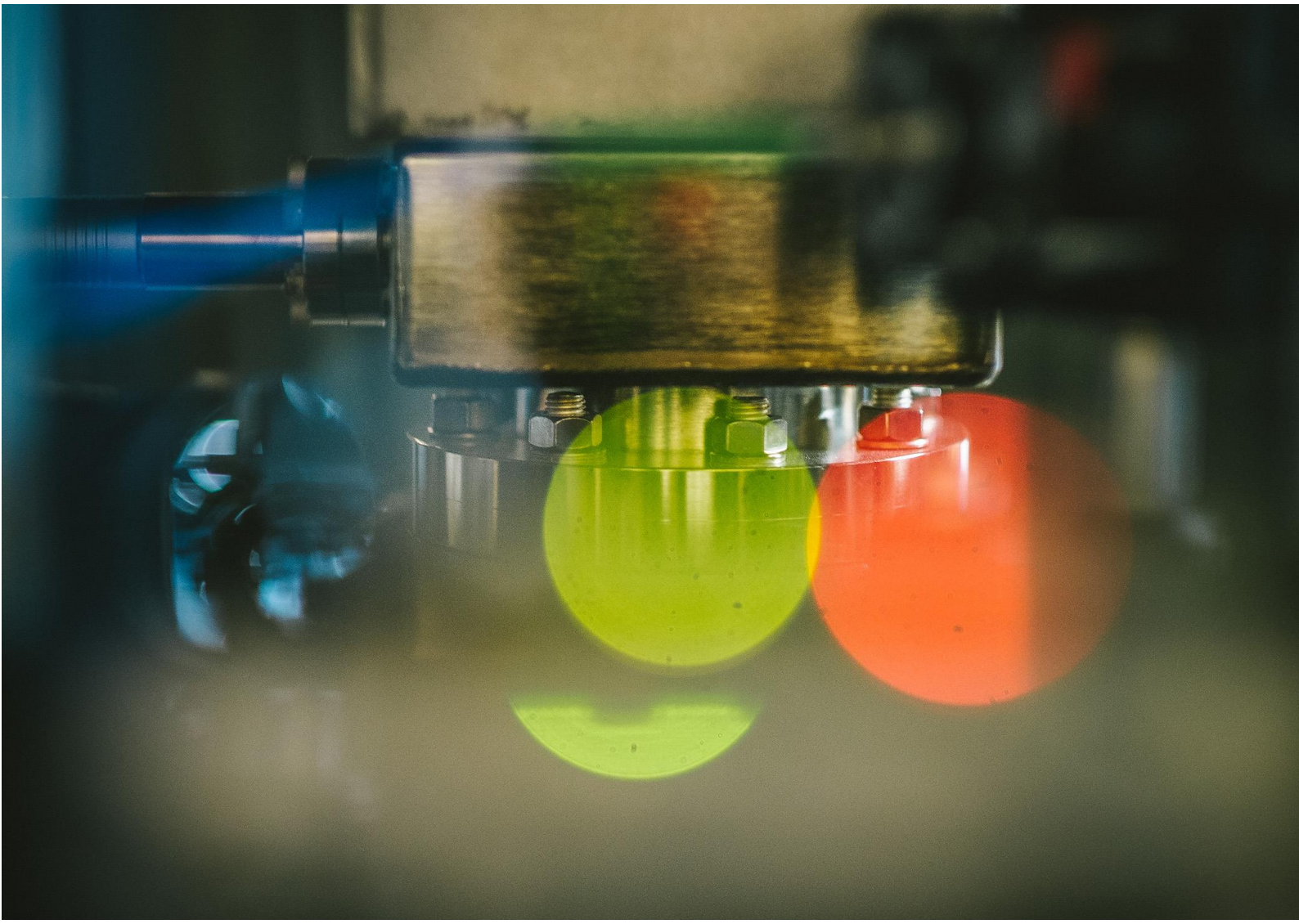
Australia's National
Science Agency

Quantum Technology Discussion Paper: Appendices

Supplementary information related to the CSIRO Quantum Technology Discussion Paper

November 2019



Contents

Appendix A: Regional quantum strategies and investment

This appendix provides a high-level overview of quantum technology strategies and government investments in key countries and regions.

