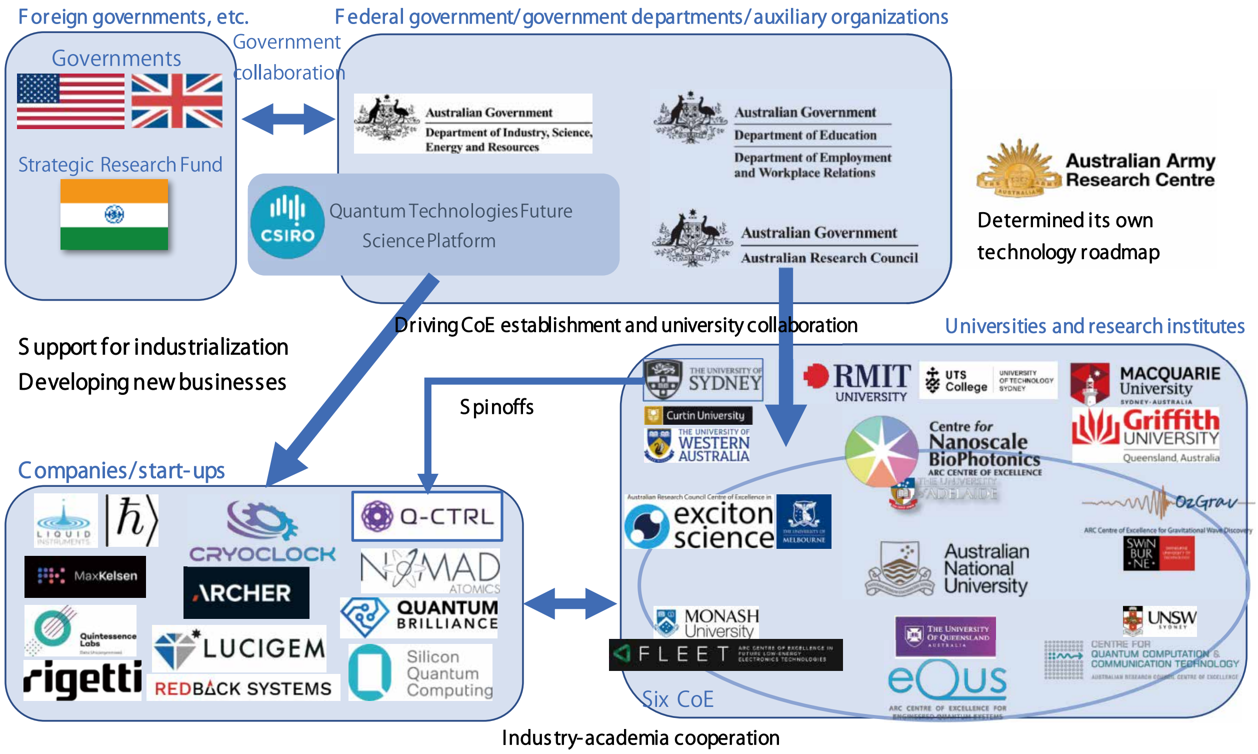


Table 5-12 Quantum innovation ecosystem in Australia

Source: Prepared by APRC

6 Quantum technology trends in South Korea

Since 2019, the South Korean government has been implementing policies to promote quantum technologies. In the private sector, Samsung Electronics and South Korea's three largest telecommunications companies turned their attention to quantum technologies before even the government did, and are investing in promising enterprises. While South Korea's quantum strategy is centered on quantum communications, the country is also focusing on quantum computing. With an emphasis on cooperation among industry, academia, and government, in 2021 South Korea's Ministry of Science and ICT launched the Future Quantum Convergence Forum, providing a means of cooperation among leading enterprises, universities, and research institutes in the country. For the most part, quantum technology-related products are being carried out by universities and research institutes such as Seoul National University, KAIST, KIST, and ETRI.

6.1 Quantum technology policy

The government of South Korea began full-scale investment in quantum technologies in 2019. While it was slow out of the gate internationally, it has dramatically increased investment year after year.

Looking back on actions taken by previous administrations[1], in 2012, the then Ministry of Knowledge Economy under the Lee Myung-bak administration selected quantum information and communications technologies as one of "10 hugely innovative information technologies." In 2014, then Ministry of Science, ICT and Future Planning under the Park Geun-hye administration pointed out that "although basic research that has been ongoing in some areas since 2005, there are no supporting policies," prompting the announcement of a vision for South Korea to become a pioneer in this field by 2020. It also released the Medium- to Long-term Strategy for Quantum Information and Communication, whose three major goals are: (1) develop core technologies, (2) build a research base, and (3) establish a foundation for achieving continuous growth.

As a move toward actualizing this strategy, the Ministry of Science and ICT (MSIT) under the Moon Jae-in administration twice requested that the Ministry of Economy and Finance conduct a "preliminary feasibility study for the medium- to long-term development of quantum information and communications technologies"[2] — once in 2017 and once in 2018 — but was denied both times, and no funding was allocated[3]. Quantum technology investment was finally able to be made in April 2018, when the authority to allocate funding to preliminary feasibility studies for national research and development projects was transferred from the Ministry of Economy of

[1] See Korea Institute of Science and Technology Information, "Current Situation and Outlook for Quantum Computer Research Development Policy" (May 2019).

[2] Preliminary feasibility studies are procedures that entail assessing the feasibility of conducting a new project (SOC, research and development, computerization, or other such project where large-scale state funding will be required) prior to fiscal authorities drawing up a budget or a plan for fund usage.

[3] The reasons for the denial included (1) project goals were unclear, (2) research and development project goals and content were abstract, (3) project priorities were unclear, (4) it was unlikely to be profitable, and (5) people had little demand for quantum computers. For more information, see "Identifying 12 Core Problems in Quantum Information and Communications — The Development of 11 Leading Technologies Worldwide," Electronic Times (July 31, 2017).

Economy and Finance to the MSIT.[4]

In 2019, MSIT drafted the Quantum Computing Technology Development Project Plan along with the 2019 Next-Generation Information Computing Technology Development Project Plan. For five years beginning in 2019, South Korea will invest 44.5 billion KRW (34.3 million USD at a rate of 1 KRW = 0.00077 USD), in the development of core technologies such as quantum computer hardware, and research and development for promising technologies that include new computing architectures, quantum algorithms, and infrastructure software. Furthermore, the MSIT announced that it would invest 13.4 billion KRW (10.3 million USD) into the development of four core technologies through next generation computing technology development projects, namely system software, software engineering, information and AI systems, and human computing interaction (HCI).[5]

South Korea's budget for quantum technology research and development has increased significantly over the past few years, from 10.6 billion KRW (8.2 million USD) in 2019 to 32.8 billion KRW (25.3 million USD) in 2021 and 60.3 billion KRW (46.4 million USD) in 2022. Although this investment falls short of investments being made by the U.S. and China, in terms of percentage increase, 2022 was an 83.8% increase over the previous year. The 60.3 billion KRW (46.4 million USD) will be allocated as follows: 19.7 billion KRW (15.2 million USD; 2021: 9.63 billion KRW [7.42 million USD]) for quantum computing technology development; 13.6 billion KRW (10.5 million USD; 2021: 7.3 billion KRW [5.6 million USD]) for quantum encryption communications integration and transfer technology improvement; and 5.8 billion KRW (4.5 million USD; 2021: same) for quantum sensor core technology development.[6] According to the MSIT R&D draft budget for FY 2023,[7] which was released in June by the Yoon Suk-yeol administration that took power in May 2022, 95.3 billion KRW (73.4 million USD) will be invested in quantum technologies, a 36.3% year-over-year funding increase.

In April 2021, the MSIT released the "Quantum Technology Research and Development Investment Strategy," saying that "the digital age will be followed by the quantum age." This strategy analyzes technology development trends in developed countries and lays out issues that South Korea's technology development needs to address. As a short-term goal, the strategy calls for the building of a 50-qubit quantum computing system by 2024. Aiming to have about 1,000 quantum research personnel in the country by 2030, South Korea will focus on theory and practical training, and will create specialized programs (doctoral-level curriculum) that will see participants engage in collaborative projects with companies. As part of this human resource development initiative, researchers who earned their PhD's will be sent to developed nations to gain practical experience. The country will also bring in highly accomplished researchers from overseas and build a program for South Koreans to acquire advanced skills. Making full use of the country's active collaboration between the public and private sectors, the South Korean government will follow the model of developed nations and formulate a strategy for beating the increasingly stiff competition to develop quantum technologies.

[4] For more information, see "Preliminary Feasibility Assessment — Transferring from the Ministry of Economy of Economy and Finance to the Ministry of Science and ICT," Daily Watcher, Center for Research and Development Strategy, Japan Science and Technology Agency (abridged translation release: July 11, 2010).

[5] See "Investment of 44.5 billion KRW over 5 Years into Full-scale Development of Quantum Computers and Core Technologies," South Korea Policy Briefing (January 31, 2019). The full text has not been released for either report.

[6] See "2022 National Budget Development Project — Draft Budget Results" (October 2021).

[7] For the 2023 budget, see "2023 R&D Budget Adjustments Proposal Finalized," Policy Briefing (June 2022).

Table 6-1: Quantum technology and research development investment strategy

<table>
<tr><td>Vision</td><td colspan="3">From digital to quantum</td></tr>
<tr><td>Target</td><td colspan="3">Become one of the four great powers in quantum technology in the 2030s: Promote industrial innovation and strengthen national security</td></tr>
<tr><td rowspan="2">Step-by-step targets</td><td>(2021–2024) Foster human resources, develop elemental technologies (Stage that will create foundation)</td><td>(2025-2030) Present potential for academic and industrial use (successful examples)</td><td>(2031–2035) Full-fledged promotion of quantum technology commercialization</td></tr>
<tr><td>・Secure 50-Qubit quantum processor
・Secure ultra-small wired encrypted communications
・Enhance elemental technologies (spatial resolution, precision, etc.)</td><td>・Secure NISQ quantum computing system
・Secure super-fast precise wireless encrypted communications (quantum drones, aircraft)
・Use the quantum sensor industry (industrial semiconductors, medical care)</td><td>・Secure error-correction all-purpose quantum computer
・Secure quantum Internet technology
・Expand quantum sensor application area (super-long distance telescope, quantum microscope, etc.)</td></tr>
<tr><td rowspan="5">Investment strategies</td><td colspan="3">1. Strengthen basic research
① Develop super-high speed quantum computing technology that overcomes existing computing limitations
② Develop super-reliable quantum communication technology linked to quantum correction in an advanced security environment
③ Develop extremely precise quantum sensor technology that will enable a landmark increase in industrial competitive power</td></tr>
<tr><td colspan="3">2. Secure human resources and build a foundation for domestic and international cooperation
① Create a hub-centric cooperative system and strengthen global cooperation ② Support human resource development to secure technological competitive power</td></tr>
<tr><td colspan="3">3. Expand research infrastructure and strengthen collaboration
① Create quantum computing infrastructure for research in stages ② Create infrastructure to support the creation of quantum devices and strengthen collaboration</td></tr>
<tr><td colspan="3">4. Promote the use of quantum technology and industrial technology
① Uncover technology and information useful to the economy and society ② Create examples of achievements based on public-private partnerships ③ Support industrialization to create a quantum market</td></tr>
<tr><td colspan="3">5. Strengthen strategy for quantum R&D project investment</td></tr>
</table>

Source: Quantum Technology Research and Development Investment Strategy

In June 2021, the South Korean government made revisions to the "Special Act on Promotion of Information and Communications Technology and Vitalization of Convergence Thereof," adding language pertaining to quantum technologies. In Articles 2, 7, and 27, the law establishes definitions along with provisions for research development, human resource development, and international cooperation, laying out legal grounds for supporting quantum technology research and development.

Another noteworthy event at this time was the June 2021 establishment of the "Future Quantum Convergence Forum." The forum is led by the MSIT and co-chaired by Kim I-han of South Korea's largest telecom, KT, and Professor Kim Ju-wan of the Korea Institute for Advanced Study (KIAS). It is expected to lead cooperation among industry, academia, and government in quantum research and development. Along with South Korea's three largest telecoms, its membership comprises 12 large companies such as Hyundai Motor Company and LG Electronics, 19 small or medium-sized companies that include IDQ, AhnLab, and CRYPTOLAB, and 40 universities such as Seoul National University, the Korea Advanced Institute of Science and Technology (KAIST), and Korea Institute of Science and Technology. All these developments suggest the actualization of the South Korean government's strategy, in which almost all the country's stakeholders are engaged which puts a particular emphasis on public-private cooperation toward achieving global competitiveness in quantum technologies, and this trend merits further observation.

With the goal of transforming South Korea into a leading nation in science and technology, the Yoon administration has announced 110 key policy tasks[8] that it will seek to achieve by investing in science and technology and developing human resources focused on achieving innovation. A key strategy will be building a science and technology infrastructure centered on such things as quantum-encrypted communications networks and supercomputers. In a speech given on October 25, 2022, at a meeting of the National Assembly, Yoon announced that the country would "invest 4.9 trillion KRW (3.8 billion USD) in areas such as quantum computing, space and aviation, artificial intelligence, and advanced bioscience.[9]"

6.2 Quantum technology research and development

According to the "Quantum Technology Research and Development Investment Strategy," while taking longer than the U.S. or European countries to turn its attention to quantum, South Korea is now standing up to the competition in technology with its "selection and concentration" strategy. Quantum communications could be one of the country's strengths here. This conclusion can be drawn from the trend regarding the number of research papers and patents applied for as described in Chapter 1. Additionally, there is the fact that, according to South Korea's National Science & Technology Information Service (NTIS), 6,059 quantum-related research papers have been published in recent years (the five-year period starting in 2017). Moreover, an R&I report from the Korea Institute of Science and Technology Information (KISTI)[10] states that 246 quantum-related papers have been published on

[8] For more information, see "Plans of the Yoon Administration — A Bold Future to be Built through Autonomy and Ingenuity," South Korea Policy Briefing (June 8, 2022).

[9] See "President Yoon to Invest in Semiconductors, Quantum Computing, AI, and More," Korea Industry Daily (October 25, 2022).

[10] For more information, see the KISTI R&I Report entitled "Science, Technology, and Industry Analysis of Quantum Technologies" (March 2, 2022), pgs. 58-76.

the Web of Science. As for the content of these papers and patents, 50.8% concern quantum communications while 41.9% and 7.3% pertain to quantum computing and quantum sensing, respectively.

The MSIT's "Quantum Technology Research and Development Investment Strategy" states that South Korea's share of worldwide patent applications in the field of quantum communications is 7.9%, which is much higher than the 3.3% for quantum computing and the 4% for sensing. While it is often companies that file for patents in Japan, the U.S., and Europe, universities and public research institutes do much of the filing in South Korea. Some standout South Korean patent filers in quantum communications are SK Telecom, the Korea Institute of Science and Technology (KIST), and the Electronics and Telecommunications Research Institute (ETRI), all of which rank among the top 10 patent filers globally. KAIST ranks 29th in quantum computing, and the Korea Research Institute of Standards and Science (KRISS) ranks 15th. Patents are focused on qubits and processors in quantum computing, quantum devices and quantum modules in quantum communications, and optical sensors in quantum sensing.

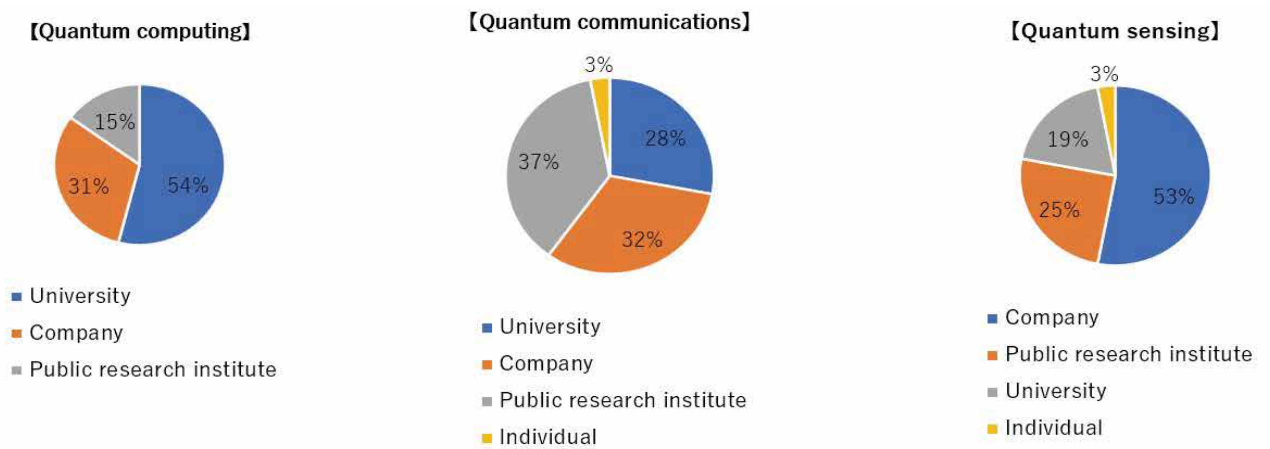


Table 6-2: Patents filed, by patent filer

Source: Quantum Technology Development Investment Strategy

The NTIS has been working on research and development projects supported by the state since 2002. There have been 16,260 such projects designated with the keyword "quantum": 1,332 in 2019, 1,342 in 2020, 1,491 and 2021, and 1,094 and 2022 (as of June 10, 2022), to cite only the past few years. Table 6-3 shows the number of projects undertaken each year since 2002. The number of high investment projects exceeding 500 million KRW (385,000 USD) is indicated by the line graph and has sharply increased beginning in 2019.

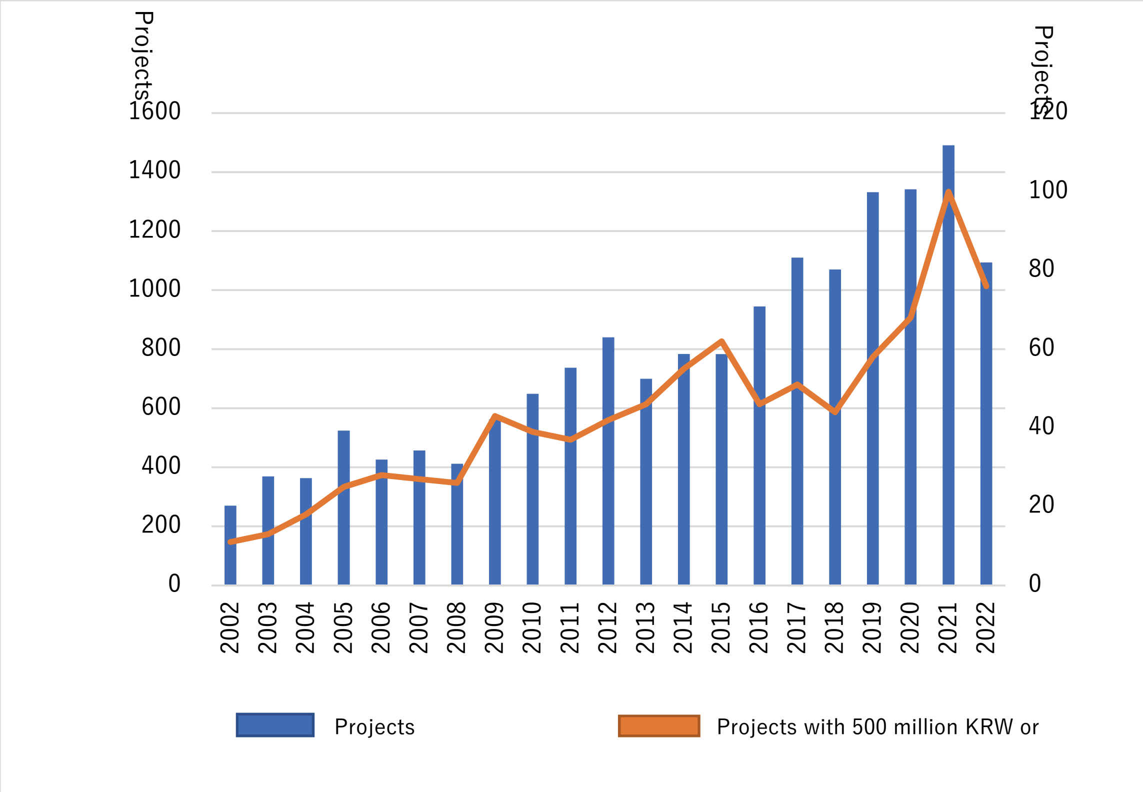


Table 6-3: Quantum-related projects, by year

Source: Prepared by the author based on data from the NTIS

Note: The left axis is the Y axis for the bar graph, and the right axis is the Y axis for the line graph.

