Australia's National Science Agency

Quantum Technology Discussion Paper

Discussion paper to enable the development of a Quantum Technology Roadmap

November 2019

About CSIRO Futures

CSIRO Futures is the strategic advisory arm of CSIRO. We draw on our vast network of 5,000 science and technology experts, and 3,000 industry partners, to help Australian businesses and government organisations prepare for the future by answering the following questions:

- What emerging trends and technologies will re-shape your sector in the coming decades?
- What opportunities are going to emerge from these rapid changes?
- What science and technology should you prioritise and invest in to maintain or create a competitive advantage?

We have a track record for helping senior decision makers tackle tough innovation challenges, from identification through to implementation. Our range of services include scenario planning, technology deep-dives, ideation workshops and strategic analysis reports. We work with businesses and government at all stages along the innovation lifecycle, to achieve a sustained competitive edge and continued growth.

Acknowledgement

CSIRO acknowledges the Traditional Owners of the land, sea and waters, of the area that we live and work on across Australia. We acknowledge their continuing connection to their culture, and we pay our respects to their Elders past and present.

Cover image

Inside the EQUS Bose Einstein Condensate laboratory. Credit: Patrick Self & EQUS

Contents

About this discussion paper

This discussion paper was prepared to help inform the development of a quantum industry roadmap for Australia. The paper summarises findings from CSIRO Futures' initial consultation and desktop research into opportunities, challenges and enabling actions related to advancing the Australian quantum technology sector by supporting the translation of Australia's quantum research. These findings are not final, and the enabling actions proposed for discussion should not be considered recommendations.

The Roadmap, *Growing Australia's Quantum Technology Industry,* is now complete and can be accessed at www.csiro.au/quantum.