COUNTRY/REGION	STRATEGY	NOTABLE GOVERNMENT INVESTMENTS[1]
United States	In 2018, the National Quantum Initiative Act (NQI) was signed into law. The NQI instructs federal government bodies (NIST, NSF, and DOE) to catalyse the growth of the quantum technology sector through collaboration with academic institutions and private industry.	• The NQI committed $1.2 billion of funding over five years.
United Kingdom	The United Kingdom (UK) published a National strategy for quantum technologies in 2015, identifying five focus areas for action: • enabling a strong foundation of capability in the UK • stimulating applications and market opportunity in the UK • growing a skilled UK workforce • creating the right social and regulatory context • maximising benefit to the UK through international engagement[2]	• The National Quantum Technologies Programme has invested more than £1 billion since its establishment in 2014.[3]

[1] Local currency unless specified.

[2] Innovate UK (2015) National strategy for quantum technologies. https://www.gov.uk/government/publications/national-strategy-for-quantum-technologies.

[3] GOV.UK (2019) £1 billion investment makes UK a frontrunner in quantum technologies https://www.gov.uk/government/news/1-billion-investment-makes-uk-a-frontrunner-in-quantum-technologies

Canada	In 2017, the National Research Council of Canada, the Natural Sciences and Engineering Research Council of Canada , and the Canadian Institute for Advanced Research published a symposium report calling for action to maintain and grow quantum science excellence and driving innovation to seize Canada's "quantum opportunity".[4]	• Canada has invested more than $1 billion in quantum research over the past decade.[5] • In 2016, the University of Waterloo received a Canada First Research Excellence Fund award of more than $76 million, with additional partner contributions of $68 million, for an overall $144-million initiative to advance the development of deployable quantum devices. [6] • In 2017, the Canadian government provided the Canadian Space Agency (CSA) with $80.9 million funding for emerging technology research, including in quantum technologies.[7]
China	In 2016, China announced a focus on quantum communications and computing as part of its 13th five-year plan. By 2030, China aims to have expanded its national quantum communications infrastructure, developed a general quantum computer prototype, and constructed a practical quantum simulator.[8]	• The local government has reportedly invested $10bn to establish a National Laboratory for Quantum Information Sciences in Hefei.[9]
Europe	The European Commission have established a Quantum Flagship with the goals to consolidate and expand European scientific leadership and excellence in this research area in order to kick-start a European industry in quantum technology.[10]	• The Quantum Flagship has been allocated €1b of funding over 10 years

[4] National Research Council of Canada (2017). Seizing Canada's Quantum Opportunity. Government of Canada. http://publications.gc.ca/collections/collection_2018/cnrc-nrc/NR16-151-2017-eng.pdf.

[5] Sussman, B, et al. (2019) Quantum Canada. Quantum Science and Technology, 4(2). https://iopscience.iop.org/article/10.1088/2058-9565/ab029d.

[6] Sussman, B, et al. (2019) Quantum Canada. Quantum Science and Technology, 4(2). https://iopscience.iop.org/article/10.1088/2058-9565/ab029d.

[7] Government of Canada (2019). Cybersecurity from space: the Government of Canada invests in quantum technology. https://www.canada.ca/en/space-agency/news/2019/06/cybersecurity-from-space-the-government-of-canada-invests-in-quantum-technology.html

[8] https://www.cnas.org/publications/commentary/chinas-quantum-future

[9] https://www.scmp.com/news/china/society/article/2110563/china-building-worlds-biggest-quantum-research-facility