Figures given are through June 10, 2022.

Some of the research institutes and universities with the most projects are Seoul National University (1,058 projects), KAIST (912 projects), and the Pohang University of Science and Technology (509 projects). Further information about these organizations' research achievements is provided in "6.3 Noteworthy research institutes and universities."

The following developments are noteworthy with regard to private sector research and development investment.

On July 15, 2022, Yonsei University and IBM signed an agreement to build the Yonsei-IBM Quantum Computing Center. This will make South Korea the fifth country in the world to have an IBM quantum computing center after the U.S., Germany, Japan, and Canada. With IBM's quantum computing technologies as a foundation, Yonsei University will focus on revitalizing quantum technology industry and research and developing software that leverages quantum computing.[11]

Initiatives are also underway between Samsung and South Korea's three largest telecoms (SK Telecom, KT, and LG Uplus). A quantum computing research team led by the Samsung Advanced Institute of Technology is collaborating with the IBM Q network, a quantum computing research hub led by U.S.-based IBM, while at the same time conducting joint research with the University of Chicago. Meanwhile, SK Telecom, KT (a telecom), WOORIRO, and WOORINET (equipment and part developers) are developing equipment and parts for quantum-

[11] See "Yonsei University and IBM Sign Agreement to Build a Quantum Computing Center," Yonsei University press release (July 15, 2022).

encrypted systems. The Quantum Technology Research and Development Investment Strategy appraises the current state of research and development investment in South Korea as follows: “As with space development and national defense technologies, quantum technologies require top-down, long-term, stable support, which is currently lacking in South Korea. While developed countries have been making quantum technology investments for more than 15 years, South Korea will need to focus on practice selection and concentration due to its lagging position. The government will need to take the lead as relying on companies is too great a risk.”

As noted above, although the government's R&D investment has been rising since 2019, along with the production of quantum devices and demand for quantum computing services, the country still needs to strengthen its device production process infrastructure. Equipment used in the semiconductor industry, an area in which South Korea excels, cannot be used to produce quantum devices due to the volume and process differences, requiring the building of specialized production infrastructure. Furthermore, with researchers in South Korea dependent on overseas quantum computing services to develop quantum algorithms and software, the U.S. and other developed countries are more staunchly safeguarding their strategic technologies. This makes it urgent for South Korea to build its own national computing hub. Along with conducting R&D projects, the government invested 29 billion KRW (22.3 million USD) between 2020 and 2021 to build a quantum-encrypted communications network, and is now running a test-bed project to build quantum-encrypted communications infrastructure aimed at testing the network and establishing a reference.

However, South Korea's overall quantum capabilities have yet to match those of developed countries. The Institute for Information & Communication Technology Planning & Evaluation (IITP, a research organization affiliated with the National Research Foundation of Korea, which operates under the MSIT) issues its “ICT Technology Level Survey and Technology Competitiveness Analysis Report” every year. In its 2020 report, it assigns Europe, the most advanced region in the world for quantum technologies, a reference score of 100 and puts South Korea's technical capabilities at 85.2% of that (the U.S., China, and Japan were 99.7%, 99.0%, and 91.9%, respectively). By category, South Korea's technical capabilities concerning quantum sensors, quantum communications, and quantum computing were 86.7%, 85.7%, and 77.4%. The average score for South Korea's ICT technologies was 88.6%, which puts quantum technologies near the bottom when it comes to South Korea's ICT capabilities. South Korea scores low both for quantum theory, superconductivity, quantum materials, and other aspects of technical infrastructure, as well as for hardware and software in general. Compared to developed countries that have released early versions of products, South Korean companies are still at the exploration stage and need to create synergistic effects through government, industry, and academia cooperation.

Looking at technology development, since 2019 the Korea Research Institute of Standards and Science (KRISS) and Seoul National University have been developing superconductivity technologies and quantum dot technologies, respectively, while the Korea Institute of Science and Technology (KIST) has been developing qubit, system, and SW technologies using NV centers. Furthermore, as part of its “project to build quantum-encrypted communications infrastructure,” the National Information Society Agency (NIA) has been carrying out a project to build a quantum-encrypted communications network for healthcare and industry since 2020. At the same time, the National Security Technology Institute, Electronics and Telecommunications Research Institute (ETRI), Korea Institute of Science and Technology (KIST), and Korea Research Institute of Standards and Science (KRISS) have all been engaged in basic and applied research in such fields as small quantum key distribution, quantum networks, and direct quantum communications. The Gwangju Institute of Science and Technology is working to develop quantum LiDAR applications for quantum lasers, while Samsung and SK Telecom are acquiring the early results of those efforts. Other companies are working to incorporate quantum sensing into quantum LiDAR development, and promote its use in gas sensing. Since 2022, large companies have been focused on developing quantum simulator technologies that can be used to solve real-world problems.

South Korea currently has 127 researchers doing quantum research, according to a filing by the NTIS, and will need a minimum of 1,000 such researchers by 2030, according to the Quantum Technology Research and Development Investment Strategy. Along with scarce human resource development projects currently underway, there are no good policies for attracting competent researchers from overseas.

Table 6-4: Ongoing quantum human resource development projects

Project name	Details of support	Number of human resources being developed (yearly)
2018–2023, Developing Human Resources for Information Communication Transmission (ITRC)	Industry-academia-research R&D projects to improve practical working abilities, entrepreneurship education, etc.	Master's and doctorate holders: 30
From 2020: Developing human resources in science, technology, and innovation (quantum information science)	Foreign postdoctoral researchers: 2 years; master's/doctoral internship: 6 months; outsourced education (master's): 2–4 months	6 months or more: 15 Less than 6 months: 35

Source: Quantum Technology Research and Development Investment Strategy

6.3 Notable institutes and universities

This section will provide an overview of leading research institutes and universities in South Korea that are researching quantum technologies. Other information provided includes research budgets, scope, and primary areas of research.

Table 6-5: Notable research institutes and universities

Status	Name	Research organization and number of researchers	Research funding (20 years)	Details and outcomes of research
Public research institute	Korea Research Institute of Standards and Science (KRISS)	・Quantum Technology Institute ・Researchers: 14; Doctoral course students/postdoctoral researchers: 4	4 billion KRW	・Design of superconducting quantum computing elements (creation and operation of 8-qubit superconducting chip made possible) ・Optical lattice ultracold atom quantum simulator
	Korea Institute of Science and Technology (KIST)	・Quantum information research team ・Researchers: 9; Master's/doctoral course students/postdoctoral researchers: 2	5.4 billion KRW	・Lattice defect spin qubits and quantum interface generation suppression technology ・Engineering-based quantum simulation
	Electronics and Telecommunications Research Institute (ETRI)	・Quantum Technology Research Division High Performance Computing Research Section ・Researchers: 20; Postdoctoral researchers: 4	4.7 billion KRW	・Foundational technologies that use quantum computing (operation algorithms) ・Quantum computing system technology (program language, compiler, synthesizer, operating system, signal processing suppression technology) ・Semiconductor substrate quantum computing technology
Universit y	Korea Institute For Advanced Study (KIAS)	・School of Computational Science and Quantum Space Research Center ・Professors: 2; Master's/doctoral course students: 6	800 million KRW	・General theories of quantum information science ・Quantum computing, quantum machine learning
	Seoul National University	・Department of Physics and Astronomy, Department of Computer Science and Engineering, and Department of Electrical and Computer Engineering ・Professors: 7; Master's/doctoral course students/postdoctoral researchers: 55	2.7 billion KRW	・Design of a 5-qubit semiconductor spin quantum processor chip, quantum measurement ・Made 20-qubit simultaneous generation possible ・Lattice based, neutral atom-based quantum computing, error correction technology, etc.
	KAIST	・Department of Physics, School of Electrical Engineering ・Professors: 9; Master's/doctoral course students/postdoctoral researchers: 43	3 billion KRW	・Superconductor quantum bit measurement, nanoscale single-atom microscope, quantum computation, Rydberg quantum simulation, etc.
	Korea University	・Department of Physics ・Professors: 2; Master's/doctoral course students: 6	500 million KRW	・Diamond NV center-based quantum information research ・Development of quantum technology based on molecular qubits
	POSTECH	・Department of Physics, Department of Electrical Engineering ・Professors: 8; Master's/doctoral course students/postdoctoral researchers: 43	5 billion KRW	・Quantum entanglement and quantum decoherence suppression, superconducting elements, cryogenic quantum transport ・Quantum computing system semiconductor design ・Ion trap quantum computer processor design
	Sungkyunkwan University	・SKKU Advanced Institute of Nanotechnology ・Professors: 2; Master's/doctoral course students: 4	200 million KRW	・Made 5-qubit superconducting computing element design and manufacturing possible ・Cryogenic high-frequency super-precision technology development quantum computing system integration technology

6.3.1 Korea Research Institute of Standards and Science(KRISS, 한국표준과학연구원)

Established as the Korea Standards Research Institute in 1975, its name changed to the Korea Research Institute of Standards and Science in 1991. KRISS was officially designated to serve as the national body for metrology standards by the Framework Act on National Standards in 1999, and is currently a research body for the National Research Counsel of Science & Technology under the Ministry of Science and ICT. The Office of Audit and Inspection, Division of Policy and Strategy, and Research Review Committee report to the president, while eight research organizations such as the Quantum Technology Institute, Interdisciplinary Materials Measurement Institute, and National Center for Standard Reference Data, as well as five divisions that include the Division of Physical Metrology and Division of Chemical and Biological Metrology, report to the vice president. Its vision, "KRISS, Standards for Life," guides its three-part mission: (1) establish, maintain, and improve national measurement standards, (2) conduct research and development in measurement science and technology, and (3) disseminate measurement standards and technology and provide support services. KRISS maintains international cooperative relations with the National Metrology Institute of Japan (NMIJ) and National Institute of Information and Communications Technology (NICT) in Japan.

The Quantum Technology Institute, founded in 2017[12], is staffed by 14 researchers and four postdoctoral and doctoral researchers whose main activities are measuring and controlling quantized physical quantities of things such as photons, atoms, electrons, and phonons, as well as developing technologies to generate and control quantum

[12] The institute was upgraded from the Quantum Metrology Center to the Quantum Technology Institute in 2017 due to the importance of quantum research.

mechanical effects such as qubits and quantum entanglement. These 18 researchers are divided into the Quantum Spin Team, Hybrid Quantum Systems Team, Quantum Optics Team, Quantum Magnetic Imaging Team, Fab Infra Team, Ultracold Atom Quantum Research Team, and Single-electron Quantum Device Team. Its 2020 research budget was 4 billion KRW (3.1 million USD), and its research achievements include the following. (1) Producing and operating 8-qubit superconductive chips as part of its superconductive computing component design and process activities, as well as designing and producing 20-qubit level devices. (2) Created a quantum simulator built on an optical lattice cooling atom quantum platform. (3) Achieved the world's highest atom transport efficiency (90%) using an innovative zoom lens optical system and laser system.

6.3.2 Korea Institute of Science and Technology（KIST, 한국과학기술연구원）

Founded in 1966, KIST merged with the Korea Advanced Institute of Science in 1981 before becoming an independent entity in 1989. KIST, South Korea's first government-funded research organization, is a major research institute with a total of 2,743 staffs, including graduate students (2234 researchers). It currently operates on a total budget of 33.5 billion KRW (258 million USD), which consists of 19.1 billion KRW (14.7 million USD) in grants from the government and 14.3 billion KRW (11 million USD) from commissioned businesses and other organizations.

The Institute consists of an Auditing Division, Planning & Management Committee, and Research Review Committee that report to the president, and 17 departments such as the Brain Science Institute Center for Brain Disorders and Next-generation Semiconductors Institute that report to the vice president. KIST also has branch institutes in Gangneung and Jeonbuk, along with KIST Europe, which serves as a global research hub in Germany. As implied by its vision, "bringing the future to the present," KIST focuses on researching and developing advanced technologies such as advanced material technologies, clean technologies, next-generation semiconductors, AI, and robots.

Next-generation semiconductors Research Lab, The Center for Quantum Information, which was added to the Next-generation Semiconductors Institute in 2012, conducts research mainly aimed at developing quantum computing core technologies used in information processing for quantum phenomena, as well as quantum communications technologies for ensuring communications security. Its 11 staffs consist of nine researchers and two postdoctoral researchers. Using a budget of 5.4 billion KRW (4.2 million USD), the Center for Quantum Information's main achievements include developing lattice defect spin qubits and technologies for controlling quantum interface generation, along with building engineering infrastructure and quantum simulations. With a concentration on basic research, its ultimate goal is to achieve core technologies for building long-distance qubit networks and conducting large-scale quantum information processing. Although there are currently no ongoing joint research projects with Japanese universities or research institutes, the Center for Quantum Information has signed a cooperation agreement with Tohoku University and the Tokyo Institute of Technology.

6.3.3 Electronics and Telecommunications Research Institute (ETRI, 한국전자통신연구원)

Established as Korean Electrical Equipment Laboratories in 1976, its name was later changed to the Korea Information Communication Industry Institute in 1997. ETRI's vision as a government-funded research Institute engaged in ICT technology R&D is “National AI Research Institute – Making a Better Tomorrow.” There are 2,298 people working at ETRI, including 2,011 engineers and other research personnel. ETRI has conducted 2,961 projects over the last five years (650 projects in 2020), with an average annual research expenditure of 61.2 billion KRW (47.1 million USD). It appears to be a research institute that plays a leadership role in ICT research, and has produced 3,800 IT experts. It consists of a global PR department and audit department that report to the president, as well as seven divisions that report to the executive vice president, including an ICT creation laboratory, communications media laboratory, and artificial intelligence laboratory.

The Quantum Technology Research Department (양자기술연구단)[13], a part of the ICT creation laboratory, mainly focuses on quantum communications, sensing, and computing technology research. It is staffed by 20 people, 20 researchers and four postdoctoral researchers, and has a budget of 4.7 billion KRW (3.6 million USD). As a reason achievement, in collaboration with research teams in South Korea and abroad, the Quantum Technology Research Department developed the world's top quantum algorithm for solving the linear LWE status encryption problem, which is viewed as key to achieving post-quantum cryptography. Other achievements include developing basic technologies powered by quantum computing (computing algorithms), quantum computing system technologies (programming languages, compilers, signal processing control technologies), and semiconductor substrate quantum computing technologies (for creating semiconductor quantum dot qubits, and superconductive qubits).

6.3.4 Institute for Basic Science（IBS, 기초과학연구원）

This institute has a shorter history than above three research institutes, and was established in 2011 under the Special Act on Establishment of and Support for International Science and Business Belt. With "Making Discoveries for Humanity & Society" as its vision, the Institute for Basic Sciences is a research organization that conducts basic research in fields such as mathematics, physics, chemistry, and the life sciences, and was established in 2017 as part of the Center for Quantum Nanoscience (양자나노과학 연구단). As an organization that values diversity, the two managers that lead its laboratory are foreign nationals, and about 40% of team members are from other countries. The institute's 40 staff comprise eight researchers, seven postdoctoral researchers, 15 graduate students, and 10 general staff.

Areas of Research Its main areas of research are: (1) the quantum coherent manipulation of individual spin on surfaces, (2) quantum coherence in spins in insulators, (3) rare earth elements that spin on interfaces, (4) molecular qubits on interfaces, and (5) theoretical research into quantum systems on interfaces. Included among its achievements are discovering a new method of supressing the auger recombination process, which reduces the efficiency of photoelectron devices that use qubits,[14] as well as developing a method to minimize the impact of

[13] Year of establishment is unclear as this information has not been publicly disclosed.

[14] For more information, see “New Method Discovered for Suppressing Qubit Auger Recombination — South Korea's IBS,” Science Portal Korea (March 2, 2022).

metrology on the quantum Otto engine.[15]

6.3.5 Seoul National University（SNU, 서울대학교）

Founded in 1946 as South Korea's first national university, Seoul National University is an internationally renowned university that has ranked 18th in Asia and 36th in the world in QS World University Rankings 2022. It is a large school, with 5,410 teaching staff, 27,924 students, 15 colleges (73 departments), 70 departments with the Master's programs, 72 departments with PhD programs, and 12 professional graduate schools.

Quantum technologies are being researched by the Department of Physics and Astronomy, Department of Computer Science and Engineering, and Department of Electrical and Computer Engineering, and there are seven teaching staff and researchers, along with 55 graduate students and postdoctoral researchers working in the field. Seoul National University's 2020 research expenditure on quantum research was 2.7 billion KRW (2.1 million USD). Its research achievements included designing and enabling the quantum measurement of 5-qubit semiconductor spin quantum processor chips, successfully generating 20 qubits simultaneously (but not resolving entanglement between the qubits), and developing basic photon technologies, neutral atom basic quantum computing technologies, and error correction technologies.

6.3.6 Korea Advanced Institute of Science and Technology（KAIST, 한국과학기술원） & Korea Institute For Advanced Study（KIAS, 고등과학원）

KAIST predecessor Korea Advanced Institute of Science (KAIS) was established in 1971 with the goal of preventing brain drain amid a low repatriation rate among South Koreans studying abroad in the 1960s. KAIS then merged with the Korea Institute of Science and Technology (KIST) in 1980 to form KAIST. KAIST has a very complicated history, merging and splitting many times, but it was officially established in 1971. After merging with the Information and Communications University in 2009, it became even bigger. Established under the Korea Advanced Institute of Science & Technology Act, KAIST differs from special research institutes in that it has no education department, and being an organization under the Ministry of Science and ICT, it also has unique entrance exams.

The institute's primary role is conducting basic, integrated, and multidisciplinary research, as well as collaborating with members of industry, academia, and government, to develop human resources in science and technology fields and promote science and technology innovation. It has 1,590 teaching staff (researchers), 10,793 currently enrolled students, seven colleges (27 departments and schools), and 43 programs. Affiliated with the institute are KIAS (see further information below), the Nano Convergence Research Institute, and the Korea Science Academy of KAIST.

Working on quantum research are nine researchers (teaching staff) and 47 postdoctoral and graduate researchers

n the Department of Physics and School of Electrical Engineering. KAIST has a quantum research budget of 3.0 billion KRW (2.3 million USD), and is engaged in R&D that includes superconductor cubit measurement, nano-

[15] For more information, see “Development of Method for Limiting Impact of Metrology on the Quantum Otto Engine — South Korea's IBS,” Science Portal Korea (December 2, 2021).

level single atom microscopes, quantum computation, and Rydberg quantum simulators.

KIAS, an institution affiliated with KAIST, was established in 1996 to enhance South Korea's basic science capabilities, and was the first institution in South Korea to focus solely on (theoretical) basic science.[16] Using the Institute for Advanced Study (IAS) as a role model, KIAS is primarily focused on creating an environment where those engaging in basic research can give their research their full attention. It is also working to give researchers strong basic research skills. KIAS has three schools (mathematics, physics, and computational sciences), and four research centers (the Quantum Universe Center, Center for Mathematical Challenges, Center for Artificial Intelligence and Natural Sciences, and Center for Advanced Computation). In 2013, the Open KIAS Center was established to serve as a foundation for collaboration between talented university researchers and research institutes in South Korea and abroad.

KIAS' Quantum Universe Center, established in 2014, conducts research involving cosmology, astrophysics, information theory, quantum gravity, particle physics, and quantum states of matter. It aims to discover and share new possibilities in fields such as matter and interaction characteristics, condensed matter and emergent phenomena, quantum information, and quantum mathematics. Through its School of Computational Sciences, it also researches quantum information science. KIAS has two researchers (at the School of Computational Science and Quantum Space Research Center) and six graduate students doing quantum research. With a budget of 800 million KRW (616,000 USD), they conduct research involving general quantum information science theory, quantum computing, and quantum machine learning.