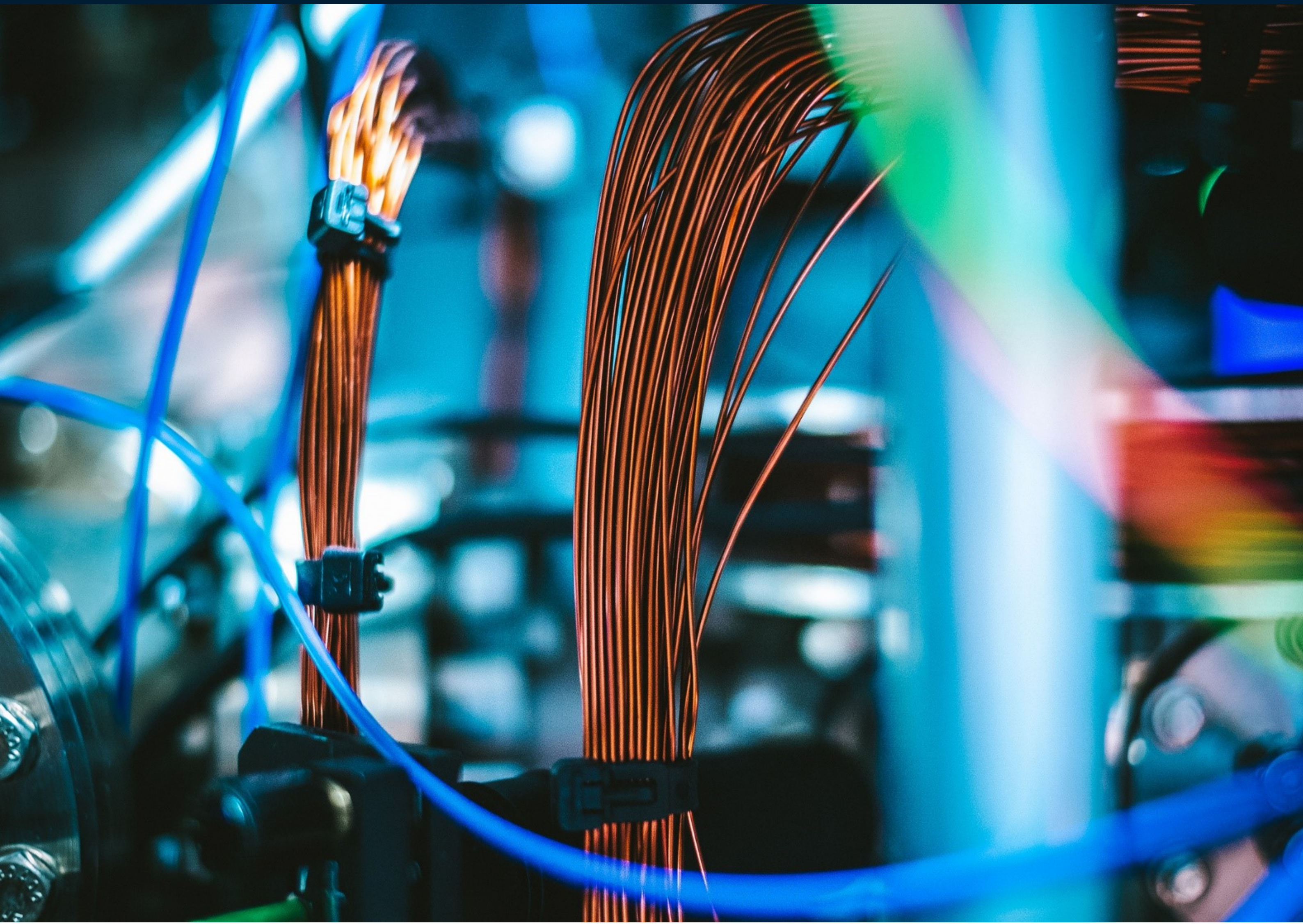
Confidentiality

All responses to this discussion paper will be treated confidentially and only viewed by CSIRO employees under CSIRO's code of conduct and research ethics procedure. The privacy of data collected using Survey Monkey will be treated in accordance with their privacy policy. At the conclusion of the consultation period this data will be downloaded and then deleted from Survey Monkey. The project team may use the contact details provided to seek clarity on a submission. Information provided in submissions will not be directly attributed to an individual or an organisation in the final Roadmap, however aggregate views may be attributed based on stakeholder characteristics.

Acknowledgements

We are grateful for the time and input of industry representatives consulted to date for this project and the many stakeholders who provided review and feedback on this paper.

Electric currents in this copper wiring generate a magnetic field to contain cold atoms.
Credit: Patrick Self & EQUS



1 Introduction

We welcome your feedback on the following questions:

1.1 Do you support the draft vision for Australia's quantum technology sector? If not, why not?

1.2 Do you have any comments on the drivers for action (why quantum, why Australia, why now)?

Draft vision: Australia will have leveraged local strengths in quantum research to grow a sustainable quantum technology industry. This industry will be centred on scalable companies with the capacity for growth and international collaboration, supplying a range of high-profit products and services for local and export markets.

The study of quantum physics emerged in the early 20th century, describing how the natural world works at the scale of atomic and subatomic particles. Quantum physics has improved scientists' ability to understand and harness a wide range of non-classical phenomena and enabled numerous advancements that have had massive impacts on society, including:

- Semiconductor technology that underpins microprocessors, currently used in everything from a simple mobile device through to a supercomputer
- Laser technology, which revolutionised communications via fibre optics, data storage via optical discs, precision surgery and engineering
- Nuclear magnetic resonance technology applied to 'image' chemicals, extrapolated to magnetic resonance imaging (MRI) for living organisms

A second wave of quantum technology (based on improved understanding and control of advanced quantum behaviours such as superposition, entanglement, and interference[1]), is currently maturing from the research domain, with some exciting recent proof of principle studies, demonstrations and developments. Like the first wave, this second wave of technology has the potential to enable game changing applications for a range of industries, such as:

- Efficient and accurate simulations of molecular behaviour leading to improved drug and material development
- Highly accurate sensing and measurement technologies for exploration and monitoring of natural resources
- Next generation secure communication systems for critical infrastructure, defence and financial systems

There is significant economic value to be captured if these possibilities are realised. However, there remains global uncertainty around the path to market for many quantum applications, and the industrial value that their development could create.

Australia has a long history of research excellence in advanced quantum technology but is yet to articulate a national strategy and vision for the development of a strong quantum industry. To begin addressing this, CSIRO is preparing a roadmap examining emerging quantum-enabled technologies and related commercial

[1] MacFarlane AGJ, Dowling JP and Milburn GJ (2003) Quantum technology: the second quantum revolution. Philosophical Transactions of the Royal Society of London. DOI: 10.1098/rsta.2003.1227

opportunities that Australia might pursue. This discussion paper reviews Australia's opportunities and challenges in the global quantum landscape and suggests potential enabling activities to realise the translation of quantum technology from research to commercial development.

CSIRO invites you to respond to this discussion paper to help build an understanding and consensus around how to capture opportunities presented by quantum technology.

Project scope

This paper defines quantum technologies as: technologies that make use of our ability to detect and manipulate single quantum objects (e.g. atoms, electrons, photons) to control or enable their function.

The quantum technology sector is defined as: stakeholders involved in the funding, research, development, demonstration, regulation, commercialisation and/or utilisation of quantum technologies. These stakeholders and their activities are listed in Table 1.

This discussion paper is centred on opportunities that can be achieved within a 20-year timeline, with a primary focus on technologies that currently sit between technology readiness level three (proof of concept) and seven (full scale demonstration in relevant environments).[2] The final roadmap will not assess Australia's fundamental quantum research capability, which is accepted to be strong.[3]

Table 1: Quantum sector stakeholders

SECTOR STAKEHOLDERS	EXAMPLE ORGANISATIONS	ACTIVITIES
Government	Federal and state governments	Funding, regulation, security, utilisation
Publicly Funded Research Agencies (PFRAs)	CSIRO, DST Group, ANSTO, NMI	Funding, research, development, demonstration
Research	Universities, Centres of Excellence, CRCs	Research, development, skills development, demonstration
Education	Universities, TAFE, Secondary schools	Skills and workforce development
Industry	Start-ups, SMEs, Large organisations, Multi-nationals	Funding, development, demonstration, commercialisation
Private investors	Venture capital, Industry	Funding
Standards bodies	Standards Australia, IEEE, NMI	Development of standards
End-users	Industry, Government	Utilisation

[2] NASA (2012) Technology Readiness Level. Viewed 25 June 2019, <https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html>

[3] Roberson TM and White AG (2019). Charting the Australian quantum landscape. DOI: 10.1088/2058-9565/ab02b4

1.1 Why quantum technology?

Consultations with industry and government highlighted a strong economic and strategic imperative for Australia to develop and commercialise quantum technologies. Central themes include creating new solutions and benefits for industry via breakthrough science, developing new export markets for the Australian economy, and maintaining national and industry security through quantum solutions.