[10] See https://qt.eu/

Japan	In 2018, the Japanese Government launched the Q-LEAP initiative that invests in R&D projects in three fields of quantum technology: quantum simulation and computation, quantum sensing, and ultrashort pulse lasers.[11]	• The Q-LEAP program includes US$200 million fundingover 10 years • Japanese government agencies have invested around US$250 million in quantum information science and technology research over 15 years.
Germany	In 2018, the German Federal Government announced a Framework Programme under its High-Tech Strategy aimed at bringing quantum technologies to market.[12]	• The German Government has allocated €650 million funding to its quantum technologies Programme.
Switzerland	Quantum sector stakeholders released *Quantum at the Crossroads,* a document that describes the Swiss quantum landscape and calls for reinforced investment to help Switzerland leverage its strengths in quantum.	• The National Centre of Competence in Research for Quantum Science and Technology received 37,820,000 Swiss Francs funding between 2010-2017.
Netherlands	In 2019, the Netherlands published a National Agenda on Quantum Technologies identifying four action areas to strengthen its role in quantum technology: • Breakthroughs in research and innovation • Ecosystem development, market creation and infrastructure • Human capital: education, knowledge and skills • Societal dialogue on quantum technology.	• €135 million from six parties will be invested in QuTech, the quantum technology institute of the TU Delft and TNO, over 10 years.

[11] Yamamoto, Y, Sasaki, M and Takesue, H (2019) Quantum information science and technology in Japan. Quantum Science and Technology, 4(2). https://iopscience.iop.org/article/10.1088/2058-9565/ab0077.

[12] Federal Ministry of Education and Research (2018) Quantum technologies – from basic research to market. https://www.bmbf.de/upload_filestore/pub/Quantum_technologies.pdf.

Appendix B: Australia's quantum landscape

This appendix provides a high-level overview of some of the key research and industry players in Australia's quantum technology landscape.

Australia's quantum research landscape

Table 1: Overview of Australian university-based quantum science and technology research

ORGANISATION	ERA[13]	PUBLICATIONS[14]	NCI[15]	RELATED COMPANIES
University of New South Wales	5	527	1.17	• Silicon Quantum Computing
Australian National University	5	349	1.84	• Quintessence Labs
University of Queensland	5	344	1.48	
The University of Sydney	5	309	1.73	• Q-CTRL
University of Melbourne	5	225	2.54	• moglabs
Monash University	5	201	2.33	
University of Technology Sydney	5	190	2.00	• H-Bar
Macquarie University	4	188	1.15	• Lucigem
Griffith University	5	150	1.47	
Swinburne University of Technology	4	128	1.38	
RMIT University	5	126	1.65	• H-Bar
University of Western Australia	5	126	1.99	
CSIRO	-	102	1.33	• HPEM
University of Adelaide	-	81	-	• Cryoclock
Curtin University	4	51	-	•

[13] ERA Ranking for Quantum Physics in: Australian Research Council (2019) State of Australian University Research 2018-19. Australian Government.

[14] Publication counts and NCI data are for 2014-2018. See Appendix C for further details.

[15] Normalised Citation Impact (NCI) is generally only shown for organisations with > 200 publications; However, there were few Australian organisations meeting this criterion. NCI for organisations with 100-200 publications shown in grey. Care should be taken with grey values as there is less statistical confidence in the value.

Table 2: Overview of ARC CoEs undertaking quantum-related research

ORGANISATION	FOCUS	MEMBERS AND PARTNERS
ARC CoE for Quantum Computation and Communication Technology (CQC2T)	• Optical Quantum Computation • Silicon Quantum Computation • Quantum Communications • Quantum Resources and Integration	Members • UNSW (lead) • University of Melbourne • ANU • Griffith University • UQ • The University of Sydney
ARC CoE for Engineered Quantum Systems (EQUS)	• Quantum materials • Quantum diagnostics and imaging • Quantum engines and instruments	Members • UQ (lead) • UWA • The University of Sydney • Macquarie University • ANU
ARC CoE in Future Low-Energy Electronics Technologies (FLEET)	• Topological materials • Exciton superfluids • Light-transformed materials • Atomically thin materials • Nanodevice fabrication	• Members • Monash University (lead) • UNSW • ANU • RMIT University • Swinburne • UQ • University of Wollongong • Many partner organisations. Additional support from NSW Department of Industry.
ARC CoE in Exciton Science	• Quantum and classical mechanical exciton theory and modelling • Spectroscopy • Design and fabrication of materials and devices for applications in solar, lighting and security, and exciton control.	• Members • University of Melbourne (lead) • Monash University • RMIT University • UNSW • The University of Sydney Partners include the Defence Science and Technology Group, The Reserve Bank of Australia, CSIRO and more.