6.3.7 Pohang University of Science and Technology (POSTECH, 포항공과대학교)

Established in 1986 with support from POSCO, POSTECH engages primarily in science and technology research. Although a relatively young university, it is said to have been providing outstanding scholarships and accepting top students at its impressive campus since its establishment, with first-year students having an average entrance exam score of 300 (a perfect score is 340). It is at the top of its class for science and technology research, conducted by an elite few that have demonstrated excellent performance, making the university particularly strong in the fields of solid-state physics, life sciences, materials science, and bioprinting. With the slogan "Dare to be Different! POSTECH paving the way to a brighter future for science and South Korea," POSTECH has 280 teaching staff and an annual research expenditure of around 200 billion KRW (154 million USD). The university publishes around 1,500 papers annually in journals listed in the Science Citation Index, and files 300-500 patent applications. Along with 18 undergraduate departments and 21 graduate departments, the university has 102 affiliated laboratories.

Its quantum research is conducted by eight researchers (teaching staff) and 43 postdoctoral and graduate researchers in its physics and electrical engineering departments. POSTECH's research expenditure, which was 5 billion KRW (3.9 million USD) in 2020, has gone toward researching quantum entanglement, quantum decoherence control, superconducting devices, and ultra-low temperature quantum transport. It has also succeeded

[16] In 2009, in response to a growing number of people with the view that strengthening basic research would be critical to making South Korea into a science and technology world power, discussions were held about breaking off from KAIST. Strong opposition saw the idea fail, however.

6.4 Notable companies

Since even before the government began investing in quantum technologies, large companies such as Samsung and SK Telecom have had their eye on quantum technologies, engaging in technology R&D and investing in promising venture companies. The following pages look at large companies that are actively engaged in the field of quantum technology, along with several small or medium-sized companies that are currently making waves.

Table 6-6: Notable companies

Field	Main company	Company quantum technology and investment
Quantum computing	SAMSUNG	Has been involved in joint research on quantum computing with IBM since 2017. Invested 6.5 billion KRW in Aliro Technologies and IONQ in 2019. Invested 57.9 billion KRW in “Quantum Machines,” an Israeli quantum computing start-up, in 2021.
	–	The development of an 8-qubit processor, and elemental and basic technologies (e.g. refrigeration engineering, super-conductivity) are late when compared to advanced nations. SW and algorithms are also in their initial stage.
Quantum communication	SK Telecom	Began quantum encrypted communication research in 2011. Developed quantum random number generation chip products in July 2017. Purchased encrypted communications startup company IDquantique in March 2018.
	KT	Established the Quantum Communications Applied Research Center with KIST and the Korea Nanotechnology Institute in 2017, and is currently researching the practical application of quantum encrypted communication. Is focused on creating standards for encrypted communication in Korea and elsewhere.
	LGU＋	Developed a quantum secure chip for IoT terminals in 2020. Secured PQC technological capabilities in 2021.
	EYL	Commercialized the world’s first solution for preventing interception using quantum random numbers in 2021.
	WOORIRO	In 2020–2023, is expected to use SPAD sensors to develop super-small single photon detection (SPD) that recovers signal transmitted by single photons.
	–	Companies such as SKT (5G, Korea–Daejeon–Daegu 380 km) and KT (Jeollanamdo–naval command office 45 km) have developed technology for the first-stage commercialization of partial priority (trial) service operations. There is a need to increase productivity, work with existing research infrastructure, ensure long distance quantum transfer, and carry out research on wired and wireless channels.
Quantum sensors	–	Developed an ultrasmall atomic clock, quantum magnetic field, gyro sensor ADD products, etc. The Korea Research Institute of Standards and Science (KRISS) is researching inertia and magnetic fields, Seoul National University is also researching magnetic fields, SKT is focused on quantum LiDAR, and WOORIRO is researching single photons, and they are developing related technologies.

6.4.1 SAMSUNG

The most enterprising company in terms of quantum R&D and investment is Samsung, which was founded in 1938. South Korea's largest multinational corporation, Samsung ranks number one for all corporate ranking criteria, including "chaebol" ranking and market capitalization, with number two far behind. The company has a massive impact not only on South Korea's economy but also its politics, society, and culture.

Samsung has chosen quantum computing as one of the technologies with the highest potential for growth, and is investing in companies with potential. Samsung invested 2.7 million USD in Aliro, a quantum computer software company founded by researchers from Harvard's quantum information science resource center, and 55 million USD in U.S.-based quantum computer hardware company IonQ in 2019, as well as 50 million USD in Quantum Machines in 2021.[17] Established in Israel in 2018, Quantum Machines developed the first standard programming language for quantum computers, and is attracting attention for having created Quantum Orchestration (QOP), a hardware platform to help build and run quantum computers.

In the first half of 2020, Samsung released Galaxy Quantum, a smartphone with a built-in quantum-encryption system.

Since 2013, Samsung has been running the self-funded "future technology development projects," for which the company selects future fields of science and technology where state support will be needed, develops themes, and provides support. In total, 923.7 billion KRW (710.7 million USD) has been used across 706 projects. Of these projects, 1,241 have been written about in international academic journals, and 93 research papers have been featured in either Science or Nature.

Quantum-related started being added to these projects in 2018 and include “development of technologies to create practical applications for quantum computing,” “development of a THz speed transistor for six GEN quantum computing applications,” and “scalable semiconductor substrate quantum relay for quantum networks.” Quantum research funding is about 12.3 billion KRW (9.5 million USD). Many of these projects have delivered results soon after being launched, with particularly impressive achievements made in quantum-encrypted communications and next-generation image sensors.[18] A research team led by Professor Dae Sung Chung of POSTECH's Department of Chemical Engineering, using funding received in 2018, succeeded in developing an optical detection technology 14.7x better than existing technologies, a result that has been seen as revolutionary in the field of next-generation image sensors.[19] Additionally, a research team led by Professor Hong-gyu Park of Korea University, using funding received in 2020, developed the world's first electrically driven single-photon emitter, an achievement covered in a Science Advances article entitled “Electrically driven strain-induced deterministic single-photon emitters in a van der Waals heterostructure.”

[17] For more information, see "Samsung Invests in Israeli Quantum Computing Company" MK Newspaper, (September 7, 2021); "Samsung: Quantum Computer Competition is Just Beginning," Korea Economic Daily (October 24, 2019).

[18] For more information on the results of these research projects, see “Results of Research Supported by Samsung Future Technology Development Projects Announced,” Samsung Newsroom (November 24, 2021).

[19] Covered by international academic journal Advanced Materials in an article entitled “Interfacial electrostatic interaction-enhanced photomultiplication for ultra-high external quantum efficiency of organic photodiodes.”

6.4.2 KT, SK Telecom, LGU+

KT, SK Telecom, and LG Uplus dominate South Korea's mobile communications industry, with market share at 44.1%, 31%, and 24.9% for SK Telecom, KT, and LG Uplus (as of February 2022). Each company is a member of the Future Quantum Convergence Forum, has an interest in quantum technologies, and is putting particular effort into standardizing quantum-encrypted communications.

SK Telecom is a communications company in the SK group and began quantum-encrypted communications research in 2011. It developed a quantum random number generation chip product in 2017, acquiring Swiss-based quantum communications startup ID Quantique the following year.[20]

Together with the Korea Institute of Science and Technology, KT established the Quantum Communications Applied Research Center at the Korea Nanotechnology Institute, which researches practical applications for quantum-encrypted communications. Among South Korea's three largest telecoms, KT is the most focused on standardizing quantum-encrypted communications. In February 2022, KT received international standard approval for the first time in the world from the International Telecommunication Union (ITU) for standards to assess quantum-encrypted communications service quality, which KT developed itself. These standards apply parameters consisting of response delay, response delay variation, and loss ratio, and enable service quality to be measured.[21]

LG Uplus developed a quantum security chip for IoT devices in 2020, along with a post quantum cryptography technology the following year.[22] On October 22, 2022, LG Uplus announced that it had developed applications for both post-quantum cryptography (PQC) technologies and a physical uncountable function (PUF), and that it had developed the world's first “PQC PUF VPN” for strengthening CCTV security.[23]

6.4.3 WOORIRO

An optical communication industry company established in 1998, WOORIRO deals in photons, which behave as quantum particle of light. WOORIRO is famous in South Korea for its optical power calibration technologies, single-photon detectors, and ultrafast photodetectors. While not a large company, it has succeeded in developing and mass-producing the country's first ultraslim splitter and has demonstrated world-class capabilities in optical communication. WOORIRO produces ultrafast photodetector chips and modules and provides the world with LTE and 5G networks. These technologies are indispensable for the above-mentioned three telecoms as they are needed to build ultrafast optical communication networks.

Optical distributors power long-distance optical communications, and WOORIRO makes optical distributor chips and the optical modules that they are used in. Armed with these technical capabilities, the company is expanding its reach into the wavelength division multiplexing (WDM) devices field in overseas markets. The

[20] Established in 2001, this company researches and develops quantum key transport systems, quantum safety network encryption, single-photon counters, and hardware random number generators. For more information, see the company's website.

[21] For more information, see “KT-developed Quantum-encrypted Communications Service Quality Assessment Standards Become ITU International Standards for First Time Ever,” Aju News (February 24, 22).

[22] For more information about these three companies, please see “Fear Not the Quantum Computer — KT, SKT, and LG Uplus on the Verge of Commercialization,” BLOTER (February 24, 2022).

[23] See “LG Uplus Strengthening CCTV Security through Post-quantum Cryptography,” NEWSIS (October 20, 2022).

single-photon avalanche diode (SPAD) developed by WOORIRO is a chip form of an ultrafast, high sensitivity optical sensor that can detect photons. It is a crucial component in quantum-encrypted communications, which are said to be impossible to hack. Because of their world-class performance, WOORIRO's SPADs are used not only by companies in South Korea but also the U.S., China, Europe, and India, and by Toshiba in Japan.

6.4.4 EVERYWHERE IN YOUR LIFE (EYL)

A startup founded in 2015, EYL is a rising star in the quantum random number generators industry. Its vision is "to provide random number generators and applications that are energy-efficient and the smallest, fastest, and most affordable in the world." It also incorporated in 2017 the U.S., where it was included in a list of 100 global ventures with the most disruptive potential, called DISRUPT 100. As further testament to the company's capabilities, it was also included in the "Startup Grind Silicon Valley 20" in 2018.

EYL also acquired security authorization from the U.S. government in 2021 for the world's first security solution to be powered by quantum random number generator technology. This security solution, a USB quantum key generator, has managed to achieve compliance with the FIPS140-2 information processing standard from the U.S. federal government, as well as U.S. CMVP encryption module certification.[24]

6.5 Notable researchers

The following six noteworthy researchers have been chosen for inclusion here due to their renown, contributions to, or achievements in academia based on the research paper and patent data presented in Chapter 1.

6.5.1 LEE Haiwoong（이해웅）

A professor emeritus at KAIST's Department of Physics. He is a leading figure in quantum research and one of the first people in South Korea to conduct quantum informatics research. His fields of research are quantum engineering, nuclear engineering, and quantum physics. After graduating from Seoul National University's Department of Physics, he received his PhD in quantum optics from the University of Pittsburgh in 1977. He then did postdoctoral research at the University of Rochester, the University of Arizona, and the University of New Mexico. He held positions as assistant teacher and assistant professor at the University of Oakland starting in 1981 before becoming a professor at KAIST in 1989. He has published more than 100 papers concerning quantum informatics, quantum optics, and quantum physics on the subjects of quantum entanglement and quantum information. In recognition of his achievements, he received the 3.1 Culture and Academia Award (Natural Sciences Category) in 2006 and the KAIST Outstanding Lecturer Award in 2008. Some of his best-known works are "Quantum Theory of Light," "A Lecture on Quantum Informatics," and "Google Knows All."

[24] For more information, see "Startup EYL Acquires U.S. Security Authorization for Security Chip Powered by Quantum Random Number Generator Technology," ETNEWS (April 23, 2012).

6.5.2 JEONG Hyunseok（정현석）

A physics professor at Seoul National University. In recent years, he has been one of South Korea's most active researchers on the subject of quantum research. His main areas of focus are nuclear, molecular, and light physics, especially fundamental quantum mechanics, as well as quantum information theory, quantum information processing using light, and quantum optics. He graduated from Sogang University's Department of physics in 1996 and then received his PhD in physics in 2003 from Queens University Belfast. Beginning in 2003, he worked as a postdoctoral researcher at the University of Queensland, becoming a research fellow at that university's Quantum Computer Technology Center in 2005. Since 2008, he has been an assistant professor at Seoul National University. He has been actively engaged in quantum research in recent years and has published numerous quantum-related papers. His best-known works include “Quantum Metrological Power of Continuous-Variable Quantum Networks (2022),” “Quantum one-time tables for unconditionally secure qubit-commitment (2021),” “Universal compressive tomography in the time-frequency domain (2021),” and “Resource-efficient topological fault-tolerant quantum computation with hybrid entanglement of light (2020).”

6.5.3 CHO Minhaeng（조민행）

He is a research team leader in molecular science and spectrometry at the Institute for Basic Science and is a named endowed chair professor in Hyundai-Kia Natural Sciences at Korea University. After graduating from Seoul National University's Department of Chemistry in 1987, he received his PhD in physical chemistry from the University of Chicago in 1993. He then worked as a postdoctoral researcher at MIT before becoming an assistant professor at Korea University's Department of Chemistry. As a visiting professor, he did research at the Institute for Molecular Science in Japan in 1997, Oxford University in 2000, and the University of California, Berkeley in 2004.

In 2005 he became a research team leader at the Institute for Basic Science (IBS) in the fields of molecular science, spectrometry, and dynamics. At Korea University, he transitioned from being a professor of chemistry to a named endowed chair professor in Hyundai-Kia Natural Sciences.

In 2021 he tested the principle of complementarity, which is seen as a difficult problem in quantum mechanics. He proposed and built a new model for complementarity in wave-particle measurement, which was covered in international journal Science Advances. This is the first new complementarity-related discovery to have been made in 100 years since the principle was proposed in 1928, and as major significance for academia. Cho received the Young Scientist Award in the Science and Technology category in 1999, the Korean Academy of Science and Technology Award in 2011, and numerous prizes in 2012, including the National Academy of Sciences award. In 2002, he held the world's first International Conference on Multidimensional Spectroscopy. Since 2014, he has been the project manager for "Molecular Spectroscopy and Dynamics Research," an R&D project receiving support from South Korea's Ministry of Science and ICT. Although he has published few papers in the last five years, he has published a total of 148 and is currently actively engaged in research.

6.5.4 LEE Younghee（이영희）

Younghee Lee is a professor in physics and energy science at Sungkyunkwan University, as well as an SKKU fellow, and since 2012 has also been the director for the Center for Integrated Nanostructure Physics, an institute for basic science at that university. After graduating from Jeonbuk National University, he acquired his PhD in physics from Kent State University in the U.S. He then returned to South Korea where he taught at that university (1987–2001) while also holding positions such as visiting professor at Michigan State University (1996–1997), IBM Research in Zürich, Switzerland (1993, and the Ames Research Center (1989–1990), and has held his current positions since 2001. His subjects of research are materials science and condensed matter physics. His primary areas of focus in material synthesis are large-area monocrystalline graphene CVD, graphene oxide, h-BN, and transition metal dichalcogenides, while his properties interests are atomic/electronic structures, optoelectronic/thermal/photo-thermoelectric properties, exciton carrier multiplications, multifunctional nanostructures and devices, and energy harvesting.

6.5.5 CHO Donghyun（조동현）

Head of the Department of Physics at Korea University. After receiving his PhD from the Department of Physics at Yale University in 1990, he was a postdoctoral researcher at Yale before returning to South Korea in 1994. After working as an assistant professor in the Department of Physics at Korea University for 10 years, he became the head of the College of Science. He has been involved in 17 different R&D projects, including the “research on the quantum interference phenomena and quantum information communications” in 2002. A number of papers he has written on quantum informatics, namely “Line Shape of a Transition Between Two Levels in a Three-Level Lambda Configuration (2011),” “Coherent Transition Between Adjacent Zeeman Sublevels In an Alkali-Metal Atom without Populating Other Sublevels (2013),” and “Magic Polarization for Optical Trapping of Atoms without Stark-Induced Dephasing (2013),” have been published in Physical Review Letters, the most prestigious journal in the field of physics.

He is known for his high-quality lectures, to the extent that he has received the Best Lecture Award ten times. This award is given to teachers that score in the top 5% based on annual evaluations of their lectures made by Korea University students. Additionally, he is known as one of the few quantum studies researchers who has expressed a negative view of quantum computers. Cho criticized the idea of the quantum computer in an interview with the Weekly Chosun in 2020[25], saying, “it will never be possible to develop a quantum computer. Google has said that a quantum computer has performed a calculation in three minutes that would take standard computers 10,000 years. But it's not the speed that's important, it's the result of those calculations. How accurately can you arrive at the desired calculation result — that's the issue. Quantum computers experience tons of errors and cannot calculate results accurately. So, Google did not perform a calculation, it merely created a random number.” He also criticized many countries' focuses on investing huge sums in quantum research without conducting proper due diligence just because it's a hot topic.

[25] For the full text of the interview, see “A Skeptical View of the Quantum Computer — Professor Donghyun Cho of Korea University's Department of Physics,” Weekly Chosun (January 14, 2020).

6.6 International collaboration and joint research

In 2021, MSIT announced that it would more than double its budget for international ICT joint research focused on 6G, AI, quantum technologies, and other areas, from 5.8 billion KRW in 2021 to 11.7 billion KRW in 2022. It noted that, with respect to quantum technologies, it would especially strengthen collaboration with the U.S., Europe, and the UK.[26]

South Korea's Future Quantum Convergence Forum signed a quantum-encrypted communications LOI with Argonne National Laboratory in the U.S. in January, 2022.[27] It also signed an MoU in June 2022 with the Finland trade representative in Korea with the goal of promoting technology exchange and joint research.[28] In a summit meeting between the U.S. and South Korea on May 21, 2022, leaders expressed their intent to strengthen cooperation between the two countries on quantum technologies, artificial intelligence, biotechnology, and other core technologies.[29] At the U.S.-Korea Standards Forum held on August 9, 2022, South Korea's Ministry of Trade, Industry and Energy announced that the two countries had shared technology policy and standardization strategies with regard to state-of-the-art technologies such as quantum technologies, next-generation semiconductors, and AI.[30]

In the Asia-Pacific region, the Future Quantum Convergence Form held a joint workshop in May 2021 with Japan-based Q-STAR (Founders' Association of the Council for New Industry Creation through Quantum Technology) that saw South Korea kick off quantum technology cooperation with Japan.[31] On September 28, 2022, Yong Hong-taek, head of MSIT's Research and Development Policy Division held a meeting with leading scientists from Australia wherein discussions were held on international cooperation regarding quantum technologies. At the meeting, the Yong Hong-taek said, "Having established a quantum technology roadmap, Australia is increasing its focus on quantum technologies and expanding technical cooperation in quantum research and development, an area on which South Korea is also focused."[32]

In industry, LG Electronics and Qu & Co, a quantum computing development firm based in the Netherlands, signed a research agreement concerning multiphysics simulation. While both companies and governments are investing effort into international cooperation in quantum technologies, the following discussion focuses on international cooperation projects from the last five years that have had government support.[33]

[26] For more information, see "Ministry of Science and ICT to Expand 6G, AI, and Quantum Joint Research with Major Countries," Aju Business Daily (December 21, 2021).

[27] See "Future Quantum Convergence Forum and U.S. Argonne National Laboratory Quantum-Encrypted Communications LOI," Future Quantum Convergence Forum Announcement (March 8, 2022).

[28] See "International Cooperation on Quantum Technologies to Expand on One Year Anniversary of the Future Quantum Convergence Forum," EDAILY (July 1, 2022).