Delivering breakthrough innovations to industry

Over the coming decades, advances in quantum technologies are expected to offer productivity gains and solutions in areas of computing, simulation, sensing, imaging, navigation, timing, measurement, communications and encryption. Stakeholders anticipate these technologies to have viable commercial applications over classical methods across a variety of industries. Examples include quantum simulation for drug and materials development, quantum encryption solutions for secure communications, and quantum sensors for mineral exploration and defence applications. Section 2 describes the emerging opportunities in quantum computing; communications and security; sensing and measurement; and enabling technologies and services.

Developing future export markets for Australia

While Australia holds the record for the longest period of economic growth among developed economies,[4] there are structural transitions and risks for industry and government to manage over the next few decades. The Australian economy's heavy reliance on mineral and agricultural exports exposes the country to long term growth risks.[5] Potential scenarios include reduced demand for coal as the world transitions toward carbon neutral energy sources[6] and production risks for Australian agribusinesses due to the impact of climate change.[7]

Quantum technologies may offer a new source of export growth, economic diversification and employment creation for the Australian economy.[8] Stakeholders consulted for this paper anticipate that the development of a universal quantum computer will stimulate and lead to growth of Australian industries for quantum-related software development alongside advanced manufacturing of associated components and devices. Each of which present potential growth opportunities for Australia in the long-term.

Maintaining national and industry security

Finally, quantum technologies will be important for supporting national and industry security. Quantum secure solutions for data management and communications will be important to defence, government agencies, healthcare and finance, even encryption risks from quantum computing will only emerge in the long term. Australian Defence is also investing in quantum sensing, positioning, navigation and timing technologies to strengthen national security. As such, Australia's sovereign capabilities across a variety of quantum technologies are of strategic and national importance.

---

[4] Austrade (2018). Investor Update 2018. Viewed on 28 October 2019, <https://www.austrade.gov.au/international/invest/investor-updates/2018/australia-holds-world-record-for-longest-period-of-growth-among-developed-economies>

[5] The Growth Lab at Harvard University. The Atlas of Economic Complexity: Australia. Viewed on 28 October 2019, <http://atlas.cid.harvard.edu/countries/14>

[6] RBA (2019). The Changing global Market for Australian Coal. Viewed on 28 October 2019, <https://www.rba.gov.au/publications/bulletin/2019/sep/the-changing-global-market-for-australian-coal.html>

[7] Climate Council (2015). Feeding a Hungry Nation: Climate Change, Food and Farming in Australia. Viewed on 28 October 2019, <https://www.climatecouncil.org.au/resources/foodsecurityreport2015/>

[8] The final report will include scenario analysis to demonstrate the potential export opportunity of quantum technologies for Australian industry over the next few decades.

Example applications of quantum technology

Advanced navigation, timing and sensing technologies for defence

The defence industry is interested in using quantum technologies for diverse applications. Under the Next Generation Technology Fund, Australian researchers are investigating quantum technologies for applications in stealth detection, precision timing, and more.[9]

Secure communications for sensitive data

Quantum key distribution (QKD) systems share cryptographic keys in quantum states. As measuring a quantum system disturbs it, any attempts to eavesdrop on the key disturbs its contents and introduces detectable anomalies. This makes it possible to detect the presence of a third party attempting to detect the key.

Quantum sensors for discovery of new mineral deposits

About 70 per cent of Australia features barren cover that obscures mineralised rocks and creates challenges for mineral exploration.[10] Given Australia's economic reliance on the minerals sector, the development of quantum-enabled precision sensors to aid mineral exploration presents a valuable opportunity for Australia.[11]

Quantum simulations for drug development

Classical computing systems are unable to efficiently simulate the probabilistic nature of molecular interactions and rely on approximations of atomic behaviour. For this reason, many predict that quantum simulations will be an important application in industries such as automotive, chemicals, energy, and drug discovery and development.[12] A valuable application of quantum computers would be to simulate the interaction of drug molecules with their target receptors to aid in drug design.

---

[9] University of Adelaide (2019) Quantum sensors to make Australia safer. Viewed 23 October 2019, < https://www.adelaide.edu.au/news/news106202.html>

[10] Australian Academy of Technology and Engineering (2018) Increasing mineral discovery success. Viewed 23 October 2019, <https://www.applied.org.au/research-and-policy/publications/publication/increasing-mineral-discovery-success/>

[11] For example, Physics World (2016) Quantum sensor targets gravity and magnetism. Viewed 24 October, <https://physicsworld.com/a/quantum-sensor-targets-gravity-and-magnetism/>

[12] Markets and Markets (2019) Quantum Computing Market by Offering (Systems and Consulting Solutions), End-User Industry, and Geography; QCaaS Market by Application (Optimization, Machine Learning, and Material Simulation) and Geography - Global Forecast to 2024.

1.2 Why Australia?

Australia has established a world-class quantum science and technology capability that is well connected with other leading countries and is attracting research funding from both industry and government. A small number of commercial start-ups have also emerged on the Australian scene and are attracting capital investment to support their commercialisation efforts.[13] This established capability places Australia favourably to capture global opportunities.