Australia's quantum industry landscape

Table 3: Overview of Australian industry activity.

COMPANY	SECTOR	TECHNOLOGY	PARTNERS	INVESTMENT
Archer	Quantum computing	• Quantum computer chip designed to operate at room temperature.	• University of Sydney	• ASX-listed • Received $15,000 from the NSW government in 2019 to support the use of the University of Sydney's prototyping facilities.
h-bar consultants	Consultancy	• Quantum technology consultants	Run by researchers from RMIT University and UTS	
Q-CTRL	Quantum Computing	• Quantum control solutions for reduced decoherence and errors	• IBM • Founder is Professor of Quantum Physics at University of Sydney	• $22m in Series A VC funding in September 2019
Quintessence Labs	Quantum Communications and Security	• Quantum cyber security products • Encryption • Random number generation	• ANU • UQ • CQC2T • Westpac	• $2m in seed funding in 2008 • $1.1m and $3.26m in grant funding from the Australian Department of Defence in 2012 and 2017, respectively.
QxBranch (headquartered in US, office in SA)	Quantum computing	• Data analysis and quantum computing	• Acquired by Rigetti Computing in July 2019	• $8.47m USD Series A funding in June 2018.
Silicon Quantum Computing Pty Ltd	Quantum computing	• Silicon-based quantum computing technology	• CQC2T • Australian and New South Wales governments • Commonwealth Bank Australia • Telstra • UNSW	• Formed for $83m as a joint venture between Telstra, Commonwealth Bank of Australia, University of New South Wales and the NSW and Australian Governments in August 2017.
MogLabs	Enabling technology	• High-performance laser technologies for research institutions	• Founded by University of Melbourne researchers	
Liquid Instruments	Enabling technology	• Reconfigurable hardware for experimental measurement and control	• Founded by ANU researchers	• $11m Series A funding in January 2019.

COMPANY	SECTOR	TECHNOLOGY	PARTNERS	INVESTMENT
CryoClock	Sensing and measurement	• Cryogenic sapphire oscillator technology for ultra-precise timing	• IPAS • University of Adelaide	
Lucigem	Enabling technology	• Fluorescent nanodiamonds for applications in quantum engineering, life and medical sciences, & biomedicine.	• Macquarie University	

Appendix C: Bibliometric, IP and capital investment analysis

This appendix describes the bibliometric, intellectual property (IP) and investment analysis undertaken to inform the discussion paper.

Bibliometric analysis

A bibliometric analysis of quantum science and technology research publications was undertaken by CSIRO's Science Impact and Policy Team using data obtained from Clarivate's Web of Science system on 3 September 2019.

Search strategy

The following terms were used to identify potentially relevant publications:

WC="Quantum Science & Technology"
OR (TS=("quantum physics" OR "quantum electronic" OR "quantum optic*" OR "quantum information science" OR "quantum key" OR "quantum bit*" OR "qubit*" OR "quantum internet" OR "quantum repeater" OR "quantum radar" OR "quantum mechanics" OR "quantum tech*" OR "quantum dot*" OR "quantum simulat*"*
OR quantum NEAR ("error correct" OR comput* or *communicat* OR network OR cybersecurity OR encryption OR cryptograph* OR algorithm* OR imag* OR sensor* OR sensing OR oscillator OR metrology OR measurement OR mechanic* OR tunneling OR tunnelling OR entangl* OR superposition* OR teleport*) NOT photosynth*)*
NOT WC=(Religion OR EDUCATION SCIENTIFIC DISCIPLINES OR HISTORY PHILOSOPHY OF SCIENCE OR Philosophy OR EDUCATION EDUCATIONAL RESEARCH))