[29] For more information, see "U.S.-South Korea Summit — Strengthening Cooperation on Space, Cyber, Quantum, and Bio Technologies," Yonhap News Agency (May 21, 2022).

[30] See "Strengthening Standards Cooperation with the U.S. in Quantum Technologies, Next-generation Semiconductors, AI, and Other Advanced Technology Fields," South Korea Policy Briefing (August 9, 2022).

[31] See "International Cooperation on Quantum Technologies to Expand on One Year Anniversary of the Future Quantum Convergence Forum," EDAILY (July 1, 2022).

[32] See "South Korea and Australia Hold Discussions on Quantum Technology and Other Science and Technology Cooperation," EDAILY (September 28, 2022).

[33] For more information, see the Korea Institute of Science & Technology Evaluation and Planning's (KISTEP) "Field of International Cooperation Research and Development"(December 2021) and Quantum Technology Development Investment Strategy.

For two years beginning in August 2020, POSTECH along with Massachusetts Institute of Technology (MIT) and Raytheon BBN Technologies in the U.S. are conducting a project to develop a graphene-based microwave single photon detector for the purpose of processing quantum information.

Since August 2020, the Ulsan National Institute of Science and Technology (UNIST) has been conducting a project for twe years with the University of Pennsylvania involving artificial materials for quantum light source and memory applications, as well as a project with the University of Maryland involving hybrid quantum photonic integrated circuit devices. Research spending on each project is around 200 million KRW (154,000 USD). In partnership with Harvard University, the City University of New York, and the University of Minnesota, the Seoul National University has launched the Van der Waals 2D Materials Quantum Computing International Joint Research Center, which from September 2020 to March 2023 conducted joint research with a budget of 6.75 billion KRW (5.2 million USD).

Outside of the U.S., KAIST is working with Kyoto University on an international collaboration project to develop an atom and molecule-based quantum simulator, with an expected expenditure of 6.75 billion KRW (5.2 million USD) for September 2020 to March 2023. Additionally, Sogang University, Imperial College London, National Tsing Hua University, Duke University, and the University of Innsbruck have launched an international joint research team to develop quantum technologies that is expected to receive an investment of 6.75 billion KRW (5.2 million USD) for September 2020 to March 2023.

The Electronics and Telecommunications Research Institute (ETRI) and the Fondazione Bruno Kessler in Italy are conducting a project from July 2020 through March 2024 to develop technologies to control small-scale quantum computing systems and assess their performance, with an expected budget of 56.3 billion KRW (43.4 million USD). At the International Workshop on Quantum Computing Security Technologies, held in 2018, ETRI expressed an intent to step up cooperation with Queen's University in the UK and the National Institute of Standards and Technology (NIST) in the U.S. on quantum security technologies.[34]

For three years beginning in July 2020, Kyung Hee University and Leibniz-Institut für Festkörper- und Werkstoffforschung Dresden (IFW-Dresden) will be developing low-dimensional thermoelectric and satellite materials while researching thermoelectric/spin quantum substance measurement technologies, using 9.99 billion KRW (7.7 million USD) in funding. For three years beginning in July 2019, KRISS will be conducting a project to develop a graphene-based quantum interface prototype together with the Physikalisch-Technische Bundesanstalt (PTB), a national research institute in Germany, with a budget of 4.5 billion KRW (3.5 million USD).

The following three projects all concern quantum communications and were carried out for three years beginning in 2017 with budgets of 3.6 billion KRW (about 2.7 million USD). Korea University and the University of Illinois Urbana-Champaign in the U.S. conducted a project to achieve a two-dimensional matter single-photon source for quantum information processing. The Gwangju Institute of Science and Technology and Purdue University in the U.S. completed a research project involving low-level encryption hardware with an integrated random laser and photo electronic device, while the Seoul National University and Florida Atlantic University in the U.S. research the effect of gravity on free space quantum encryption system semiconductors for satellite communications. While a relatively small project, Incheon National University and Khalifa University in the UAE conducted research

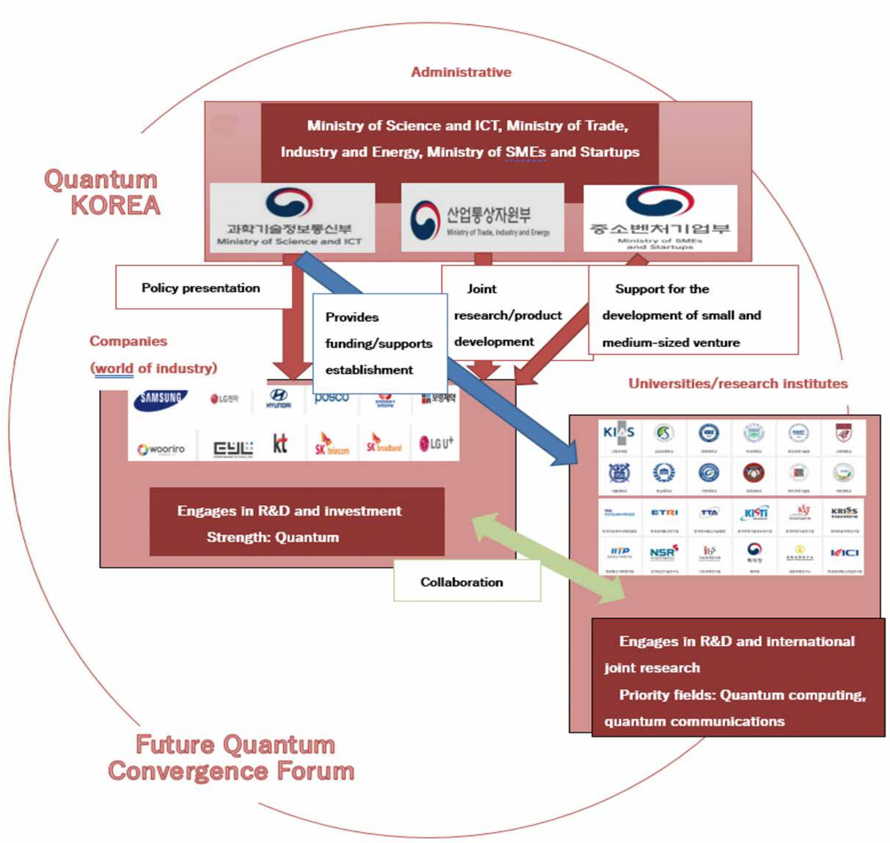
[34] For more information, see "ETRI Working with Queen's University in the UK and NIST in the U.S. to Build Foundation for International Quantum Computing Technology Research," DIGITAL TODAY (September 19, 2019).

into developing quantum security infrastructure technologies based on big data risk analysis, which presented new implications for international cooperative business that was conducted primarily in the US and certain European nations. For 2.5 years beginning in 2019, Kyungpook National University and the French Centre Nationale pour Recherche de Sciences (CNRS) conducted joint research focused on international cooperation toward developing new quantum science theories and applications for excited state the dynamics. Between December 2018 and November 2020, KAIST and the University of KwaZulu-Natal in South Africa collaborated on a project to research digital quantum interfaces for the practical application of quantum computing, along with basic core technologies for quantum process management.

6.7 Quantum innovation ecosystem

Table 6-14 presents a map of the quantum innovation ecosystem in South Korea based on the above overview and characteristics of the country as a player in the domain of quantum technologies.

Table 6-14: Quantum innovation ecosystem in South Korea



Source: Prepared by APRC

7 Quantum technology trends in Singapore

In Singapore, the government began providing funding for quantum technology research at the beginning of the 21st century, establishing a research facility at the National University of Singapore in 2007. However, it is not until 2018 that quantum R&D became a full-fledged part of Singapore's national strategy. The country's Quantum Engineering Programme, which launched in 2018 and entered its second phase in April 2022, aims to advance quantum technology R&D by establishing new pillars such as a national computing hub, hardware production facility, and communications network.

7.1 Quantum technology policy

Individual researchers in Singapore began conducting quantum technology research at the end of the 1990s, and state funding that began in 2002 led to the establishment of distinguished research facilities and the start of coordinated research. However, no clear mention is made of quantum technologies as a key area of focus in any of Singapore's national science and technology plans from the third plan (RIE2005, 2001–2005) to the sixth plan (RIE2020, 2016–2020)[1]. The launch of the Quantum Engineering Programme in 2018 is thus likely to get national policy more focused on quantum technology R&D.

Science and technology policy in Singapore is handled by the Research, Innovation and Enterprise Council (RIEC)[2], and the Ministry of Trade and Industry (MTI) and the Ministry of Education (MOE) also serve in policy design and execution capacities[3]. The Agency for Science, Technology and Research (A*STAR) and state holding company Temasek, established in 2002 by the MTI, were the first to provide funding (5 million SGD = 3.75 million USD at a rate of 1 SGD = 0.75 USD) to the National University of Singapore's Quantum Information Technology Research Group[4]. In December 2007, the MOE and National Research Foundation (NRF) officially recognized the research group as a Research Centre of Excellence (RCE), and the NUS reestablished the group as the Centre for Quantum Technologies (CQT). Immediately after being established with 158 million SGD (118.5 million USD) as core funding, the CQT received additional funding of 36.9 million SGD (27.7 million USD) following an international review. In 2017, the CQT's core funding (100 million SGD, 75 million USD) was extended through 2022 by the MOE and NUS.

1 Data obtained from Singapore's national science and technology plans, which have been released every five years since 2001. As explained below, the MTI published S&T Plan 2005, S&T Plan 2010, RIE2015, and RIE2020, while the NRF published RIE2025.

2 2006 年 設 立。 Chaired by the prime minister, it deliberates on the fundamental direction of R&D and innovation in Singapore with a top-down approach, and is the top deliberative body in the country's science and technology policymaking process. Institute for Future Engineering, "Survey and Analysis of Trends Concerning Science and Technology Innovation in Major Countries," (March 2020), pg. 266.

3 JST/CRDS, "Science and Technology Landscape in Singapore," last accessed June 10, 2022.

4 The data on policy trends and funding amounts that follows is primarily from Angelakis, D. et al. (eds) (2019) Quantum Technologies in Singapore: Preparing for the Future. Singapore: QuantumSG, and Kung, J., and M. Fancy (2021) A Quantum Revolution: Report on Global Policies for Quantum Technology. Toronto, ON: CIFAR, p.46.

After NUS, research prioritizing quantum technologies was also begun at other research institutes. In 2017, the Quantum Technologies for Engineering (QTE) research program was launched (4-year term, 25 million SGD = 18.75 million USD) by A*STAR's Institute of Materials Research and Engineering (IMRE). IMRE had been engaged in basic research in materials science since the late 1990s, before A*STAR was established, with a focus on quantum technology research.

As far as this author was able to determine, 2018 was the first time that quantum technologies were given a position in Singapore's national strategy. "Smart Nation and Beyond," announced in November 2014 as Singapore's most recent outlook on its smart nation plan was released in November 2014. As part of this outlook, in November 2018, the Prime Minister's Office announced that it would digitize 94% of the government's functions in a bid to improve convenience for Singaporean people, and would focus on quantum computing and emerging technologies such as augmented reality, virtual reality, IoT, and the block chain as means to this end. Also in 2018, the NRF provided 25 million SGD (18.75 million USD, 5-year term) to form the Quantum Engineering Program (QEP). Focused on the three areas of quantum secure communications, quantum sensing, and quantum computing, the QEP conducts research that is led by the NUS, receives project proposals, and conducts international reviews and assessments to determine whether to adopt those proposals. In 2021, it received additional funding of 26.14 million SGD (19.6 million USD) and had around 230 researchers.

As the Prime Minister's Office was making its announcement and the NRF was providing funding, academia was also making moves. In 2018, Alexander Ling and other NUS CQT principal investigators launched an R&D initiative known as Quantum SG. October 2019 saw these PI publish a proposal from the Quantum SG research community entitled "Quantum Technologies in Singapore — Preparing for the Future." Speaking from the perspective of Singapore's academic community, the proposal enumerated specific and actionable steps that could be taken to build an international hub for quantum technologies in Singapore.

The Research, Innovation and Enterprise 2025 Plan, Singapore's most recent five-year plan, was released by the NRF in 2020 and outlines the country's medium-term goals. Looking back on events from the establishment of the NUS CQT to the formation of the QEP, the plan lauds the country's achieving international competitiveness in quantum information, optics, communications, encryption, and simulation, and expresses Singapore's intent to provide even stronger support as part of its commitment to achieving a smart nation and digital economy. More specifically, Singapore will begin providing support for new fields such as quantum communications, quantum key distribution, quantum sensing and imaging, and quantum algorithms, and will make an ongoing effort to further strengthen and internationally develop its quantum technologies, investing 25 billion USD over five years beginning in 2020.

During an address on May 31, 2022, at Asia Tech x Singapore (ATxSG), a major international technology event in the Asia-Pacific region, Deputy Prime Minister and NRF Chairman Heng Swee Keat announced that Singapore will establish the National Quantum Computing Hub, National Quantum Fabless Foundry, and National Quantum-Safe Network (details provided in section 7.2) as three new QEP initiatives. The Prime Minister also expressed Singapore's intent to step up its existing efforts to promote quantum technologies.[5]

[5] "S'pore boosts investments in quantum computing with 2 new programmes," Straits Times (May 31, 2022); "Singapore to Launch National Platforms to Enhance Quantum Computing, Safe Communications, and Device Production Capabilities," Science Portal ASEAN (July 1, 2022).

7.2 Quantum technology research and development

According to the research paper analysis conducted in Chapter 1, 2,399 quantum-related research papers have been published in Singapore, giving the country an average annual growth rate of 5%, which is on par with South Korea. The top three subjects of the papers were quantum materials at 36%, basic quantum technologies (quantum sensing and metrology) at 30%, and quantum computing at 20%. Looking at the number of papers published every five years, quantum computing and basic quantum technologies saw significant growth after 2011, while quantum encryption, communications, and materials increased significantly after 2016.

While quantum materials research has been ongoing in Singapore for some time, these indicators suggest that the establishment of things such as research hubs have brought attention to quantum computing, and that research has also advanced in recent years the in area of wide-area quantum communications involving quantum key distribution (QKD), optical fiber networks, and CubeSats.

Universities and research institutes engaged in quantum R&D are shown in Table 7-1, and consist primarily of the NUS, Nanyang Technological University (NTU), and A*STAR. In the field of computer science, there is also National Supercomputing Centre Singapore (NSCC, associations with quantum technologies explained in section 7.3).

Table 7-1 Overview of relevant R&D institutes in Singapore

Type	Name	Staff & Students	Areas of Research
University	National University of Singapore, Centre for Quantum Technologies (NUS CQT)	8 professors, 13 associate professors, 6 visiting associate professors, 7 assistant professors, 22 researchers, 60 graduate students	Quantum secure communications (quantum key distribution, quantum encryption) quantum communications among large cities using optical fiber, wide-area quantum communications using satellites, quantum computing and simulation (mainly using trapped ions), quantum sensing
	Quantum and Complexity Science Initiative (QuCSI) of Nanyang Technological University	1 associate professor, 2 visiting professors/ researchers, 6 researchers, 7 graduate students	The interdisciplinary fields of quantum information science and complex science. In particular, the systematic construction of quantum models for overcoming traditional mathematical model limitations and reducing complexity
	Singapore University of Technology and Design (SUTD)	1 professor, 1 associate professor, 1 assistant professor, several researchers	Quantum computing, quantum materials
Public research institute	Agency for Science, Technology and Research (A*STAR)	About 40 IMRE and IHPC researchers each	Sensing and materials devices (IMRE), computing NAI, large-scale complex system modeling, social computing, cognitive computing, computer engineering, mechanical engineering, etc. (IHPC)

Source: Prepared by APRC based on various literature

7.2.1 Quantum Engineering Program (QEP)

The QEP is an R&D program funded by the NRF and directed by the NUS. In terms of both investment and number of researchers, it is Singapore's largest such program doing the highest level of research, and taking part in the program are a majority of the noteworthy researchers mentioned in section 7.5. Phase 1 of the project ran from 2018 to March 2022, and Phase 2 (QEP 2.0) began in April 2022.

The QEP is cochaired by NRF CEO Low Teck Seng and Ministry of Defense (MINDEF) Senior R&D Consultant Quek Gim Pew, and Alexander Ling has been program director since September 2020. The program is run by 10 program coordinators (in charge of computing, communications, sensing, the National Quantum Fabless Foundry, cloud quantum computing, and the National Quantum-Safe Network). As of the end of December 2022, there are 27 projects underway across three priority areas and enabling technologies.

The aforementioned statement made by the prime minister at the end of May 2022 announced and kicked off the three platforms that constitute Phase 2 of the QEP.

As the first platform, the National Quantum Computing Hub will be built using new quantum computers unique to Singapore. Development lead time is expected to decrease as companies and government organizations will be able to directly access and test the hub rather than having to go through a cloud network.

The National Quantum Fabless Foundry (NQFF) is the second platform to have been officially announced and will be an organization that provides support to the quantum research community through the development of quantum devices needed for micro and nano fabrication. Aimed at serving the QEP's three areas of focus, the NQFF will serve to advance academic research and practical application while acting as a bridge among industries in different countries.

Table 7-2 Projects funded through the QEP (as of May 2022)

Area	Name	Principal Investigator (PI)	Organization
Quantum communications and security	Architecture and Protocols for the Quantum Internet	Biplab Sikdar	NUS
	Evaluation of all-transparent optical routers for a quantum network embedded in a classical optical fiber network	Christian Kurtsiefer	NUS
	Heterogenous quantum interfaces over metropolitan distances		
	Island-wide quantum key distribution using electrically driven single photon emitters	Weibo Gao	NTU
	Optical Fiber Characterization and Noise Mitigation for Quantum Clock Comparison and Application	Yusong Meng	A*STAR
	Quantum homomorphic encryption: the Swiss army knife for the quantum internet?	Marco Tomamichel	NUS

Quantum computing and processors	A scalable, programmable atom-array platform for quantum simulation of dynamical and material physics	Loh Huanqian	ANU
	Advanced Quantum Processor Platform	Rainer Dumke	UNSW
	Advancing cavity QED: materials and algorithms	Dario Poletti	SUTD
	Atomic Engineering of Donor-based Spin Qubits in Silicon	Kuan Eng Johnson Goh	A*STAR
	Computer science approaches to quantum computing for finance	Patrick Rebentrost	NUS
	Quantum computing for accelerated design of auxetic mechano-luminescence materials	Lu Dingjie	A*STAR
	Quantum-Enhanced Modelling of Financial Time-Series Data for Rare Event Forecasting	Mile Gu	NTU
	Quantum processor with trapped ions	Dzmitry Matsukevich	NUS
	Resource efficient quantum algorithms and applications for chemistry, route optimization and finance	Dimitris Angelakis	NUS
	Towards a scalable quantum machine learning solution using trapped ions	Manas Mukherjee	NUS
	VCSEL-based quantum annealer	Aaron Danner	NUS
Quantum sensing	Atom Interferometer based Gravimetry: Development and Application	Rainer Dumke	NTU
	Quantum assisted navigation and magnetic sensing		
	Building non-cryogenic centimeter scale magnetometers with 10 fT/Hz1/2 sensitivity in Singapore for Earth science and defense applications	Junyi Lee	A*STAR
	Exploration of a fibre communications network for seismic sensing	Christian Kurtsiefer	NUS
	Optical Ranging using Thermal Light	Tan Peng Kian	NUS
	Plasmonic nanopore: Toward on-chip quantum-based genome sequencing	Wu Lin	SUTD
	Quantum imaging for aging studies exemplified by lipid content detection of bio-tissues	Anna Paterova	A*STAR
	Quantum sensing for health science based on NV centers in diamond	Weibo Gao	NTU
	Single Photon Detectors for Quantum Sensing and Communications	Victor Leon	A*STAR
Enabling technologies	Development of Integrated Chips to Control Geiger-mode Avalanche Photo-Diodes for High Speed Single-Photon Counting	Gao Yuan	A*STAR
	Fabrication of ultra-pure 'quantum grade' diamond via MPCVD	Edwin Hang Tong Teo	NTU

Source: Source: Translation by APRC of the QEP 2.0 R&D Projects

As for the third platform, the QEP announced on February 17, 2022, ahead of the above-mentioned statement, that domestic testing would begin on quantum-safe communications technologies that would ensure robust network security for companies using critical infrastructure or confidential data.[6] With support from Singapore's NRF, this project will launch with 15 private enterprises and government agencies.