World class quantum research

Australia currently has two quantum-focused Australia Research Council (ARC) Centres of Excellence (CoEs), and eight of Australia's universities are performing quantum physics research well above the world standard.[14] Australia only publishes around three per cent of quantum science and technology research but is cited 60 per cent more than the global average (a rate equal to or better than countries with higher publication volumes). When considering more specific fields, such as quantum computing, Australia performs even better on citation metrics.[15]

Australia's strong research capability has been supported by over 20 years of research funding. Due to the pioneering efforts of several leaders in the sector, Australia has built a competitive position in research on the technology applications of quantum mechanics. Because of this Australia successfully attracted global talent while other countries were still establishing technology-focused quantum research centres.

Global connectivity

Australia's quantum researchers regularly collaborate on publications with other leading countries (including China, the US, the UK and Germany)[16] and have attracted investment and attention from international stakeholders including Microsoft[17] and the US Government[18]. This global connectivity is an essential enabler of an industry in which successful local efforts are likely to require input and collaboration from global peers, and where sustainable businesses will be established via strong export pathways.

Targeted investment

Researchers and entrepreneurs in Australia's quantum sector have attracted public funding and private capital investment to support their quantum research and commercialisation objectives. Public funding for quantum technology research ramped up significantly in 2003 when the first two quantum ARC CoEs were established. The federal government alone has committed over AU$130 million funding commitments since 2016.[19] Australia's leading quantum technology companies have also attracted more than $108 million AUD of capital investment in the last three years.[20]

---

[13] Appendix B provides a brief overview of key organisations in Australia's quantum research and industry landscape

[14] Australian Research Council (2019) State of Australian University Research 2018-19. Australian Government. Viewed 29 August 2019, <https://dataportal.arc.gov.au/ERA/NationalReport/2018/>

[15] Dhawan SM, et al. (2018) Global Publications Output in Quantum Computing Research: A Scientometric Assessment during 2007-16. Emerging Science Journal. DOI: 10.28991/esj-2018-01147

[16] CSIRO Analysis. See Appendix C for more information.

[17] The University of Sydney (2017) Microsoft and University of Sydney forge quantum partnership. Viewed 9 October 2019, <https://sydney.edu.au/news-opinion/news/2017/07/25/microsoft-and-university-of-sydney-forge-quantum-partnership.html>

[18] Australian Government (2018) Australian and US universities to collaborate on defence research. Viewed 4 October, <https://www.minister.defence.gov.au/minister/christopher-pyne/media-releases/australian-and-us-universities-collaborate-defence-research>

[19] Includes ARC funding for four CoEs in 2017, and federal funding for the UNSW Centre for Quantum Computation. Roberson TM and White AG (2019). Charting the Australian quantum landscape. DOI: 10.1088/2058-9565/ab02b4

[20] CSIRO analysis of data provided by PitchBook, private capital market data provider. See Appendix C for more information.

1.3 Why now?

The global quantum technology sector is attracting significant public and private investment, supporting R&D breakthroughs and commercialisation efforts. If Australia fails to maintain and develop its strengths and overcome its challenges in quantum technology development, it may miss an opportunity to capture the long-term economic and security benefits of quantum technology.

Scientific and technical breakthroughs

Sustained efforts and recent global focus on quantum R&D are leading to significant advances in technology. In quantum computing, for example, records for the size and performance of a variety of different quantum processors are regularly being broken by R&D teams in both private and university-based research labs. Google recently published the first claim of quantum computing supremacy (using a quantum computer to perform a task significantly faster than known classical algorithms are able), although this claim is contested by IBM.[21,22]

Accelerating commercial activity

Alongside the scientific developments is a growing focus on the commercialisation of quantum technologies. There has been significant global investment in quantum technology by both venture capital firms and large technology companies.[23] A recent analysis identified 52 quantum technology companies that received private funding between 2012 and 2018. Over this period, the value of these deals grew from US$52 million in 2012 and 2013 to over US$450 million in 2017 and 2018. Large technology companies are also investing in quantum technology.

A long-term investment

While there may be opportunities to commercialise quantum technologies in the short term, many quantum technologies require longer time horizons. Because of a drive for short term returns, private investments alone are unlikely to foster the development of long-term applications.

Governments have historically played a critical role in the development of many general-purpose technologies (e.g. semiconductors, the internet, mobile phones).[24] Due to the potential of quantum technologies to impact national security and create economic growth, governments are strategically investing in quantum technology R&D. For example, the US, UK and European Commission have all established billion-dollar scale quantum technology initiatives.[25]

In this context, Australia will need to be strategic in its investments and enabling actions to support the long-term growth of a quantum technology industry. Australia performs well at knowledge creation but has a poor record on the transfer and application of this into new technologies and businesses.[26] Targeted efforts to support the quantum sector and broader reforms (such as those recommended by Innovation and Science Australia[27]) will both be essential if Australia is to capture the full value of its quantum technology intellectual property.

---

[21] Arute F et al. (2019) Quantum supremacy using a programmable superconducting processor. Nature. 574, 505–510. DOI: 10.1038/s41586-019-1666-5

[22] Pednault, E et al. (2019) On "Quantum Supremacy". IBM Research Blog. Viewed on 23 October, <https://www.ibm.com/blogs/research/2019/10/on-quantum-supremacy/>

[23] Gibney E (2019) Quantum gold rush: the private funding pouring into quantum start-ups. Nature. 574, 22-24. DOI: 10.1038/d41586-019-02935-4

[24] Mazzucato M (2014) Building the Entrepreneurial State.