The following settings were used to constrain the results:

- DOCUMENT TYPES: (Article OR Proceedings Paper OR Review)
- Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH
- Timespan=2001-2018

Results

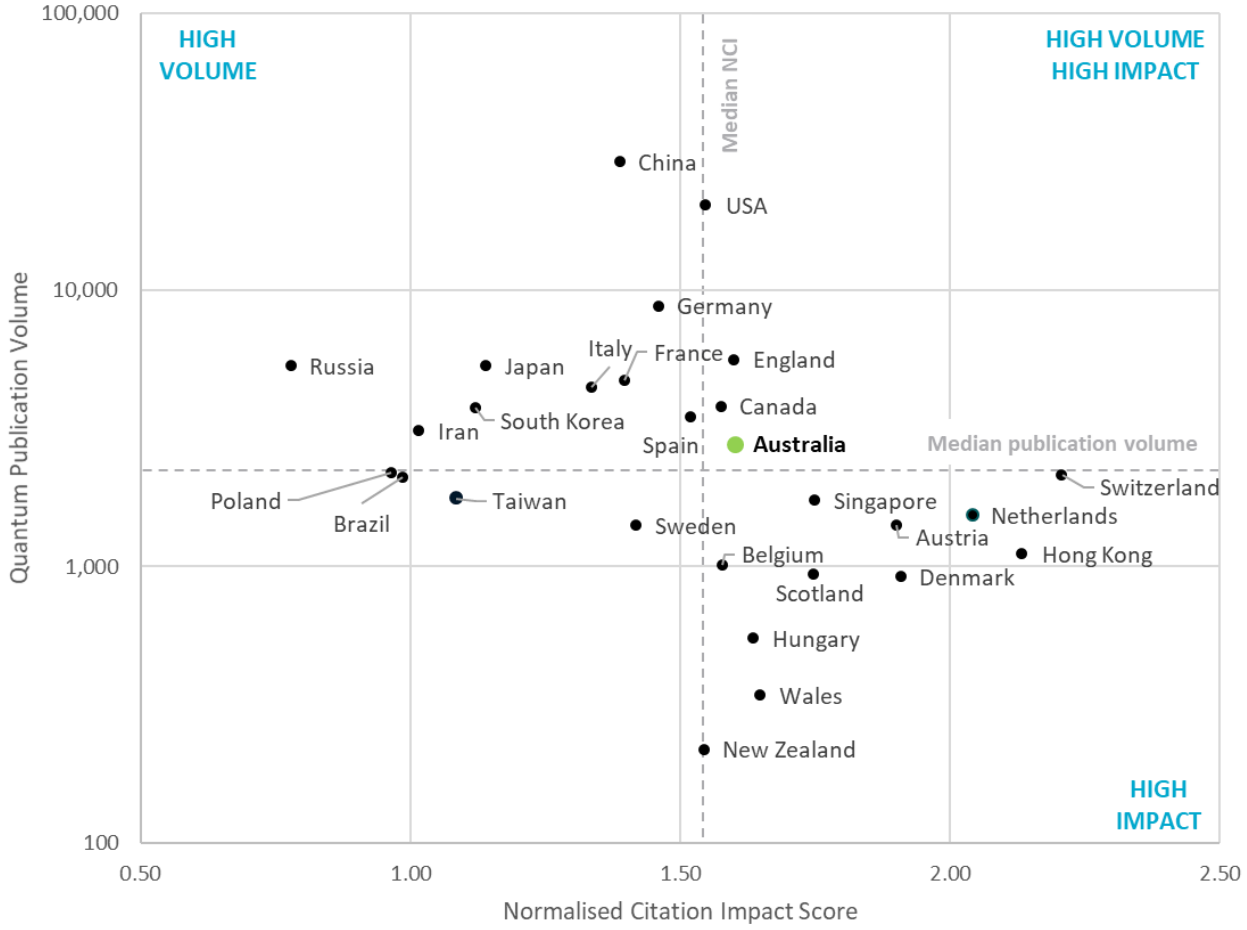
This search returned 269,675 results published between 2001-2018 inclusive. Most of the analysis reported below focuses on the 102,518 documents published in the last five years (2014-2018).