7.2.2 Latest trends in research and development

Although noteworthy outcomes are yet to be announced, progress is being made with the following R&D projects in recent years.

- **Coordination between global companies and research institutes in Singapore:** In a press release dated April 28, 2022, the QEP and Keysight Technologies signed a memorandum of understanding (MoU) to collaborate toward promoting quantum technology R&D and education.[7] This MoU will see the two organizations work closely on developing a package for quantum metrology instruments and technologies to achieve quantum system expandability and extensibility. Additionally, researchers with the QEP will establish a "program to enhance innovation in quantum collaboration" with the goal of making it easier to access Keysight Technologies' design tools and sophisticated testing and metrology instruments.
- **Development of technologies for self-repair space radiation exposure damage:** According to a NASA media report dated March 7, 2022,[8] the NUS CQT will work with the University of Illinois Urbana-Champaign (UIUC) and Jet Propulsion Laboratory to conduct a pilot for a laser annealing detector and waveguide entangled photon resources. These technologies are expected to enable satellites to self-repair damage inflicted by radiation exposure in space.
- **Development of new technologies that use expanded quantum algorithms:** Dax Koh and other researchers from A*STAR's Institute of High Performance Computing (IHPC) have scaled up quantum algorithms to achieve a quantum advantage and are now working to develop new technologies to solve practical problems.[9] In order to suppress quantum decoherence and speed up the variational quantum eigensolver algorithm, Koh's research team developed a framework called the engineering likelihood function (ELF) to perform Bayes estimation. By maximizing the information that can be output for each execution of the algorithm, ELF makes it possible to reduce measurement costs while more quickly finding the solution to the model.

[6] Singapore National University of Singapore news release, "Singapore to build National Quantum-Safe Network that provides robust cybersecurity for critical infrastructure," February 17, 2022, and media report "S'pore creates first quantum cryptography testbed, gets closer to building an unhackable Internet," Straits Times, February 17, 2022. (both last accessed June 10, 2022)

[7] Singapore National University of Singapore press release, "Keysight and Singapore's Quantum Engineering Programme to accelerate research, development and education in quantum technologies," April 28, 2022, and Keysight Technologies press release, April 27, 2022. (both last accessed June 10, 2022)

[8] NASA Jet Propulsion Laboratory, "Space Station to Host 'Self-Healing' Quantum Communications Tech Demo," March 7, 2022 (last accessed June 10, 2022).

[9] A*STAR, "Delving into a spectrum of quantum capabilities," September 24, 2021. (last accessed June 10, 2022)

- **Exploring materials for achieving quantum computing that strikes a balance between stability and accessibility:**[10] Kuan Eng Johnson Goh, a Principal Investigator at A*STAR's Institute of Materials Research and Engineering (IMRE), has focused on creating qubits from tungsten disulfide (WS2), a two-dimensional transition-metal dichalcogenide (TMDC) semiconductor material. To give quantum devices the optimal characteristics of WS2 while overcoming technical limitations arising from synthesis, the research team employed chemical vapor deposition and uniformly encapsulate the ABC crystals with a protective dielectric layer made of hafnium oxide (HfO2). Through this technique, the team managed to synthesize stable wafer crystals over an area hundreds of times larger than that of conventional mechanical exfoliation.

7.3 Notable institutes and universities

With universities NUS and NTU leading the charge, Singapore is actively engaged in gauging in cutting-edge, distinctive research and development activities. Elsewhere, the Singapore University of Technology and Design, founded in 2009, has three researchers working on quantum computing and quantum materials. The Fraunhofer-Gesellschaft (FhG), a private research institute in Germany that promotes applied science research, has established in Singapore its only research facility in Asia, to promote quantum secure communications R&D and provide an online ongoing education program for engineers entitled "Post-quantum Cryptography."[11] However, neither organization has made any noteworthy contributions to quantum technologies in Singapore.

The following pages look at major universities and research institutes in Singapore in order of the depth of their connection to domestic policy and size of the organization (in terms of number of researchers, research scope, and research budget).

7.3.1 Centre for Quantum Technologies, National University of Singapore (NUS-CQT)

Founded in 1905, the National University of Singapore (NUS) began as a medical university and was given its current name after a 1980 merger between the University of Singapore and the University of Malaya. It has 17 faculties and schools that include joint-degree options for Yale or Duke University students, and has some of the best R&D capabilities in the Asia-Pacific region, let alone Singapore. With a diverse research and education environment and 38,000 students from over 100 countries, it ranked 11th overall and 1st in Asia for QS World University Rankings 2022.

The Centre for Quantum Technologies (CQT), created as a part of NUS following the 2007 approval of the Research Centres of Excellence (RCE), owes its legacy to the Quantum Information Technology Group (informally "quantum lah"), the formation of which was prompted by a series of informal seminars launched by Kwek Leong Chuan and three others in 1998. It is home to 26 of Singapore's more than 40 research institutes and currently receives 748,000 USD (FY 2017–2022) in funding from the NRF.

Its primary fields of research are quantum secure communications (quantum key distribution, quantum encryption) quantum communications among large cities using optical fiber, wide-area quantum communications

[10] A*STAR, "A new recipe for quantum computers," April 27, 2022. (last accessed June 10, 2022)

[11] Fraunhofer Singapore, "Post-quantum Security," last accessed June 10, 2022.

using satellites, quantum computing and simulation, and quantum sensing, along with applied device development and basic science. CQT Director José Ignacio Latorre oversees all of the institute's research activities, which are conducted by eight professors, about 20 associate professors (including visiting professors), and seven assistant professors. Five (as of May 2022) principal investigators (PI) collaborate on quantum computing simulation, while basic technology and sensing research are conducted by 20+ research fellows and 60+ graduate students under the guidance of one PI (in principle).

Among the CQT's other activities alongside R&D, it develops "quantum games" to spur interest in quantum technologies among younger researchers, holds short film contests, and publishes primers.

7.3.2 Agency of Science, Technology and Research (A*STAR)

A*STAR was established in 2002 when it was renamed from the National Science and Technology Board (NSTB), Singapore's largest organization conducting R&D and promoting science and technology. It carries out R&D policy specific to fields that include biomedicine, information engineering, and physical science. The Institute of Materials Research and Engineering (IMRE) and Institute of High Performance Computing (IHPC), now part of A*STAR but formerly affiliated with the Science and Engineering Research Council (SERC), have numerous research teams and researchers working in the field of quantum technologies.

The IMRE, established in 1997, has strong capabilities in the areas of polymeric & organic materials, composite and structural materials, advanced materials characterization and fabrication, optics, and electromagnetics. Its two research units are respectively focused on sensing and materials/devices, with research led primarily by Kuan Eng Johnson Goh.[12]

IHPC has considerable expertise in large scale complex systems modeling, social and cognitive computing, computational engineering mechanics, fluid dynamics, and photonics, and materials science and chemistry.

7.3.3 The Quantum and Complexity Science Initiative, Nanyang Technological University (QuCSI)

Nanyang Technological University (NTU) was founded in 1955. Founded in 1955, Nanyang Technological University (NTU) is Singapore's second university to have more than 33,000 students, most of whom are in science and technology faculties. It ranked 12th overall and second in the Asia region for QS World University Rankings 2022. It was the top university in the country for five consecutive years (2012–2016) for the number of AI-related research papers published (Nikkei, Elsevier, 2017) — one factor behind the growing interest in the university's digital technology research.[13]

The university's Quantum and Complexity Science Initiative was launched in 2018. Based at the Nanyang Quantum Hub located in the School of Mathematical and Physical Sciences at Nanyang Technological University, it is run by more than 10 research fellows and graduate students and receives financial and staffing support from NUS CQT. NTU assistant professor Mile Gu leads the organization, which engages in research and technology development in the interdisciplinary fields of quantum information science and complex systems science. It has a

[12] IMRE, A*STAR, "Quantum Technologies for Engineering," last accessed May 31, 2022.
[13] "QS World University Rankings - About Nanyang Technological University," last accessed May 31, 2022.

particular focus on overcoming the limitations of conventional mathematical models, whereby the volume of input data greatly exceeds the volume of prediction data that is output, and systematically building a quantum model to reduce complexity.

The NTU also established the Quantum Science and Engineering Centre (QSec) in December 2021, which aims to advance quantum chip development.[14] Staffed by around 30 researchers, the center has received an Academic Research Fund Tier 3 grant from Singapore's Ministry of Education. The center's President Professor, Subra Suresh, specializes in engineering and materials science (biomaterials) and has also been NTU's President Professor since 2018.

Both the NTU and NUS engage in international cooperation with France, a part of which has been ongoing international joint research following France's dispatch of visiting researchers to these universities in 2005 (see section 7.6 for more information).

7.3.4 Centre for Advanced 2 Dimentional Materials, National University of Singapore (NUS-CA2DM)

NUS-CA2DM was established in 2010 as an NUS research facility with 40 million SGD (30 million USD) in funding from the university. Originally known as the Graphene Research Centre, it was renamed in 2014 following an expansive reorganization. Aimed at the conception, characterization, theoretical modeling, and development of transformative technologies based on two-dimensional crystals such as graphene, it comprises four research groups focused on graphene, two-dimensional materials, two-dimensional devices, and theory. During NUS-CA2DM's reorganization period, in 2011 it received 10 million SGD (7.5 million USD from the NRF through the Competitive Research Programme (CRP) along with 50 million SGD (37.8 million USD) as part of the Create Campus for Research Excellence and Technological Enterprise (CREATE) program. It is expected to undergo further development as a quantum materials research hub in Singapore.

7.3.5 National Super Computing Centre (NSCC)

Established in 2015 as national research infrastructure funded by the NRF, the NSCC helps address the needs of those researching and developing high-speed computers in the public and private sector, which includes research institutes, institutions of higher learning, government agencies, and enterprises. It hosts three platforms: ASPIRE 1, Singapore's first supercomputer; the AI Platform powered by AI and capable of high-speed computing; and the Köppen System, which is mainly designed to support research activities in climate and environment research. Although these high-speed computing systems take a different approach to supporting the research of quantum phenomena, with regards to quantum computing, NSCC has signed an MoU with SingAREN, the Quantum Engineering Programme of NUS, and Finland's CSC-IT Centre for Science as a form of collaboration between Finland and Singapore (details provided in 7.6) to explore more secure ways of protecting data transfer through quantum technology.

[14] Nanyang Technological University news release, "New quantum engineering centre to unleash chip-based technologies," December 7, 2021. (last accessed June 10, 2022)

7.4 Notable companies

Most of the large science and technology companies doing business in Singapore are global companies that are headquartered in the U.S. and that have work to do when it comes to business incubation in Singapore. With respect to venture companies, both the NUS CQT and NTU actively collaborate with industry, and recent years have seen enterprising businesses undertaken by quantum technology venture companies spun off from these universities. The above-mentioned 2019 policy paper from Quantum SG provides a list of startups and scientists with roots in prominent universities, calling them "enterprises providing enabling technologies and exploring potential applications for quantum technologies.[15]" This section will provide a business overview and summary of quantum technology contributions made by primarily the companies mentioned in that policy paper.

7.4.1 Horizon Quantum Computing

Horizon Quantum Computing was founded by NUS CQT Principal Investigator Joseph Fitzsimons. Focusing on the practical problem of "quantum computing being unintuitive and difficult to code algorithms for," the company has developed a compiler that allows for developing quantum computer software in classical languages, without a reliance on hardware. Although it has not published any details on its products, the company's mission is to automate the process whereby scientists with classical programming knowledge can compile programs into quantum circuits. The company is also focusing on cross-industry self-promotion through means such as CSO Si-Hui Tan's talk during the quantum technology session at the Deep Tech Summit hosted by SGInnovate in November 2021.

The company's interdisciplinary team consists of about 10 postdoctoral researchers each with eight or more years of practical experience and academic backgrounds in mainly quantum computing and quantum information and communication.

7.4.2 SpeQtral

This quantum technology venture company is a spinoff from the laboratory of Alexander Ling, an associate professor at NUS-CQT. It is known for its 2016 demonstration of creating a miniaturized source of entangled photons in space. Its primary business domains are quantum computing and quantum information and communications, with a particular focus on wide-area quantum communications in space. As to collaboration with Japanese companies, SpeQtral announced on August 31, 2021, that it would work with Toshiba Digital Solutions to provide solutions for implementing quantum key distribution (QKD) at government agencies and companies. At the end of November 2021, the company announced that it had received 8.3 million USD in funding from Xora Innovation, an early-stage investment platform of Temasek.[16]

[15] "Young Quantum Technology Companies with Strong Links to NUS CQT," Centre for Quantum Technologies, National University of Singapore, last accessed June 10, 2022

[16] "SpeQtral closes US$8.3m funding round," SpeQtral's website

In collaboration with RAL Space,[17] an organization that promotes space development as part of the UK's Science and Technology Facilities Council, SpeQtral launched SpooQy-1, a 3U (30 cm cube) quantum CubeSat, on April 17, 2019. Built using small photon-entangling quantum systems (SPEQS), SpooQy-1 has been covered by several media outlets including Computer Business Review, Laser Focus World, and Asian Scientist.[18]

SpeQtral's team comprises the following members. SpeQtral's team comprises CEO Chune Yang Lum, CTO Dr. Robert Bedington, and eight employees.

7.4.3 Entropica Labs

Entropica Labs is a quantum technology venture company founded in 2018 by two then NUS-CQT researchers. Entropica Labs is a quantum technology venture company founded in 2018 by two young researchers who were at NUS-CQT at the time. With a focus on developing quantum optimization models, algorithms, tools, and software, the company offers two products: EPOS and EQAQA.

The Entropica Physics-based Optimisation Suite (EPOS) is a collection of physics-based solvers for optimization and a tool for quickly comparing the relative performance of quantum algorithms and highly-customized classical methods. It provides a unified framework for running, testing, replicating, and benchmarking classical and quantum optimization algorithms.

EQAOA is a Python library for conducting quantum computer and optimization research using the Quantum Approximate Optimization Algorithm (QAOA). Users can freely configure QAOA parameters and choose from a wide range of classical optimization routines. Algorithms can be run through IBM Q, AWS Braket, and a pool of specially selected simulators.

SpeQtral has received funding from organizations such as Wavemaker, SGInnovate, and Lindley PTY LTD. In May 2020, it received an investment of 2.6 million SGD (1.95 million USD) from deep tech venture capital firm Elev8, which is based in Singapore.[19]

The company is led by cofounder and CEO Tomasso Demarie and CTO Ewan Munro.

7.4.4 Atomionics

Atomionics is a tech company working in the field of quantum sensing. Gravio, a new gravimeter developed and marketed by Atomionics, can provide a cost-effective way to give the best possible data in the shortest amount of time using quantum sensing. A $1m^2$ grid high image resolution allows for significantly reducing survey costs. It offers a number of benefits to the operator, including its ability to be used by survey vehicles directly, eliminating the need for operator skill, and dramatically shortening survey time by inputting the optimal route when mining tunnels and drawing on large amounts of data. With a high sensitivity of $10\mu gal/\sqrt{Hz}$ and small pixel size, Gravio can detect small structures and faint signals, enabling optimal mapping of underground spaces. This ensures reliable detection of extremely dense rock and sinkholes, and enables optimal construction and excavation planning. As it

[17] "Mission to Singapore 2020," RAL Space's website

[18] As of October 16, 2021. Information obtained from a SpooQy-1 information portal site in the EU.

[19] Entropica Labs blog post, "On to greater things," May 11, 2020

can also accurately pinpoint hydrocarbon and mineral locations, Gravio can also perform nondestructive monitoring of structures such as pipelines and slag dams.

Gravio's high data rate of 10 Hz makes it capable of extremely accurate measurement. This allows it to be mounted on vehicles, significantly reduce environmental costs associated with measurement, save time, and enable optimal planning.

Atomionics' personnel are CEO and cofounder Sahil Tapiawala, CTO and cofounder Dr. Ravi Kumar, and 10 employees.

7.4.5 S-Fifteen Instruments

This quantum technology venture company specializes in quantum optics and quantum secure communications. It manufactures and sells quantum technology devices that include quantum key distribution devices, random number generators, and entangled photon pair sources, along with control and measurement devices such as digital optical power meters.

The company's quantum key distribution system uses a BBM92 protocol with fewer vulnerabilities than general BB84 protocols. To distribute quantum states, the system uses quantum entangled photon pairs (one photon is distributed to each user through an optical link), and individual photon states are fundamentally random regardless of correlations caused by quantum entanglement. This unique randomness is achieved through preparation and measurement protocols without any standard active optical components.

The company's implementation system uses only passive components, simplifying system vulnerability checking. As the inclusion of active elements such as phase modulators has been shown to potentially result in information leaks, this countermeasure increases system complexity and requires further security testing.

Overall, S-Fifteen's system based on an BBM92 protocol is fundamentally resilient to attacks targeting Trojan horse, multiple photon transition, signal pulse phase correlation, and other such security vulnerabilities.

S-Fifteen consists of its Managing Director Brenda Chng and Research Scientist Syed Abdullah Aljunid.

7.5 Notable researchers

Based on research and patent data presented in Chapter 1, the following noteworthy researchers have been selected for mention in this paper in light of such factors as their position in Singapore's quantum research community and the research awards that they have received.

7.5.1 Artur Konrad Ekert

A venerable figure in quantum information. Formerly a Distinguished Professor with the National University of Singapore's (NUS) Department of Physics, as well as a Professor at NUS' Institute for Mathematical Science. He specializes in quantum information and quantum secure communications. He presented numerous theoretical bases for quantum technologies in the mid-1990s, and has since been a driving force behind quantum research and development. His many research achievements include Quantum Measurements in Optics, a paper he authored in 1992. In education, he has been a longtime teacher of the "Introduction to Quantum Information Science" the physics Master's program introductory course conducted by Oxford University, the lecture notes for which are distributed in electronic format and edited by Artur Ekert pupil and Stockholm University researcher Timothy Hosgood.

7.5.2 Antonio Helio Castro-Neto

Antonio Helio Castro-Neto is a pivotal figure in quantum materials science. Distinguished Professor at the National University of Singapore (NUS) and Director of NUS' Centre for Advanced 2D Materials (CA2DM). He received his PhD in physics at the University of Illinois at Urbana-Champaign, with a focus on quantum materials, quantum magnetism, and superconductivity. With a focus on theoretical research involving two-dimensional materials, he has been in charge of the CA2DM since its founding and is drawing interest at home and abroad for having published a prodigious number of research papers. He has more than 50 invention disclosures and patents under his name. He is an active entrepreneur in materials research, founding and serving as CEO of 2D Materials (a developer of high-quality graphene) in 2016, MADE Advance Materials in 2017, PHASE Events (an event planner for people in industry and academia engaged with nanomaterials) in 2018, and Graphene Watts (a company that develops and commercializes graphene-based lithium-ion batteries) in 2019. He is from Brazil.

7.5.3 Alexander Ling

A young leader in wide-area quantum communications research in Singapore. An associate professor at the National University of Singapore's Centre for Quantum Technologies (NUS-CQT), he specializes in quantum secure communications, quantum communications, quantum sensing, and metrology. His research team at the NUS is focused on developing a practical test for polarization-entangled quantum light sources powered by CubeSats (small satellites). His laboratory has spun off SpeQtral, a technology venture capital company focused on wide-area quantum communications in space (see section 7.4.2).

He received his Bachelor of Science degree in 2000 and the Master's degree in physics in 2008, both from the NUS. He has been a Principal Investigator (PI) at the NUS-CQT since 2010 and has taught at the NUS' Department of Physics since 2017.