[25] Appendix A provides an overview of quantum technology strategies, investments and industry activity in key regions.

[26] Innovation and Science Australia (2016) Performance Review of the Australian Innovation, Science and Research System. Australian Government.

[27] Innovation and Science Australia (2017) Australia 2030: prosperity through innovation. Australian Government.

Behind the scenes in a quantum laboratory.
Credit: Patrick Self & EQUS

2 Commercial quantum opportunities for Australia

We welcome your feedback on the following questions:

2.1 Do you have feedback on the summary of Australia's commercial quantum opportunities?

2.2 What commercial applications of quantum technology is Australia's quantum sector best positioned to develop and commercialise? For each application:

- What is the underlying quantum technology?
- Why is Australia well placed to develop and commercialise this application?
- Who would be the primary customers or end-users?
- What benefits does quantum technology have over existing technologies?
- When do you expect this application to become commercially available?
- What are the scientific and technical challenges to overcome?

Presented in this section are opportunities that Australia's quantum sector has potential to capture in the global quantum industry. This is reflected in early innovations led by Australian universities, start-ups and CSIRO across numerous segments, including computing and sensing. Australia's quantum technology industry is also backed by a variety of major investors, including the Department of Defence, ASX-listed companies, Australian and international venture capital funds, and multinational companies across industries such as banking and aerospace.

Consultations with industry highlighted near-term opportunities for early revenue streams in commercialisation of applications and instruments for organisations in quantum technology research and development, as well as enabling services in the form of education and training, and advisory services for companies and governments seeking to explore the opportunities offered by quantum technologies.

It is recognised that at present there are limited examples of advanced quantum technologies providing commercial advantages over classical alternatives. Stakeholders emphasised that the adoption of quantum technologies in the long term requires a clear return on investment for potential customers, and that technology needs to deliver on a well-defined product profile (cost, usability, performance, etc.). As such, the acceleration of demonstration projects and niche applications are an important opportunity for the quantum industry in the medium term.

While timelines are challenging to predict, stakeholders agree that Australia has a longer-term opportunity to provide software and hardware quantum technology solutions as industry moves from early applications and demonstrations to commercial development.

Table 2 summarises findings from consultations on potential commercial opportunities for the Australian quantum industry. Table 3 provides an overview of potential industry users of quantum technologies by industry group.

The following sub-sections discuss opportunities across computing, communications, sensing and imaging, and enabling services in more detail Several case studies are also included to highlight Australia's existing commercial activity. Feedback on this discussion paper assist in refining these broad opportunity descriptions to concise opportunity themes that clearly leverage Australia's comparative advantages and are associated with clear enabling actions.

Table 2: Commercial opportunities for Australia's quantum industry

<table>
<tr><th rowspan="2">CATEGORY</th><th rowspan="2">DESCRIPTION</th><th colspan="3">POTENTIAL COMMERCIAL OPPORTUNITIES</th></tr>
<tr><th>NEAR TERM</th><th>MEDIUM TERM</th><th>LONG TERM</th></tr>
<tr><td>Computing</td><td>Quantum computing offers the potential to solve problems that are practically impossible on classical systems. Quantum computers use quantum bits (qubits) that code information in the properties of quantum particles and take advantage of quantum phenomena to create a new form of computation.</td><td>• Develop small-scale processors, software and modelling tools, and error correction operators
• Develop useful algorithms for quantum computers</td><td>• Commercialise applications on noisy intermediate scale quantum (NISQ) computers
• Demonstrate quantum simulation for materials and pharmaceutical design applications</td><td>• Establish quantum computer server farms for industry engagement
• Commercialise quantum hardware and software solutions, via licensing of software applications and technology designs, manufacturing hardware or high-value components</td></tr>
<tr><td>Communications and security</td><td>Quantum technologies have potential to enable new forms of secure communications networks and cryptographic techniques, such as quantum key distribution (QKD) systems in which cryptographic keys are stored in the states of quantum particles.</td><td>• Demonstrate quantum-safe cryptography solutions and QKD for highly sensitive communications networks</td><td>• Demonstrate advanced quantum communication networks over longer distances and for satellite optical communications
• Transition highly sensitive communications to quantum-safe cryptography.</td><td>• Transition all online communications to quantum-safe cryptography
• Commercialise advanced quantum-based systems for secure communications</td></tr>
<tr><td>Sensing, measurement and imaging</td><td>The incredibly sensitive nature of quantum particles to external stimuli can enable precision sensing and imaging technologies. For example, quantum-enabled technologies can be used to sense ultra-weak signals such as electromagnetic and gravitational fields and may overcome fidelity, noise and sensitivity limitations in imaging applications.</td><td>• Demonstrate quantum sensing, measurement and imaging technologies for applications in defence, resources and health.</td><td colspan="2">• Commercialise field-deployable sensing, measurement and imaging technologies for precision applications in diverse industries.</td></tr>
<tr><td>Enabling technologies and services</td><td>The emerging quantum technology industry will create ongoing opportunities to supply enabling services and technologies to organisations to the sector. This includes education and consulting services as well as specialised tools and instruments that support quantum technologies.</td><td colspan="3">• Establish Australia as a preferred destination for quantum science and technology education and training.
• Offer advisory services to help enterprises and governments understand and respond to the opportunities and threats that quantum technologies present.
• Commercialise enabling tools, instruments and services organisations undertaking research, development and commercialisation of quantum technology industries.</td></tr>
</table>