Figure 1 shows Australia's top research collaborators including China (631 collaborative publications published between 2014-2018), the USA (503), Great Britain (277), and Germany (232).

Figure 2 plots the top countries by publication count and normalised citation impact (NCI). Australia is one of the few countries that has both a publication counts and an NCI above the median of the countries plotted.

Figure 1: Australia's top quantum research collaborators (2014-2018)[16]

Figure 2: Top countries by quantum science and technology publication count and NCI (2014-2018)[17]



[16] CSIRO Analysis. Powered by Bing. ©GeoNames, HERE, MSFT, Microsoft, NavInfo, Thinkware Extract, Wikipedia

[17] Contains all countries that featured in the top 20 countries by output and the top 20 by normalised citation impact (NCI) for publications between 2014 and 2018 inclusive. Medians are for the displayed set of 29 countries.

Intellectual property (IP) analysis

IP landscape searching and analysis was performed by CSIRO's Intellectual Property Team using Google Patents and Orbit FAMPAT Database in August 2019. This included broad patent landscape searching and analysis in relation to quantum technology and more focused patent searching on the following categories:

- Quantum computing;
- Quantum (communications and computer) networks and security;
- Quantum sensing and measurement; and
- Quantum Optics / Imaging.

Search strategy

The search strategy used combinations of the following key words to locate relevant patent families:

quantum+, comput+, process+, simulat+, supercomput+, super-comput+, "super comput+", memor+, "error+ correct+", bit+, qbit+, qubit+, communicat+, telecom+, network+, secur+, secret+, cybersecur+, cyber-secur+, cryptograp+, encrypt+, key, keys, "random+ number generat+", "random+ noise+ generat+", sens+, detect+, measur+, metrolog+, radar+, navigat+, clock+, time+, timing+, synchron+, interferomet+, microscop+, optic+ and imag+ (where + indicates a word truncation and " " indicates that a combination of words within a certain proximity was required)

The search strategy also used the following International Patent Classifications (IPCs) and / or Cooperative Patent Classifications (CPCs):

G01+, G02B+, G04F-005/14+, G06F-021+, G06N-010+, H03L-007+, H04K-001+, H04L-009+, H04L-009/0852, H04L-009/0855 and H04L-009/0858 (where + indicates a class truncation).

To focus the results on the more recent developments, all results were limited to where a patent family member was published since 1 January 2010.

Results

This search strategy identified 18361 potentially relevant patent families with a family member published from 1 January 2010. A high-level summary of these results is included in Table 4.

Table 4: Results of patent search (NB: Some patent families fall in more than one application category)

	ALL QUANTUM TECHNOLOGY	COMPUTING	NETWORKS AND SECURITY	SENSING AND MEASUREMENT	OPTICS/IMAGING
Total patent families	18361	4240	3654	10844	3925
Patent families originating in Australia (relative ranking)	83 (11th)	36 (7th)	12 (10th)	48 (10th)	12 (10th)
Top two countries for originating patent families	China (10636) USA (3211)	China (1945) USA (1209)	China (2253) USA (535)	China (7149) USA (1540)	China (1607) USA (827)

The results for the limited number of patents that were first registered in Australia were manually assessed for relevance and technology category. The top patent assignees for patent families first registered in Australia are listed in Table 5.