7.5.4 Kuan Eng Johnson Goh

Head of the Department for Quantum Technologies for Engineering, and Principal Investigator at A*STAR's Institute of Materials Research and Engineering (IMRE). He received his PhD in 2007 from the Centre of Excellence for Quantum Computer Technology in the University of New South Wales, Sydney. Joining A*STAR in 2006, he contributed to materials science and engineering research that includes atomic-scale 3D printing with silicon atoms, highly conductive 3D printable thermoplastics, 2D semiconductors, and quantum devices. He currently melds his multidisciplinary research expertise in quantum information technologies, nanoelectronics, machine learning, and additive manufacturing toward disruptive quantum technologies.

7.5.5 Jason (Ching Eng) Png

Director of the Electronics and Photonics Department at the Institute of High Performance Computing (IHPC), A*STAR. He received his PhD degree from the University of Surrey, UK (2004), and MBA from INSEAD, France (2014) and Tsinghua University, China (2014). He joined IHPC in 2005 with research interests including quantum, high-speed photonics and plasmonics, and electromagnetics. He has received numerous awards, including the prestigious Royal Academy of Engineering Prize, Vebleo Fellow, Vebleo Scientist Award, IET Innovation Award – Software Design, Skolkovo Prize at INSEAD Venture Competition, and Spring TECS Proof-of-Value grant.

7.6 International collaboration and joint research

Singapore has signed an international agreement with the UK government in the field of quantum information, and has also received investment from the UK as part of collaborative initiatives aimed at specific technology applications. Additionally, core Singaporean research facilities have long been conducting joint research with France. Singapore has also been working with Australia at the university and research institute level. As for collaboration with other Asia-Pacific nations, Singapore has only collaborated or done joint research at the individual project level.

The UK has made frequent quantum technology investments in Singapore, and in recent years has collaborated on specific projects involving wide-area quantum communications from space.[20] In 2013, the UK government announced that it would make a 270 million GBP (332 million USD) investment in its National Quantum Technologies Programme (5-year term), part of which will go to Singapore. In 2018, it launched a project to build and deploy a quantum key distribution (QKD) testbed using satellites, with a total investment of 1.8 million SGD (1.35 million USD) from the governments of both countries. As part of these collaborations, Singapore and the UK used pioneering quantum key distribution technologies from Singapore to jointly develop the QKD QubeSat, a CubeSat for testing a method of distributing cryptographic keys securely over global distances. This satellite went into operation in the latter half of 2021 and already has a successor.

There has also been inter-governmental collaboration between Singapore and Finland in recent years. In September 2022, the National Quantum Office of Singapore, VTT Technical Research Centre of Finland, IQM Quantum Computers, and CSC-IT Center for Science (Finland) agreed to explore and promote research and development collaboration in the areas of quantum technologies.[21] Under the MoU, the parties aim to accelerate the development of quantum technology hardware components, algorithms and applications, and collaborate in the areas of quantum-accelerated high-performance computing and both terrestrial and satellite quantum communications. The MoU will also pave the way for knowledge exchange on national strategic roadmaps for quantum technologies.

Additionally, the NUS signed an MoU with the Centre national de la recherche scientifique (CNRS) in June

[20] Singapore National Research Foundation press release, "Singapore and UK collaborate on S$18m project to develop quantum-secured communications networks," September 27, 2018 (last accessed June 10, 2022).

[21] A*STAR press release, "Finland and Singapore's National Quantum Office Ink MoU," September 2, 2022; VTT Technical Research Centre press release, "Finland and Singapore's National Quantum Office ink MoU to strengthen quantum technology research cooperation," August 30, 2022.

2009, which was followed by the establishment of the France Singapore Quantum Physics and Information Lab (LIA FSQL), a public- academic partnership, in January 2010. In the LIA FSQL partnership, Christian Miniatura and Berthold-Georg Englert oversaw operations for France. The partnership consists of the NUS, NTU, Institut Non Linéaire de Nice (INLN) of the University of Nice Sophia Antipolis (UNS), Kastler Brossel's Laboratory (LKB) of UNS; and Paris-Sud 11 University (UPS11).

Following an update in May 2014, partnership membership was changed to CNRS, NUS, NTU, and LKB-UNS, with its first phase of the new partnership running from January 1, 2014, to December 31, 2017. A joint research lab known as MajuLab was later established at the NUS-CQT and the Physics Laboratory at the NTU. In October 2017, the partnership was reappraised and extended for a further five years, until the end of 2022.

In 2020, the UMI MajuLab was renamed to the International Research Laboratory (IRL).[22] This scientific committee is staffed by representatives from universities in both countries, and collaborating institutions from France are the CNRS, Côte d'Azur University, and the University of Paris.

The results of researchers from both countries have been published in several international jointly authored papers of high interest. Some examples are “Machine-learning engineering of quantum currents” (Physical Review Research 3 (1), 013034, 2021), “Two-dimensional network of atomtronic qubits” (Physical Review A 97 (4), 042306, 2018), and “Roadmap on Atomtronics: State of the art and perspective” (AVS Quantum Science 3 (3), 039201) by Christian Miniatura and Leong Chuan Kwek (NUS-CQT Associate Professor and MajuLab Deputy Director)

Singapore and Australia have only signed agreements at the university and research level, and no information could be found about any cooperation or collaboration between the governments. Research institutes the NUS-CQT and ARC CoE for Quantum Computation and Communication Technology (CQC^2T) at the University of New South Wales are in an organizational partnership between their research facilities.[23]

Singapore has also signed MoUs with several other research institutes outside the country, but no projects have been completed together and future goals and plans have been established. Singapore also has a three-year research agreement with the University of Catania's Department of Physics and Astronomy "E. Majorana" that began in September 2019, and is aiming to collaborate with Thailand's National Institute of Metrology in several ways with regard to quantum measurement and the development of an atomic clock. Additionally, Singapore has agreements with TCG CREST in India and with the University of Otago in New Zealand.

In education, the NUS and Yale University together opened Yale-NUS College in 2013 as a liberal arts college, and established a quantum information science group. Yale-NUS College provides a basic education in quantum communications and computing.

[22] History obtained from the IRL MajuLab timeline. Last accessed May 31, 2022.

[23] A global network for quantum computing that also includes a focus on quantum secure communications and distributed quantum information processing, CQC^2T was established in 2011 and is a Centre of Excellence that receives funding from the Australian Research Council (ARC), Australia's Department of Defence, DEVCOM ARL, the Semiconductor Research Corporation, the government of New South Wales, and seven other collaborating organizations in Australia. Also see section 5.3.2. For more information about this partnership, see "International collaboration with CQT," and "International collaboration with CQC2T," (last accessed June 10, 2022).

7.7 Quantum innovation ecosystem

According to A*STAR and NUS-CQT there are more than 40 quantum technology research groups in Singapore, 26 of which can be found at NUS' Centre for Quantum Technologies. These groups are engaged in all fields related to quantum computing, quantum communications, and quantum materials. Meanwhile, companies spun off from NUS-CQT are working to develop products through collaboration between industry and academia. Directing the efforts of all these players is the Research, Innovation and Enterprise Council of the Prime Minister's Office.

Figure 7-1 presents a map of the quantum innovation ecosystem in Singapore based on the above overview and characteristics of Singapore's major players.

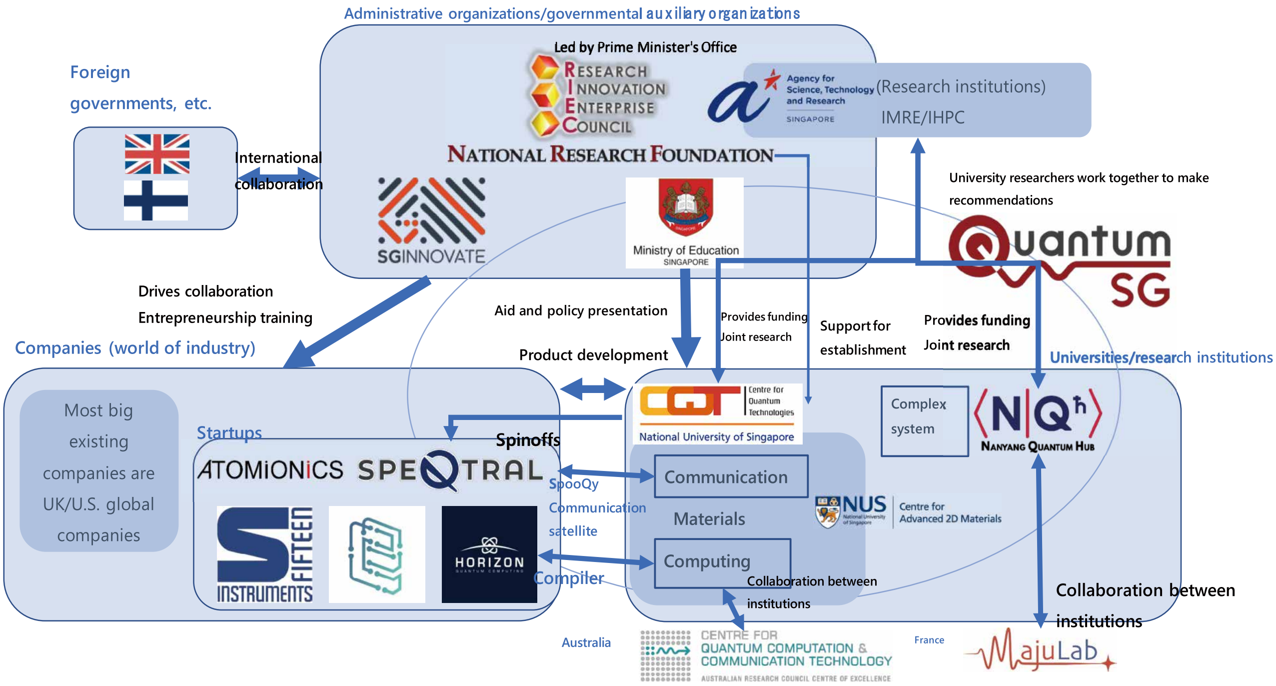


Figure 7-1: Quantum innovation ecosystem in Singapore

Source: Prepared by APRC

8. Quantum technology trends in Taiwan

In Taiwan, policymaking aimed at promoting quantum research began in earnest in 2018. The Taiwanese government is making concentrated investments in R&D at prominent national university that include National Taiwan University, National Tsing Hua University, and Academia Sinica, which reports directly to the government. In recent years, the government announced a plan to invest 3.96 million USD over five years to build a quantum research facility in Tainan for industry-academia-government cooperation. The facility is currently being built and is slated to be completed in 2024. Leveraging globally competitive advantages in semiconductor-related industries, Taiwan is looking for opportunities to engage with the supply chain for key products related to quantum technologies, including quantum computers.

8.1 Quantum technology policy

The general direction of Taiwan's science and technology policy is set forth in National Science and Technology Development Plans released every four years in accordance with the Fundamental Science and Technology Act (1999). No mention was made of quantum technologies in the 10th National Science and Technology Development Plan (2017–2020)[1], released in September 2017. Organized quantum promotion policy began in 2018 with a focus on quantum computing by the Ministry of Science and Technology (MOST)[2].

With the growing importance of quantum technologies prompting other governments to focus on related policy, the MOST launched the five-year Quantum Computer Project (August 1, 2018–July 31, 2023)[3] in April 2018 with the goal of integrating the quantum computer research resources of the country's universities, academic institutions, and industry players. Taiwan is investing approximately 120 million TWD (3.96 million USD at a rate of 1 TWD = 0.033 USD) annually into building an IBM Quantum Hub at National Taiwan University and a Quantum Technology Center at National Tsing Hua University. It has also provided grants to research teams at National Taiwan University and National Central University, as well as a joint research team from National Tsing Hua University and National Cheng Kung University. Quantum components and physics, quantum algorithms and programming, quantum computers, and quantum communications and encryption have been added to the subjects researched by these universities. Before it is done, the project aims to develop performance indicators, an open data information platform, and an application that can be shared among stakeholders in industry and academia.

The "Blueprint for Technology Development Strategy (2019–2022)[4]" released by the MOST in July 2019 is believed to be the first time a Taiwanese policy document has indicated a focus on quantum technologies. The blueprint cites a need for Taiwan to "leverage its strengths in ICT development, aggressively integrate research

1 Ministry of Science and Technology, "National Science and Technology Development Plan (2017–2020)," September 7, 2017

2 The Ministry of Science and Technology was reorganized as the National Science and Technology Council (NSTC) on July 27, 2022.

3 Ministry of Science and Technology, "Exploring the Secrets of Quantum Computers — The Ministry of Science and Technology Launches a Quantum Computer Research and Development Project," April 27, 2018; Ministry of Science and Technology, "Quantum Technology Innovation Breakthrough," November 3, 2020.

4 Ministry of Science and Technology, "Blueprint for Technology Development Strategy (2019–2022)," July 25, 2019

capabilities and resources across a range of disciplines, and begin joint research concerning basic theory for technologies such as quantum, quantum memory, semiconductor and superconductive qubits, and entangled photons," putting an R&D focus on "quantum control, quantum information (quantum computing and quantum communications), quantum sensors, and quantum components."

As part of policy aimed at aggressively promoting quantum technologies, the MOST announced a plan in December 2020 to collaborate with Academia Sinica and the Ministry of Economic Affairs in building a research facility for quantum science and technology in Shalun, Tainan in southern Taiwan over five years with an investment of 8 billion TWD (0.26 billion USD)[5]. Between 2021 and 2025, the MOST, the Ministry of Economic Affairs, and Academia Sinica will respectively provide funding of 4 billion TWD (0.13 billion USD), 1.8 billion TWD (59 million USD), and 2.2 billion TWD (72 million USD). The plan calls for Academia Sinica, which has already begun basic quantum research, to expand on its quantum technology research center, located in the southern part of Academia Sinica's research complex. This step is being taken to focus more on fields such as quantum computers, quantum computing, and quantum communications. With an emphasis on industrialization, the Ministry of Economic Affairs has defined three goals for itself: (1) develop key quantum technology products by leveraging Taiwan's advantages in semiconductors, (2) develop a digital quantum annealing system, and (3) develop encryption technologies for quantum communications.

As Taiwan accounts for over 60% of the world's semiconductor contract manufacturing, the "development of key quantum technology products leveraging Taiwan's advantages in semiconductor manufacturing" is arguably one pillar in its policy to promote quantum technologies. With regard to the development of next-generation semiconductor technologies, in January 2021 the MOST released the "□ (Angstrom) Next-generation Semiconductors: A Plan for the Research and Development of Tomorrow's Semiconductors and Quantum Technologies[6]." The plan aims to "develop a silicon-based quantum computing subsystem" with the following goals to be achieved by August 2025: (1) develop a circuit wafer subsystem for operating, powering, and reading cryo-CMOS and qubits, (2) build cryo-CMOS components, and (3) operated a silicon-based cubit device at low temperature and develop a circuit model.

Released in May 2021, the 11th National Science and Technology Development Plan (2021–2024)[7] states that "because quantum technologies will have a significant impact on information security, industry, finance, and defense, ... Taiwan will further strengthen its quantum technology capabilities and work to ensure that it plays a key role in the quantum age on the world stage, just as it does with semiconductors," demonstrating Taiwan's intent to create a new industry by promoting quantum technologies.

In the literature for industry policy governed by the National Development Council (NDC), building an industry of quantum technologies or other quantum fields is given no mention in the "5+2 Industrial Innovation Plan (2016),[8]"

[5] Ministry of Science and Technology, "Towards a New Quantum Generation in Taiwan," December 7, 2020. Taiwan has three industrial clusters, with quantum industry and precision machinery the core focus for the northern and central clusters, while the southern cluster is concentrated on petrochemicals and heavy industry.

[6] Ministry of Science and Technology, "Angstrom Semiconductor Initiative — Forward-looking Semiconductor and Quantum Technology Research and Development Plan," Japan External Trade Organization, "Taiwan Aims to Strengthen Upstream Semiconductor Supply Chain," June 21, 2021

[7] "11th National Science and Technology Development Plan (2021–2024)"

[8] National Development Council, "Plan for Cooperative Promotion of Industrial Innovation"

which has been a key policy of the Tsai Ing-wen administration, or a policy that succeeded it, the "Program for Promoting Six Core Strategic Industries (2020).[9]" However, revisions made to this program in 2021 state the necessity of investing in specially quantum computers in connection with developing next-generation semiconductor technologies.[10] The program aims to develop a next-generation semiconductor industry by pooling "domestic industry research resources to develop quantum chip technologies by leveraging Taiwan's expertise in silicon-based semiconductors" while also seeking to "develop a silicon-based quantum computing subsystem," a goal shared by the MOST's next-generation semiconductor development plan.[11] This is another hint suggesting Taiwan's fundamental leaning toward participating in the industrial value chain for quantum computing while leveraging its semiconductor-related technologies, including the microfabrication technologies in which it enjoys a competitive advantage.

In September 2021, the MOST announced the "Quantum Technology Project," a program that puts the call out for innovative research proposals. According to explanatory documents, the program "aims to develop key technologies for realizing quantum computers with high compute performance in three areas, namely materials technologies, qubits, and the integration of control, measurement circuits, and systems." Proposals are sought from three main areas: (1) quantum computer hardware technologies, (2) light quantum technologies, and (3) quantum technology software technologies.[12] The five-year research period will begin in March 2022 and annual funding will be provided of up to 10 million TWD (0.33 million USD) for research conducted by individuals and up to 30 million TWD (0.99 million USD) for group research projects. The MOST is expected to receive proposals on the following research subjects.[13]

① Quantum computer hardware technologies: Build qubits and quantum computer hardware technologies using qubits. Materials technologies, qubit design and production technologies, quantum-related control circuits and system integration, etc.

② Light quantum technologies: develop hardware and software technologies related to quantum computers and quantum communications that use light. Light quantum computing, quantum communications, etc.

③ Software technologies for quantum technologies: software technologies used for quantum computers. Research themes include quantum algorithms, quantum programming languages, encryption and post-quantum cryptography,[14] and quantum inspired computing.

As one priority project for FY 2022, the MOST has launched the "Taiwan Project to Develop Next-generation Quantum Key Technologies" and has announced priority areas, principal programs, and targets for quantum policy to be carried out in FY 2022 (Figure 8-1).

Figure 8-1: "Taiwan Project to Develop Next-generation Quantum Key Technologies," in the MOST's

[9] National Development Council, "Six Core Strategic Industries," December 2020

[10] National Development Council, "Program for Promoting Six Core Strategic Industries," May 2021

[11] Japan External Trade Organization, "Semiconductor Industry in Taiwan — A Study of Related Policies and Supply Chains of Major Companies," May 2022

[12] Ministry of Science and Technology, "Ministry of Science and Technology 2022 — Explanatory Materials (Draft) for Quantum Technology Plan," September 29, 2021

[13] Ministry of Science and Technology, "Quantum Technology Plan — Announcement of Call Commencement," September 29, 2021

[14] What the Taiwanese government's documents refer to as "post-quantum encryption" this paper has generally translated as "post-quantum cryptography."

To ensure the evolution of core software and hardware technologies for quantum computing and communication, which will be necessary for the quantum
generation of the future, we will maintain a leading position in the manufacturing and packaging industries and respond to the future influence of quantum
technology on industries such as information security and national defense. Among limited resources, we will bring together talents and teams from different
fields, and create an optimal route for Taiwan's development.

1. The inter - agency collaborative planning project is broken down into the following seven key fields.
   (1) The development of technology at the heart of quantum computers and communication hardware.
   (2) The creation of a quantum software research and development platform.
   (3) The establishment of a platform for exchange and cooperation with the world of industry.
   (4) The development of human resources in the research and development of quantum next - generation technology.
   (5) The promotion of quantum science and education.
   (6) The creation of a quantum research infrastructure and the development of cutting - edge core facilities.
   (7) The development of futuristic hardware technology for quantum subsystems.

2.The main impact of the Ministry of Science and Technology should be directed toward (1) to (7) above, and our strategy for this consists of the following.
   (1) To integrate research and development energy and create an interdisciplinary national team, to develop technology for quantum technology hardware and create a foundation for the quantum industry in Taiwan.
   (2) To create research and development infrastructure for software technology, including quantum theory, to develop applied technology for quantum computers and encryption technology.
   (3) To create a platform for industry exchange and cooperation to promote information exchange with academia and the research industry and create bridges for industry - government - academia collaboration.
   (4) To develop human resources for quantum research and development and expand teams in response to upcoming changes in the quantum generation.
   (5) To promote education concerning the science and technology of quantum technologies to raise people's recognition of quantum technologies in Taiwanese society and enable young students to work in quantum technology research.