Table 3: Quantum technology adopters

Commercial opportunities	Australian examples	Potential adopters by industry group																
		Agriculture	Mining	Pharmaceutical and chemical	Materials manufacturing	Other manufacturing	Electricity, gas, water and waste	Construction	Wholesale and retail trade	Transport, postal and warehousing	Information and communications	Financial and insurance	Scientific, technical and professional	Public administration	Defence	Education and training	Healthcare and social assistance	Other[28]
Computing	Q-Ctrl; Silicon Quantum Computing Pty Ltd	Followers	Followers	Earlier Adopters	Earlier Adopters	Followers	Followers	Followers	Followers	Followers	Early Innovators	Earlier Adopters	Early Innovators	Followers	Early Innovators	Followers	Earlier Adopters	Observers
Security and communications	Quintessence Labs	Followers	Followers	Followers	Followers	Followers	Followers	Followers	Followers	Followers	Early Innovators	Earlier Adopters	Early Innovators	Earlier Adopters	Early Innovators	Followers	Earlier Adopters	Followers
Sensing, imaging and measurement	CSIRO LANDTEM; Lucigem;	Followers	Earlier Adopters	Earlier Adopters	Earlier Adopters	Followers	Followers	Earlier Adopters	Observers	Observers	Earlier Adopters	Earlier Adopters	Early Innovators	Observers	Early Innovators	Observers	Earlier Adopters	Observers
Education and training	Sydney Quantum Academy; University of Queensland	Observers	Observers	Observers	Observers	Observers	Observers	Observers	Observers	Observers	Earlier Adopters	Observers	Early Innovators	Observers	Observers	Early Innovators	Observers	Observers
Advisory services	H-Bar	Followers	Earlier Adopters	Earlier Adopters	Earlier Adopters	Followers	Followers	Earlier Adopters	Followers	Followers	Earlier Adopters	Earlier Adopters	Early Innovators	Earlier Adopters	Earlier Adopters	Followers	Earlier Adopters	Followers
Enabling technologies	MogLabs; Liquid Instruments; ANFF	Observers	Observers	Observers	Observers	Observers	Observers	Observers	Observers	Observers	Observers	Observers	Early Innovators	Observers	Observers	Early Innovators	Observers	Observers

Key: Early Innovators, Earlier Adopters, Followers, Observers

[28] Other includes arts and recreation, real estate and rental services, accommodation and food services, and administration and support services.

2.1 Computing

Australia's opportunity

Commercialising technologies and services to support quantum computing research efforts presents an early opportunity for the quantum technology sector. In the medium-term we could see the commercialisation of technologies and software for specialised simulation, machine learning and optimisation applications in which noisy intermediate scale quantum (NISQ) devices might provide an advantage over classical systems. In the long-term, following the expected development of a universal quantum computer (whether domestically or overseas), the Australian quantum industry can begin to identify and provide quantum software and infrastructure services and manufacture components and devices for high value applications in global industries.

Why Australia

Research strength

Australia has established Centres of Excellence and research hubs, including the Australian Centre of Excellence for Quantum Computation and Communication Technology (CQC2T) and the University of Sydney's Microsoft Quantum Laboratory, with a critical mass to scale research and translation across domains. CQC2T has focussed programs on silicon and optical quantum computing with research in algorithms, hardware development, scale-up engineering, quantum information theory and quantum communications. The University of Technology Sydney's Centre for Quantum Science and Information (QSI) have research programs in quantum architectures, programming and algorithms, as well as AI applications of quantum computing (e.g. quantum constraint solving, machine learning and property testing).

Commercial growth

The country is also home to world-leading spinout companies in silicon-based quantum computing technology (Silicon Quantum Computing Pty Ltd) and quantum control engineering (Q-Ctrl). These Australian companies have attracted investment from venture capital firms, ASX200 companies and the Australian Government.

Local verticals

There are complementarities from scaling quantum technologies with applications in areas such pharmaceuticals, leveraging Australia's industry strengths in that sector. This could provide a commercial pathway for quantum technologies and a first-mover advantage for Australian industries in global markets.

Indicative timelines for commercial opportunities

TIMEFRAME	POTENTIAL COMMERCIAL OPPORTUNITIES
Near term (0-5 years)	• Develop small-scale processors, software and modelling tools, and error correction operators that support the development of quantum computing systems. Software opportunities may include programming languages, application programming interfaces, visualisation and modelling tools, compilers and error correction operations for quantum technology development. Hardware agnostic software offerings may have an early advantage due to their larger potential market. • Develop useful noisy intermediate-scale quantum (NISQ) algorithms **Potential end-users:** research, technology, defence
Medium term (5-15 years)	• Demonstrate early applications on NISQ devices in areas such as simulation or optimisation. • Conduct demonstrations with quantum algorithms that outperform classical methods in niche applications, but with clear return on investment for industry partners. • Develop quantum simulator devices to investigate the functionality of quantum systems in physics, biology and chemistry. **Potential end-users:** research, technology, defence, information and media, finance and insurance, advanced materials, and drug discovery
Long term (15+ years)	• Offer quantum computing applications as a service via access to a quantum server farm • Commercialise hardware-agnostic software and quantum software-as-a-service for applications such as optimisation, simulation or machine learning. • License out chip and component designs for commercial fabrication and packaging in international markets • Manufacture and package hardware units and high-value components; offer integrated quantum infrastructure-as-a-service. **Potential end-users:** Defence, research institutions, information and media, finance and insurance, advanced materials, and drug discovery