Table 5: Top patent assignees for patent families originating in Australia

ASSIGNEE	SECTOR	STATUS	PATENT FAMILIES	DESCRIPTION
NewSouth Innovations	University	Active	9	Newsouth Innovations is the Technology Transfer and Innovation Office at the University of New South Wales.
Northrop Grumman Systems	Industry	Active	5	Northrop Grumman (NG) is a global defence and security technology company. NG appears to be active in the development of quantum computing/annealing[18] and sensing/metrology technologies. In 2017, NG provided an AU$75,000 scholarship to a UNSW researcher focuses on satellite quantum communications research.[19]
University of Sydney	University	Active	5	
Qucor	Start-up	Inactive	3	Qucor Pty Ltd was a start-up company activated in 2003 to commercialize technologies developed from quantum computing research undertaken in Australia.
University of Melbourne	University	Active	3	
University of Queensland	University	Active	3	
Google	Technology multinational	Active	3	Google's AI Quantum research group is developing quantum processors and quantum algorithms.
Accenture Global Solutions	Professional services	Active	2	Accenture Global Solutions provides quantum computing consulting services with a focus on quantum computing applications.
Macquarie University	University	Active	2	
Q-CTRL	Start-up	Active	2	Q-Ctrl is start-up spunout from University of Sydney's Quantum Science group. It has attracted VC-support and is one of the first Australian start-ups to offer a commercial product.

[18] See https://www.northropgrumman.com/Jobs/Burlington/Engineering-Product-Development/Physicist-(level-3-4)----Super-classical-Quantum-Annealing/

[19] https://www.industry.nsw.gov.au/development/invest-news/news/unsw-researcher-wins-scholarship-for-satellite-quantum-communications-research

Caveats

Due to the large volume of results the results of the global patent search and analysis (as reported in Table 4) were not manually assessed for relevance and are sure to contain false positives.

Patent Cooperation Treaty (PCT / WO) and European applications (EP) which relate to legal jurisdictions rather than physical countries, have been excluded from the country-based patent analysis. Our analysis found that several patents invented by notable Australian researchers or assigned to Australian companies (e.g. QuintessenceLabs) were first registered in the US or under the PCT and as such were not attributed to Australia. Because of this, the amount of IP generated by Australia is underestimated by this analysis.

Investment analysis

A company and deals search was undertaken using PitchBook (a private capital market data provider) on 1 September 2019. The results were updated on 24 September 2019.

Search strategy

The following quantum technology related keywords were used to identify potentially relevant companies and deals:

quantum technology OR quantum cryptography OR quantum computing software OR quantum computing technology OR quantum OR quantum computing OR quantum computer OR quantum computer technology OR quantum computing platform OR quantum algorithm OR photonics quantum computing OR quantum computing application OR quantum computing hardware OR qubit OR quantum bit

This search returned over 260 company results, from which over 140 companies were excluded, such as:

- Companies producing quantum dots for consumer electronics but quantum dots for other applications including medical imaging and solar applications were left in.
- Companies supplying quantum cascade laser and LiDAR technology
- Out of business companies

The following quantum-related company types were not excluded:

- Companies commercialising post-quantum and quantum safe cybersecurity solutions.
- Companies explicitly supplying enabling technologies or services to quantum technology companies (e.g. cooling systems or nanofabrication)

Results

313 deals involving 392 investors and 122 companies were recorded by Pitchbook. A total of US$1.44 billion of investment in quantum technology companies was identified in this analysis.

Figure 3 shows the top countries receiving venture capital (VC), private equity (PE) and mergers and acquisition (M&A) investments in quantum technology companies. Figure 4 shows the capital invested and number of deals in quantum technology companies from

Figure 3: VC, PE and M&A investment (USD, millions) in quantum technology companies by country[20]