3. The Ministry of Science and Technology will collaborate with academic interdisciplinary research institutions such as Academia Sinica, as well as the Ministry of Finance
   (6) To create a quantum core facility infrastructure and
   (7) To focus on hardware technology for quantum subsystems.

Source: Translated by APRC from the "Ministry of Science and Technology Administration Plan 2022[15]

[15] Ministry of Science and Technology, "Ministry of Science and Technology Annual Policy Plan 2022"

The MOST, Ministry of Economic Affairs, and National Development Council have released quantum technology promotion policies in quick succession while quantum-focused research is being done primarily by Academia Sinica and prominent national universities. To strengthen coordination among government agencies and among government, industry and academia, it was announced in 2022 the inter-agency "Quantum Systems Advancement Group" would be established.[16] Through collaboration with organizations such as the MOST's Engineering Center, the group aims to help organizations achieve quantum technology achievements and develop industrial applications. With its administrative office at National Taiwan University, the group is putting together a team of project managers that consists of Professor Shangjr (Felix) Gwo (National Tsing Hua University) and Professor Wen-Hao Chang (National Yang Ming Chiao Tung University), which have led quantum research in Japan, along with experts from industry, academia, and the Industrial Technology Research Institute (ITRI).

There are also efforts underway to promote exchange among industry players engaged with quantum technologies. These include an announcement by the National Science and Technology Council (NSTC, formerly the MOST) in August 2022 that it would establish the "Quantum Technology Industry Platform," as well as the holding of a quantum technology-related forum to promote the use of quantum technologies and industry.[17]

One area needing improvement regarding Taiwan's efforts to promote quantum technologies is its lack of programs for developing specialists. A declining birthrate and rapidly rising demand in the semiconductor industry has led to labor shortages and intense competition to find scientists. In response, the Executive Yuan formulated the "Plan to Develop and Attract Experts" in 2019 as part of efforts to develop scientists in Taiwan and attract them from abroad. In May 2021, the government formulated the "Regulations for Industry-Academia Collaboration and Innovation in Human Resource Development in National Priority Areas," and established "Taiwan Institutes for National Priority Research Areas," which see universities and companies undertake joint programs to educate and train people in five areas, namely semiconductors, AI, smart manufacturing, the circular economy, and finance.[18] To attract people from abroad, the "Act for the Recruitment and Employment of Foreign Professionals" was formulated in 2018 and revised in 2021 to put more emphasis on incentives to encourage foreign experts (other than those of Chinese nationality) to live and work in Taiwan.[19] Although Taiwan has yet to establish policy for developing people specifically for the quantum technologies field, this field is noted as a priority area in the above-mentioned annual plan from the MOST and is likely to be fleshed out further in the future.

[16] Ministry of Science and Technology, " 量子國家隊領航員成軍　推動人才培育　掌握關鍵技術 ," February 25, 2022

[17] National Science and Technology Council, "Inauguration of Quantum Technology Industry Platform and Taiwan General Quantum Computer Forum — Joining Hands With Industry to Advance The Future of Quantum Technology," August 24, 2022

[18] Japan Science and Technology Agency, Asia and Pacific Research Center (2020), "Science and Technology Capabilities in Taiwan: Innovation Policy and Basic Research Trends in the Tsai Ing-wen Administration"; currently, Taiwan Institutes for National Priority Research Areas have been established at National Taiwan University, National Yang Ming Chiao Tung University, National Tsing Hua University, National Cheng Kung University, and National Sun Yat-sen University.

[19] Yoshikuni Tazaki, "Impact of and Countermeasures for Taiwan's 'Six Shortcomings' in Industry," Exchange, May 2022 issue, Japan–Taiwan Exchange Association

8.2 Quantum technology research and development

In Taiwan, quantum research has gradually grown since the mid-1990s.[20] However, according to the analysis presented in Chapter 1, Taiwan has published 2,116 quantum-related research papers in recent years, putting it far behind China (27,987) and Japan (13,845), and roughly on par with Singapore (2,399). Taiwan's number is growing at 10% a year, however, placing it third behind India and China,[21][22]. By area of research, quantum materials account for 46% of all quantum research, followed by basic quantum technologies (20%), which includes quantum measurement and quantum sensing, quantum computing (19%), and quantum communication (11%). As discussed in the previous section, Taiwan's policies to promote quantum technologies lay out long-term strategic goals aimed having Taiwan participate in the industry value chain for quantum computing, and the country believes that leveraging the competitive advantage it has in semiconductor technologies will be a useful strategy. Quantum physical properties, qubits, topological insulators, and other such technologies categorized as quantum materials are closely associated with next-generation semiconductor technology development and the development of quantum computing as hardware. This is thought to be contributing to the rise in the number of papers pertaining to quantum materials.

Looking at support provided by the government for quantum research, the Taiwanese government has released information on government-funded research projects dating back to 1993 through the Government Research Bulletin,[23] a website administrated by the MOST. There were 9,078 research plans that include the keyword "quantum" in the plan documents. A breakdown by year is provided in the bar graph in Figure 8-2 (left axis). The figure shows that quantum-related research projects began to rise in the mid-2000s. The line graph (right axis) in Figure 8-2 shows the number of projects receiving funding of at least 10 million TWD (0.33 million USD) and indicates that these projects begin to rapidly increase in 2018 with the start of government programs to promote quantum technologies.

[20] James Lai, "Research and Analysis on the International Quantum Science and Technology Development Strategy," pgs. 50-57, Science & Technology Policy Research and Information Center (October 2021)

[21] Japan Science and Technology Agency, Center for Research and Development Strategy, "International Trends in Quantum Technology has Seen in Papers and Patent Maps," (March 2022)

[22] Taiwan has published a total of 2,743 research papers according to a survey conducted by a government think tank in Taiwan. The search was conducted using the Web of Science and the think tank's own search criteria (search was conducted on July 24, 2020) James Lai, "Research and Analysis on the International Quantum Science and Technology Development Strategy," Science & Technology Policy Research and Information Center (October 2021)

[23] Government Research Bulletin. Search date is December 12, 2022.

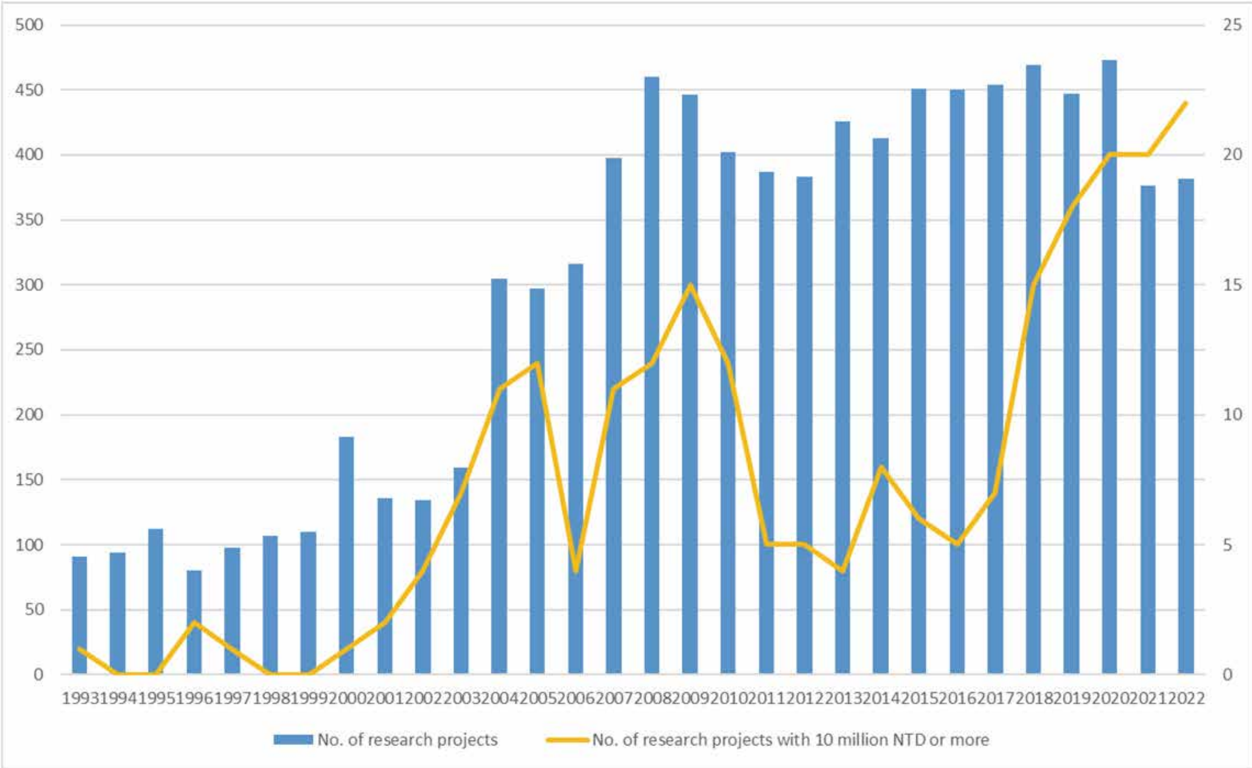


Figure 8-2: Quantum-related research projects, by year

Source: Prepared by APRC using data from the Government Research Bulletin

According to aggregate data from the website, the research organizations conducting the most research projects are as follows (project numbers are in parentheses). Prominent national universities such as National Taiwan University, National Yang Ming Chiao Tung University, and National Cheng Kung University, as well as relevant research institutes under the Academia Sinica, are core institutes for quantum science and technology research.

① National Yang Ming Chiao Tung University, Department of Electrophysics (348)
② National Taiwan University, Department of Physics (336)
③ National Cheng Kung University, Department of Physics (314)
④ National Tsing Hua University, Department of Physics (296)
⑤ Academia Sinica, Institute of Physics (202)
⑥ Academia Sinica, Institute of Atomic and Molecular Sciences (192)
⑦ National Taiwan University, Graduate Institute of Photonics and Optoelectronics (185)
⑧ National Sun Yat-sen University, Department of Physics (165)
⑨ National Taiwan Normal University, Department of Physics (163)
⑩ National Yang Ming Chiao Tung University, Department of Electronics and Electrical Engineering (143)

While the extent to which this research has produced results is unclear, the following are some examples that these universities and the MOST have called attention to as research achievements.

- In November 2019, with joint support from the MOST and the Ministry of Education, a group led by Associate Professor Chihsung Chuu of National Tsing Hua University's Centre for Quantum Technologies managed to conduct the first quantum-encrypted communications test in Taiwan.[24] Its next goal is to build a quantum communications network next to the Hsinchu Science Park and pave the way to an even larger quantum network.

- In November 2020, an Academia Sinica team at National Taiwan University led by Professor Hsisheng Goan of National Taiwan University made important progress in research involving quantum encryption and silicone-based qubits.[25] The team's Rainbow digital signature scheme made it to final selection at a post-quantum cryptography system standardization workshop held by the National Institute of Standards and Technology (NIST) in the U.S. The team is currently engaged in various research that includes using quantum encryption for safe communications encryption and developing an entrustment-type quantum computing protocol that allows users to quickly verify the accuracy of quantum computing results.

- In March 2021, a research team consisting of Assistant Professor Chinghao Chang and Distinguished Professor Emeritus from the Center for Quantum Frontiers of Research & Technology at National Cheng Kung University announced that it had made significant progress in research involving the conversion of graphene to a new electronic component with quantum properties.[26] The team's article entitled "Hall effects in artificially corrugated bilayer graphene without breaking time-reversal symmetry" was published in the February 2021 issue of Nature Electronics.[27]

- In July 2021, a research team led by Assistant Professor Yi-hsin Liu of the Department of Chemistry at National Taiwan Normal University announced that it had succeeded in synthesizing atomic-scale two-dimensional monolayer semiconductor material that undergoes giant Zeeman splitting at room temperature.[28] These diluted magnetic materials are said to be usable in quantum electrodynamics and in developing single quantum dot light emitters.

The future direction of quantum technology R&D in Taiwan appears to be "evolving core technologies for quantum computing and communications software and hardware," as indicated by the MOST's "Taiwan Project to Develop Next-generation Quantum Key Technologies," which was covered in the previous section. This is expected to take the form of "developing a silicon-based quantum computing subsystem" as noted in the above-mentioned "Program for Promoting Six Core Strategic Industries," and individual research subjects with this goal in mind are

[24] Ministry of Science and Technology, "Ministry of Science and Technology Press Release: Taiwan Quantum Encryption Communication Network Professor at National Tsing Hua University Successfully Develops 'Quantum Encryption' to Fight Against 'Quantum Hackers' ," November 26, 2019

[25] Ministry of Science and Technology, " Quantum Technology Innovation Breakthrough," November 3, 2020

[26] Ministry of Science and Technology, "Breaking Away from a Century-old Framework to Lead Quantum Black Technology — Taiwan Research Team Sculpts New Electronic Structures from Graphene," March 31, 2021

[27] Nature Electronics, "Hall effects in artificially corrugated bilayer graphene without breaking time-reversal symmetry," February 2021 issue

[28] Science Portal Asia Pacific, "Taiwan Succeeds in Synthesizing a Diluted Magnetic Material that Undergoes Giant Zeeman Splitting, with Quantum Technology Applications," September 2021; National Taiwan Normal University, "The Discovery of Diluted Magnetic Material from Prof. Liu Yi Hsin Published on International Journal," July 20, 2021

summarized below.[29]

- Development of a subsystem for controlling, powering, and reading cryo-CMOS and qubit circuits
- Evaluation, design, and 4K measurement verification for 1–20 GHz control driver architecture to support multiple silicon-based qubits
- Evaluation, design, and 4K measurement verification for an electric current fluctuation reading circuit architecture capable of detecting sub nA
- Fabrication of high-fidelity silicon qubit devices
- Development of isotopically purified 28Si epitaxial technologies and fabrication of silicon-based qubits
- Observation of Coulomb blockade in single electron limiting for silicon-based qubits and qubit devices
- Silicon-based qubit Rabi oscillation
- Integration of subsystems for achieving a quantum computer that can execute two-qubit gates

Team for coordinating on quantum technology R&D with Academia Sinica, the Ministry of Economic Affairs, and the Ministry of Science and Technology in accordance with a plan for establishing a quantum science and technology research center in the city of Tainan.[30] The team consists of 17 research teams comprising 72 scholars and experts and 24 companies engaged in R&D focused on quantum components, quantum computers, quantum algorithms, and quantum communications.

Seventeen collaborating universities and research institutes have been named: three Academia Sinica research institutes (the Institute of Astronomy & Astrophysics, Institute of Atomic and Molecular Sciences, and Institute of Information Science), two national institutes (the Taiwan Semiconductor Research Institute and National Center for High-performance Computing), and ten national universities (Taiwan, Tsing Hua, Yang Ming Chiao Tung, Cheng Kung, and Central, as well as the Graduate Institute of Applied Physics at National National Chengchi University, National Chung Hsing University, National Changhua University of Education, National Sun Yat-sen University, National Chung Cheng University, and two private universities [Tamkang University, Chang Gung University]).

There are 24 collaborating companies and organizations: ITRI Electronic and Optoelectronic System Research Laboratories, Taiwan Semiconductor Research Institute, Taiwan Academy of Banking and Finance, Foxconn, MediaTek, Chunghwa Telecom, Taiwan Synopsys, Chroma, ASE, MA-tek, Land Mark, Fujitsu, E-Elements, TCI, Rohde & Schwarz Taiwan, Applied Optoelectronics, TMYTEK, Aliner, EzInstrument, Quantaser Photonics, Southport, HC Photonics, Polaris Photonics, and Optilab L.L.C.[31]

According to announcements and reports by the government and various media organizations, R&D being done at quantum research institutes in Tainan can be put into three categories: general-purpose quantum computer hardware technologies, light quantum technologies, and the development of quantum software technologies and applications (Table 8-1). One recent example is an announcement by Fujitsu, which has pledged to collaborate

[29] National Development Council, "Program for Promoting Six Core Strategic Industries," May 2021, pgs. 30-31

[30] Ministry of Science and Technology, "Joint Press Release of the Office of Science and Technology Report of the Executive Yuan, Academia Sinica, Ministry of Economic Affairs, and Ministry of Science and Technology — Joining Hands with Industry to Create a New Quantum Future for Taiwan," March 16, 2022

[31] Economic Daily News, "Quantum National Team Receives 8 Billion TWD Investment for Five Years — Hon Hai, MediaTek, and Zhonghua Electronics On Board," March 16, 2022

with the National Team, that it would provide its digital annealer technologies to the Digital Annealer Quantum Information Center established by Chungwon University in the city of Taoyuan.[32]

Figure 8-3: R&D themes at quantum research institutes in Tainan

Number of companies	Research topics	Related industries
12	Building scalable superconducting quantum computer, research and development of superconducting parametric amplifier, high - coherence superconducting quantum circuit materials, silicon - based quantum dot quantum computing, CMOS integrated germanium qbits, low - temperature CMOS component DC/RFSPICE model, quantum computation and simulation using neutral atoms	Chip factories, circuit factories, packaging factories
8	Multifunctional quantum communication network, quantum chips to be applied to integrated multichannel quantum random number generators, non - gaussian continuous variable integrated optoelectronic chip quantum computing, research and development of quantum key development, system integration in the demultiplexing of fiber optic quantum communication networks	Solar power plants, telecommunications companies, packaging factories, the defense industry
4	Development of scientific theories for quantum computers, quantum virtual machines, quantum program verification and conversion, quantum computing optimization and financial application, quantum noise algorithms for chemical system quantum simulations, quantum error correction design	Software companies, Internet companies, pharmaceutical companies, the finance industry, the logistics industry

Source: Prepared by APRC based on MOST literature, media reporting, etc.[33]

[32] "Fujitsu to Provide Digital Annealers to the Digital Annealer Quantum Information Center," Nihon Keizai Shimbun, November 1, 2022 Collaboration with the National Team by universities and companies is fluid, and it is not clear if Chungwon University will be collaborating.

[33] United Daily News, "Government, Academia and Research Come Together into Taiwan's Quantum Technology National Team," March 24, 2022

8.3 Notable institutes and universities[34]

8.3.1 IBM Q Hub at National Taiwan University

As part of its collaboration on the MOST's Quantum Computing Project, the IBM Q Hub at the National Taiwan University was established in January 2019 by National Taiwan University (NTU). The NTU signed an agreement with IBM and established the network on its campus, enabling users to access IBM's cutting-edge quantum computers through the IBM Cloud network. The hub provides services to Taiwan's entire academic community. Originally headed by Department of Physics Professor Ching-ray Chang, the hub is now led by Hsi-sheng Goan. The hub's overall vision is to strengthen R&D capabilities with respect to quantum computer programming, software development, and future applications with a focus on four areas: (1) providing a platform for research, education, and training in quantum computing for Taiwan's academic research community; (2) developing scientists and engineers in quantum computer-related fields; (3) participating in quantum computer R&D and promoting the formation of R&D teams with members from research organizations at universities and companies; and (4) paving the way to industry-academia collaboration involving quantum computers.

The Center for Quantum Science and Engineering (CQSE), previously established as a research center for quantum researchers at the NTU, is engaged in research in four areas: (1) ultrafast science and highly accurate quantum technologies, (2) quantum computers and quantum communication networks, (3) quantum design of properties for new materials, and (4) computing science and engineering. The CQSE is headed by Acting Director Hsi-sheng Goan and Associate Director Sy-yen Kuo, a Distinguished Professor with the Department of Electrical Engineering.

8.3.2 National Tsing Hua University, Center for Quantum Technology

The Center for Quantum Technology, hosted by the Department of Physics at National Tsing Hua University (NTHU), was established in 2018 with funding through the MOST's Quantum Computing Project.[35] With the advantages that the atomic, molecular, and optical physics group of the NTHU enjoys in current technologies concerning ultracold atom and photon systems, along with the extensive research experience that the condensed matter physics group has in developing solid-state materials, the Center for Quantum Technology aims to develop core technologies needed for quantum computers and quantum communications. It is led by Chung-yu Mou of NTHU's Department of Physics, with a research team of about 50 people.