PhD student Prasanna Pakkiam working on a scanning tunnelling microscope.
Credit: CQC^{2}T

CASE STUDY: Silicon Quantum Computing is developing a quantum computer based on world leading intellectual property[29]

Silicon Quantum Computing Pty Ltd (SQC) has an ambition to develop a 10-qubit quantum integrated circuit prototype in silicon by 2023, a forerunner to a silicon-based quantum computer. Their work is based on the intellectual property of CQC2T, which achieved the longest coherence time, first two-qubit gate in silicon, lowest noise silicon devices, and highest fidelity qubits in a solid state. The company operates parallel platforms within CQC2T's headquarters at UNSW to develop a silicon-based quantum computer using atomically engineered phosphorus donors, quantum dots using CMOS technology and hybrids. In partnership with the CQC2T, SQC is working to develop error corrected processors and establish access to a quantum computing server farm at UNSW. SQC is jointly owned by the Australian Government, NSW State Government, the University of New South Wales, the Commonwealth Bank of Australia and Telstra, with initial funding in excess of $83 million AUD.

CASE STUDY: Q-Ctrl is supporting the ecosystem for entrepreneurs and technologists that are working on the next generation of quantum computing[30]

Sydney-based company Q-Ctrl provides a hardware-agnostic software suite (Black Opal) for advanced quantum control solutions on a cloud platform to allow users to analyse single-qubit controls, multi-qubit gates, and multilevel circuits; output a variety of control solutions for integration in experiments; and analyse noise in quantum hardware under controlled settings. It claims that its cloud architecture optimises tasks to run around 9x faster than on standalone machines. Q-Ctrl began as the first spin-off from the University of Sydney's Quantum Science group and has attracted more than $22 million AUD investment from global venture capital firms, including DCVC, Main Sequence Ventures, Horizons Ventures and Sequoia Capital.

[29] Silicon Quantum Computing (2019) Quantum Computing Dawns – About Us. Viewed on 21 August 2019, < https://sqc.com.au/ >; UNSW (2019) 200 times faster than ever before: the speediest quantum operation yet. Viewed 18 August 2019, <https://newsroom.unsw.edu.au/news/science-tech/200-times-faster-ever-speediest-quantum-operation-yet>

[30] Q-Ctrl (2019) Take Control of Your Quantum Hardware. Viewed on 21 August 2019, < https://q-ctrl.com/products/ >; The University of Sydney (2019) Q-Ctrl – A Quantum Technology Company. Viewed on 21 August 2019, < https://sydney.edu.au/nano/industry-and-innovation/case-studies/q-ctrl-a-quantum-technology-company.html >

2.2 Security and communications

Australia's opportunity

Australian companies have developed and commercialised quantum-enhanced security solutions, incorporating quantum random number generator and quantum key distribution technology, for early industry adopters such as defence and communications. The stakeholders expect growing industry and government investment in quantum communications and security as the next generation of quantum technologies and disruption emerge, and demand for quantum-safe encryption solutions increase.

Why Australia

Research strength

Australia has established centres of excellence and research hubs with a critical mass to scale research and translation across domains. CQC2T for example has research programs in quantum repeater technology, quantum communications theory, and quantum memory. The ACT Government, CSIRO and ANU have also invested in quantum communications and securities research in areas such as Australia's first quantum optical ground station.

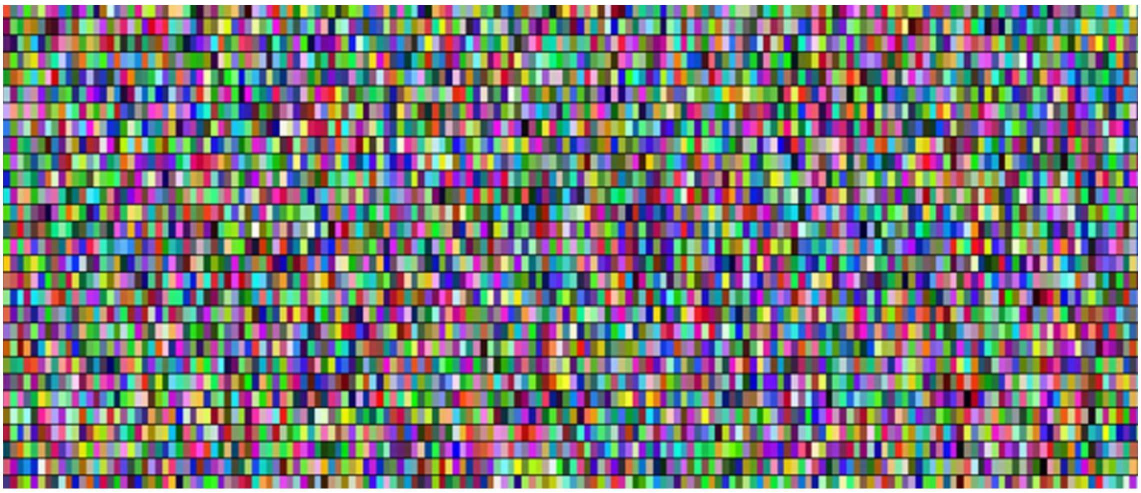
Commercial growth

Canberra-based Quintessence Labs has become a supplier of quantum random number generator enabled cybersecurity solutions to global markets, an early sign of Australia's commercial strengths in quantum security and communications with potential for scale.