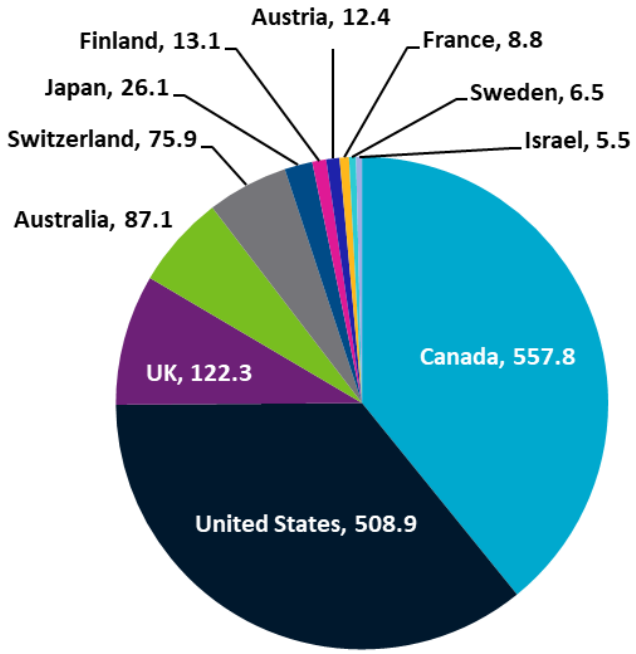
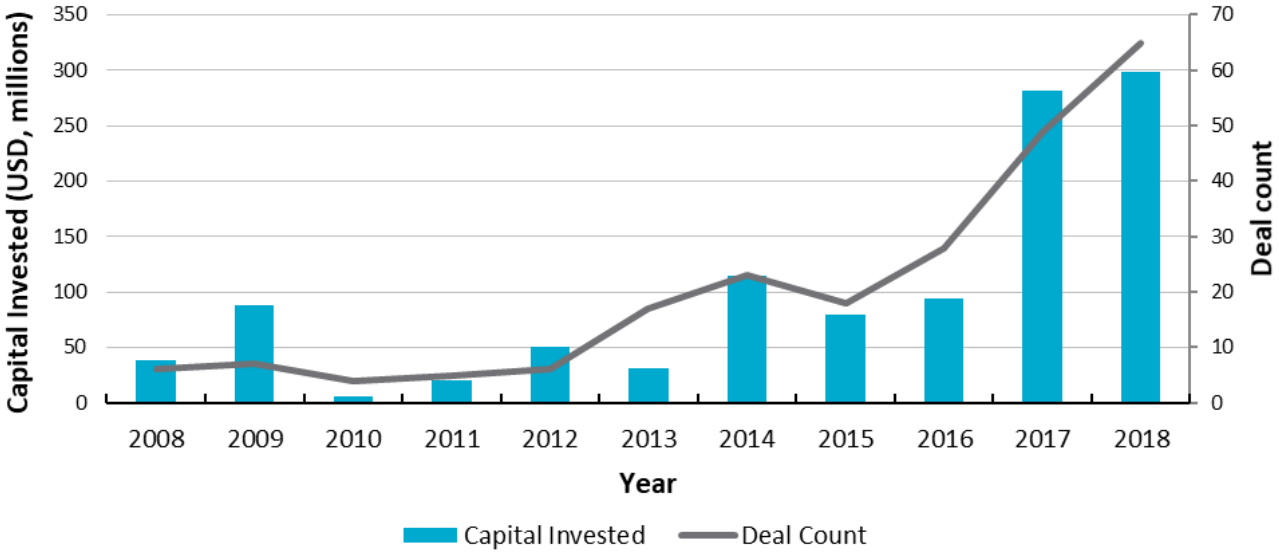


Figure 4: Capital investments in quantum technology companies (2008-2018)[21]



Attribution and Caveats

Analysis is based on data provided by PitchBook, private capital market data provider. This is not an exhaustive list of quantum companies and investment deals. PitchBook's coverage of investment deals is strongest in the US and may underreport companies and investment in other regions such as Asia.

[20] Excludes countries with less than US$5 million capital investment. CSIRO Analysis. Data provided by PitchBook, private capital market data provider.

[21] CSIRO analysis. Includes venture capital, private equity and mergers and acquisition deals. Data provided by PitchBook, private capital market data provider.

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