It is focused on four areas of research, namely (1) Realization, manipulation and computation of quantum bits: processing and development of superconducting qubits, quantum simulation using superconducting qubits; (2) Quantum communication: establish a quantum communication network and test platform for quantum key distribution, develop single photon and entangled photon sources, and develop related techniques (such as quantum memory) for a quantum repeater; (3) Quantum metrology and simulation: generation of squeezed light and development of continuous variable

[34] See the following for general information about Taiwan's universities and research institutes: Japan Science and Technology Agency, Center for Research and Development Strategy, "Science, Technology and Innovation Trend Report Taiwan Edition (2016)," March 2017

[35] Written as " 前瞻量子科技研究中心 " in Chinese. " 前瞻 " means "visionary" or "forward-thinking."

qubits, quantum simulations based on ultra cold atoms (Rydberg atoms, etc.), and precision measurement and quantum metrology; (4) Quantum materials: development of quantum materials that can potentially host qubits, development of topological materials that can host Majorana Fermions, and development of Majorana Fermion based topological qubits.

8.3.3 Center for Quantum Frontiers of Research and Technology

The Center for Quantum Frontiers of Research & Technology (QFort) was established in 2020 leveraging the previous 10 years of experience accumulated by National Cheng Kung University (NCKU), located in Tainan in southern Taiwan. Staffed by more than 40 talented NCKU scientists, QFort aims to not only explore fundamental aspects of quantum physics but also develop and find applications for next-generation technologies based on the benefits of quantum. Its primary research subjects are (1) theories involving quantum devices and quantum computing, (2) hybrid quantum devices and qubits based on superconductors and semiconductors (and other new materials), and (3) quantum material foundries. QFort is also focused on education, providing curriculum to students at a number of stages including the high school, graduate school, and doctoral levels. QFort's Director is Professor Yueh-nan Chen of the Department of Physics.

8.3.4 Institute of Physics, Academia Sinica

The Institute of Physics, Academia Sinica was established in Shanghai, China in 1928 and reestablished in Taiwan in 1962. It is currently focused on three areas: quantum materials physics, physics of active biological systems, and medium and high energy physics. Its subjects of research with respect to quantum materials physics are quantum material interface microscopy and lithography, quantum material and low temperature physics, spintronics, magnetic nanostructures and magneto-transport physics, modeling, simulations and computational physics, biology-inspired physics, physics of granular gas, granular flow and granular chain, theoretical particle physics and cosmology, and experimental nuclear and particle physics. Its director is National Taiwan University Department of Physics Professor Chia-seng Chang, who specializes in surface physics. The institute currently has 44 research staffs: five distinguished research fellows, 19 research fellows, 11 associate research fellows, two assistant research fellows, two senior research scientist, one associate research scientist, and three assistant research scientists. It also has 480 visiting scholars, postdoctoral research associates, and both full and part-time research assistants, as well as graduate students.

8.3.5 Research Center for Applied Sciences, Academia Sinica

This institution was established in 1993 and consists of four thematic centers focused on bio and medical science, green technologies, quantum Photonics, and quantum computing. The Quantum Photonics Center aims to develop basic technologies for quantum information in the fields of optoelectronic materials, metastructures, optoelectronic measurement, and device manufacturing, with a key research focus on (1) single-photon transmitters and receivers, (2) manipulation of wafer-level quantum entanglement states, and (3) development of topological photonics systems. Pei-kuen Wei is the center's director. The center has 28 research staff members: three distinguished research fellows, 15 research fellows, five associate research fellows, three assistant research fellows, one associate research specialist, and one assistant research specialist. There are also 200 staff that include visiting scholars, postdoctoral fellows, research assistants, full-time and part-time research assistants, and graduate students.

8.3.6 Institute of Information Science, Academia Sinica

Established in 1982, the Institute of Information Science, Academia Sinica conducts basic research involving information science. The institute has eight research labs: the Bioinformatics Lab, Computer System Lab, Data Management and Information Discovery Lab, Multimedia Technologies Lab, Network System and Service Lab, Programming Languages and Formal Methods Lab, and Computation Theory and Algorithms Lab. The Computation Theory and Algorithms Lab researches quantum encryption with a focus on exploring device independent quantum encryption, quantum computing, post-quantum cryptography, and new quantum encryption hypotheses and tasks. Headed by Director Mark Liao, it has 39 full-time research fellows, 29 postdoctoral research fellows, and over 300 full-time information technology specialists and part-time research assistants.

8.4 Notable companies

8.4.1 Taiwan Semiconductor Manufacturing Co. Ltd. (TSMC)

Founded by Morris Chang in 1987 as a spinoff from the Industrial Technology Research Institute (ITRI), Taiwan Semiconductor Manufacturing Co. Ltd. (TSMC) is the world's largest contract semiconductor manufacturer, headquartered in the Hsinchu Science Park. In addition to those in Taiwan, it also has production facilities in the U.S., China (Shanghai, and Japan, and accounted for 53% of the global semiconductor foundry market in 2021 with revenues of approximately 57.3 billion USD. In terms of aggregate market value, it has grown into a global company that ranks among the world's top dedicated semiconductor foundries.

TSMC has been an investor in quantum computing for many years,[36] and holds 22 quantum-related patents (see Chapter 1). Although TSMC is reported to have collaborated on the MOST's Quantum Computing Project (2018), no details of this involvement could be found.[37] Though details are elusive, according to a report by a state-backed think tank,[38] TSMC has partnered with National Taiwan University and made investments toward the research and development of technologies to fabricate qubit components on silicon wafers using microwave resonance technologies, as well as R&D for silicon-based quantum dots for quantum computer applications.[39]

[36] "TSMC is working on creating quantum processors," Hardwaresfera, 18 December 2018

[37] TSMC joins forces with academia to develop quantum computer, DigiTimes, 17 December, 2018; TSMC to work with Taiwan Govt on Quantum Computer, HEXUS, 18 December, 2018

[38] James Lai, "Research and Analysis on the International Quantum Science and Technology Development Strategy," Science & Technology Policy Research and Information Center (October 2021), pg. 61

[39] "Taiwan urged to accelerate quantum computing development," i-Micronews, 31 July 2020

8.4.2 Quantum computing Research Center, Hon Hai Research Institute

The Hon Hai Research Institute (HHRI) was established in June 2020 as an R&D center by Hon Hai Precision Industry Co. Ltd., also known as Foxconn, the world's largest electronics manufacturing services (EMS) company. The HHRI has five research centers, each focused on artificial intelligence, semiconductors, next-generation communications, information security, and quantum computing, and its R&D activities support Foxconn's "3 plus 3" initiative, which refers to "three key industries" — EVs, robots, and digital healthcare — that are being developed through the application of "three emerging technologies": artificial intelligence, semiconductors, and next-generation communications technologies.

The Quantum Computing Research Center consists of hardware and software departments. The hardware department is building a trapped ion laboratory where it will develop quantum control systems and miniaturization to facilitate the production of quantum computers. The software side will conduct research in areas such as quantum optimization, quantum metrology, and fault-tolerant quantum computation.

The HHRI collaborates with the IBM Quantum Hub (IBM Q Hub) at National Taiwan University toward algorithm research and application optimization.[40] In November 2022, the institute announced that it had signed a memorandum of understanding with Canadian non-profit organization Mitacs to conduct cutting-edge quantum technology research in Canada. Min-hsiu Hsieh, who formerly conducted research in Australia, is HHRI's current director. [The HHRI will collaborate with the "National Team" quantum research hub in Tainan]

8.4.3 Advanced Semiconductor Engineering, Inc. (ASE)

Established in 1984 and headquartered in Kaohsiung, Taiwan, ASE is the world's largest provider of semiconductor packaging and testing services. A leading company in IC chip packaging and testing services, ASE provides semiconductor users with a comprehensive suite of services that includes front-end engineering testing, wafer pin testing, and testing of packages, materials, and final products. It provides semiconductor packaging and test services to more than 90% of the world's electronics companies. [ASE will collaborate with the "National Team" quantum research hub in Tainan]

8.4.4 MediaTek Inc.

Established in 1997 and headquartered in Hsinchu Science Park in the city of Hsinchu, MediaTek Inc. is the world's fourth largest fabless semiconductor manufacturer (fabless IC design company). It leads the market in chipset technologies for digital televisions, voice assistant devices (VAD), mobile phones such as smartphones, and devices such as optical drives, Blu-ray drives, and DVD players. It is Taiwan's second largest company in the mobile phones space. ICs for mobile devices, together with IoT, computing, and ASIC products, account for roughly 80% of the company's sales. [MediaTek will collaborate with the "National Team" quantum research hub in Tainan]

[40] James Lai, "Research and Analysis on the International Quantum Science and Technology Development Strategy," Science & Technology Policy Research and Information Center (October 2021), pg. 61

8.4.5 Chroma Electronics Co. Ltd.

A manufacturer of semiconductor fabrication and testing devices established in 1984, Chroma ATE ranked fourth in Taiwan for sales in FY 2021. The company is one of the world's leading suppliers of precision testing and measurement equipment, automated testing equipment, manufacturing execution systems, and turnkey test solution provider, with products and services sold worldwide under the Chroma brand. It provides services to market that include semiconductors, LEDs, solar energy, flat-panel displays, power electronics, electric vehicles, automated optical inspection, and systems for the ICT and environmental conservation industries. [Chroma ATE will collaborate with the “National Team” quantum research hub in Tainan]

8.4.6 Materials Analysis Technology Inc. (MA-tek)

Established in 2002, MA-tek is a world-class contract analysis company that services focused on materials analysis (MA). Since its founding, its business has expanded to include failure analysis (FA) and product reliability testing (RT). The company focuses on capital investment for solid-state electronics engineering and new material analysis systems, and has numerous facilities that boast high equipment capacity and performance characteristics. Its main customers include the IC industry, materials manufacturers, and manufacturing equipment manufacturers. [MA-tek will collaborate with the “National Team” quantum research hub in Tainan]

8.4.7 LandMark Optoelectronics Corporation

Established in 1997 and headquartered in the Southern Taiwan Science Park, LandMark is an IC materials manufacturer that supplies mainly epitaxial wafers. It manufactures gallium arsenide (GaAs) and indium phosphide (InP) based epitaxial wafers for optical communication, industrial application, and special-purpose usage. Its products are widely used in products that include optical fiber communications devices, consumer devices, and industrial equipment. [LandMark will collaborate with the “National Team” quantum research hub in Tainan]

8.4.8 Quantaser Photonics Co., Ltd.

Established in 2013 and headquartered in Taipei, this startup company develops quantum optics testing equipment and sells products to quantum optics research facilities at National Cheng Kung University and National Tsing Hua University, as well as such facilities in the U.S., Europe, and China. Its main products include temperature-stabilized Fabry-Perot Etalon for spectral filters useful in quantum memory experiments, as well as ultra-stable precision temperature controllers for scientific research. [Quantaser Photonics will collaborate with the “National Team” quantum research hub in Tainan]

8.4.9 Polaris Photonics, Inc.

Established in 2016 and headquartered in Taoyuan, Polaris Photonics is a startup specializing in lithium niobate material based optical waveguides, modulators, and multifunction integrated optical device research, design, and manufacturing. It has developed products such as multifunction integrated optical chips (MIOC) and waveguide phase modulators (PM) for laser modulation, short pulse generation, frequency shifting, inertial navigation, optical communication, and fiber optical sensing applications. MIOCs are a key component in optical fiber gyroscopes (IFOGs) for the high precision measurement of aircraft position. PMs offer more power efficiency, environment tolerance, and reliability than other modulators. [Polaris Photonics will collaborate with the "National Team" quantum research hub in Tainan]

8.4.10 Chelpis Co., Ltd.

Chelpis was established in 2017 as a startup specializing in cryptographic security products in the digital world. With a focus on post-quantum cryptography, the company develops encryption technologies and algorithms in collaboration with Academia Sinica, and has announced AORTA, an encryption product for use by software companies as a decentralized transfer authentication and encryption solution. The company cites blockchain and information security startup companies among the users of its services. It was recently reported that the company had secured 58.5 million TWD (1.93 million USD) in funding from sources such as the National Development Fund, Executive Yuan.[41]

8.5 Notable researchers

Based on research and patent data presented in Chapter 1, the following researchers have been selected as noteworthy in this paper in light of such factors as their position in Taiwan's quantum research community and the research awards that they have received.

8.5.1 Shangjr (Felix) Gwo

Professor of the Department of Physics at the National Tsing Hua University, as well as the founder and a core member of the Quantum Systems Promotion Group, a group that supports quantum-related projects of the Taiwanese government. His subjects of research include surface physics, condensed system physics, scanning probe microscopy, and nanotechnology. He graduated from National Chiao Tung University (Electronic Engineering) in 1905 and received his PhD in physics from the University of Texas at Austin in 1993. He was an Associate Professor of Physics at National Tsing Hua University from 1997 to 2002, after which he became a Professor of Physics at that university. Among the major awards he has received the Outstanding Research Award from the National Academy of Sciences (NAS) and the 59th Academic Award from the Ministry of Education, Taiwan.

[41] "Taiwanese Post-Cryptography Startup Chelpis Secures 263 Million JPY in Funding," BRIDGE, May 4, 2022

8.5.2 Meng-fan Luo

Meng-fan Luo is Director General of the Department of Natural Sciences and Sustainable Development at the Ministry of Science and Technology, Department Chairman of the Department of Physics at National Central University, and Director General of MOST. His subjects of research are surface visits and nanoscale physics. After graduating from the Department of Physics at National Taiwan University, he received his PhD in physics from Cambridge University in the UK. From 2000 to 2002 he worked at the Institute of Surface and Interface Science and Department of Chemistry at UC Irvine, and joined the Department of Physics at NCU in 2002. He became a professor at NCU in 2010 and Department Head in 2013. He has participated in projects such as Effect of Charge Transfer within Nanoparticles on Catalytic Properties most recently.

8.5.3 Wen-hao Chang

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8.5.4 Ching-ray Chang

President of the Taiwan Association of Quantum Computing and Information Technology (TAQCIT), as well as a distinguished professor of the Department of Physics and the previous director of the IBM Q Hub at National Taiwan University. He is also an adviser at the Hon Hai Research Institute. His areas of research include condensed matter physics, spintronics, quantum computing, and the application of these fields. After graduating from the Department of Physics at National Taiwan University, he received his PhD in physics from the University of California, San Diego in 1988. After a stint as a researcher at the Industrial Technology Research Institute, he joined the Department of Physics at National Taiwan University in 1989 and became a professor in 1994. He has been a Dean of the Department of Physics, a Dean of the College of Sciences, a General Director and Vice President, and an Interim President. He has received the award for special contribution to the Physics Community of Taiwan Physics Society, and is an IEEE fellow and a fellow of the American Physical Society.

8.5.5 Hsi-sheng Goan

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8.6 International collaboration and joint research

Due to the cross-Strait problem between China and Taiwan, Taiwan has only had interactions with 14 countries, including Paraguay and seven other countries in South America. However, "international" collaboration is being done between counterparts in both the public and private sectors. With respect to science and technology collaboration, while representative offices of the MOST are carrying out operations at 17 locations in 13 countries and regions such as the US and Europe, no information could be found about any significant international collaborative activities in quantum-related fields (that are led by the government) other than those noted below.

8.6.1 Collaboration with Japan

In June 2015, the MOST signed a letter of confirmation for a joint research support project with the National Institute for Materials Science (NIMS) in Japan as well as academic institutions in Taiwan.[42] The project will see the MOST solicit joint research projects with NIMS and Taiwanese organizations, select several of these, and provide funding to researchers in Taiwan. The project is currently focused on joint research in areas that include advanced ICT and advanced, energy, environment, magnetic, spin, quantum, and structural materials.[43]

[42] National Institute for Materials Science, "Taiwan's Ministry of Science and Technology Signs Letter of Confirmation for Joint Research Support Project," June 5, 2015

[43] Ministry of Science and Technology, "Ministry of Science and Technology Solicits Projects through 2023 Taiwan-Japan (MOST-NIMS) Bilateral Agreement to Expand Add-on International Cooperation Research Project," January 17, 2022

8.6.2 Collaboration with Slovakia

In October 2021, a trade and investment delegation led by the National Development Council's Ming-hsin Kung and the MOST's (currently the NSTC) Tsung-tsong Wu visited the Slovak Academy of Sciences and held discussions with representatives from SAS leadership, the Slovak Research and Development Agency, and the Ministry of Education, on matters concerning science, technology, higher education, and innovative research.[44] In 1996, the MOST and SAS signed an MoU that has facilitated personnel exchange and joint research between the two countries' research organizations. Attending the signing was Dr. Vladimir Buzek, director of the Quantum Technology Center of SAS and member of the Strategic Advisory Board for the Quantum Technologies Flagship, a quantum technologies research initiative. Minister Wu indicated Taiwan's intent to simultaneously develop quantum computers while also focusing on quantum communication technologies as a major player in the ICT industry, and expressed his expectation for Dr. Buzek to further cooperation between Taiwan and Europe in the quantum field.

The genesis of this collaboration between the two countries can be attributed to a global reorganization of supply chains in central and eastern European countries such as Lithuania, the Czech Republic, and Slovakia that has led to an increased interest in semiconductors, an area where Taiwan excels.[45] The visit to Central and Eastern Europe by Ministers Kung and Wu in the fall of 2021 was also an aspect of semiconductor diplomacy with Taiwan. A parliamentary delegation from Slovakia also visited Taiwan in June 2022 with the aim of strengthening relationships with counterparts in economics, science, and technology, paving the way to further cooperation among the two countries' research organizations.[46]

8.7 Quantum innovation ecosystem

Figure 8-6 presents a map of the quantum innovation ecosystem in Taiwan based on the country's quantum-related policies and R&D community. Quantum innovation policy is set by the MOST (currently the NSTC) and the Ministry of Economic Affairs, with research and development carried out by primarily Academia Sinica, which is supervised directly by the government, as well as prominent national universities such as National Taiwan University, National Tsing Hua University, and National Cheng Kung University. With a quantum research center in the southern part of Academia Sinica's research complex, where organizations from industry, academia, and the government collaborate, as well as the Quantum Systems Promotion Group at National Taiwan University, the government has built infrastructure to support industry-academia-government collaboration. In industry, plans are being discussed by semiconductor companies such as TSMC and EMS companies like Foxconn, but no significant R&D activities have begun. Although there are a few quantum startups, they have little renown. In the field of quantum computing, an area of interest to industry, the Taiwan Association of Quantum Computing and Information Technology (TAQCIT) has begun a number of activities aimed at promoting industry-academia

[44] Ministry of Science and Technology, "Minister Wu of the Ministry of Science and Technology Visits Slovak Scientific Research Institutions to Enhance Cooperation between the Hsinchu Science Park and the Space Industry," October 23: 2021; "Taiwan and Slovakia Sign MoU for Seven Industries, Including EVs and Aerospace," Taiwan Today, October 25, 2021

[45] "Taiwan to use tech knowhow to build ties with other democracies," Financial Times, February 3, 2022; "Taiwan Approaches Central and Eastern European Countries Over Semiconductor Technologies," Nihon Keizai Shimbun, February 4, 2022

[46] "Slovak Parliamentary Delegation in Taiwan to Meet with President Tsai Ing-wen," Nihon Keizai Shimbun, June 5, 2022

cooperation. As technology development advances in industry, there will likely be a bigger role to play for the National Development Fund, a state-backed investment fund, and the ITRI, which supports industrial technology development.

While Taiwan's strategy is focused on leveraging its strengths in the semiconductor industry to develop core quantum technologies, some have pointed to a risk of the country falling behind in quantum technology development precisely because of its success in the semiconductor business. Where the industry goes next will be something to watch.

Figure 8-6: Quantum innovation ecosystem in Taiwan

Development of core quantum technology products using the strengths of the semiconductor field through industry-academia-government collaboration

Source: Prepared by APRC

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