Local verticals

Industries with highly sensitive communications needs are likely to be earlier adopters of emerging technologies in quantum communications and security. This includes defence, government, finance, healthcare and communications. Local investment and scale in quantum communications is important for both national and industry security. Development of quantum communications technology is also well aligned with development of Australia's space industry.

Random colours generated by the ANU Quantum Random Numbers Server[31]



[31] ANU Quantum Random Numbers Server Colours Livestream (2019). Viewed on 16 October 2019, <https://qrng.anu.edu.au/RainCol.php>

Indicative timelines for commercial opportunities

TIMEFRAME	POTENTIAL COMMERCIAL OPPORTUNITIES
Near term (0-5 years)	• Demonstrate quantum-safe cryptography solutions and QKD for highly-sensitive communications networks **Potential end-users:** Defence, research, space, communications, gaming
Medium term (5-15 years)	• Demonstrate quantum communication networks over longer distances, including satellite optical communications (e.g. ANU's InSpace Laser Communications Program) • Transition early adopters with sensitive data and communication needs towards quantum-safe communications and cybersecurity. This includes sensitive military communications and space communications. **Potential end-users:** Defence, research, space, communications, finance, healthcare, government
Long term (15+ years)	• Commercialise services, infrastructure and hardware to manage, store and transmit online communications with quantum-safe cryptography • Commercialise advanced quantum-based systems for secure communications **Potential end-users:** Defence, research, space, communications, finance, healthcare, government

CASE STUDY: Quintessence Labs has developed and commercialised quantum safe cybersecurity technologies

Quintessence Labs provides quantum-enhanced cybersecurity solutions. This includes quantum random number generators (QRNG), quantum entropy enhancers, encryption key and policy manager, and cryptographic software development kits. Unlike most QRNGs based on single photon detections with limited throughput, Quintessence Labs' QRNG uses quantum tunnelling to provide truly random numbers for larger-scale security and practical applications. Quintessence Labs is also developing quantum key distribution (QKD) technology. Quintessence Labs emerged from research by the ANU's Quantum Optics Group and has received funding from Westpac Group and the Australian Department of Defence.

CASE STUDY: Australian National University's InSpace Laser Communications Program is developing technology for quantum-secured communications network

ANU has embarked on research program to develop and demonstrate technology required for optical quantum communications networks. The first stage includes a $2.4 million Quantum Optical Ground Station dedicated to space and optical communications research.[32] Future initiatives include the development and demonstration of free-space continuous variable QKD technology in collaboration with the German Aerospace Centre.[33]

[32] Australian National University (2019) Station to Help Unlock Data and Mysteries of the Universe – News. Viewed on 22 August 2019, <https://science.anu.edu.au/news-events/news/station-help-unlock-data-and-mysteries-universe>

[33] Australian National University (2019). InSpace Laser Communication Program – News. Viewed on 22 August 2019, <https://inspace.anu.edu.au/news/inspace-laser-communications-program>

2.3 Sensing, imaging and measurement

Australia's opportunity

Australia can develop and demonstrate quantum sensing and imaging devices in collaboration with industry partners with appetite for early investment and adoption (e.g. defence, research institutions, and mining exploration companies). In the longer term, Australian industry has potential to be a global commercial supplier of field-deployable sensing and imaging devices.

Why Australia

Research strength

Australia has established centres of excellence and research hubs with a critical mass of talent and infrastructure to enable research and translation in quantum sensing, imaging and measurement technologies. The Australian Research Council Centre of Excellence for Engineered Quantum Systems (EQUS) for example has projects in quantum-enabled diagnostics and imaging across areas such as optomechanics, hyperpolarised MRI for enhanced bio-imaging and nano-diamond based sensors with large-scale entanglement. Adelaide's Institute for Photonics and Advanced Sensing (IPAS) also has major research programs in quantum radar for stealth detection, portable quantum optical clocks, quantum magnetometer array for anti-submarine warfare, and hybrid diamond fibre optic quantum magneto-sensors.[34] The University of Queensland is also working with the Australian Defence Force, NASA, Orica and Skyborne Technologies under the Next Generation Technologies Fund to develop quantum accelerometers, gyroscopes, sonar and magnetometers for defence applications.[35] Defence is also investing in R&D in areas such as quantum gravimeters for mapping and structure detection, and inertial sensing with quantum gas photon interferometers.[36]

Commercial growth

Australia has a track-record in commercialisation of quantum-enabled devices for sensing and measurement. CSIRO for example was one of the first to successfully commercialise portable magnetic sensors for detection of mineral deposits deep underground. Adelaide-based Cryoclock has also commercialised its cryogenic sapphire oscillator technology to deliver ultra-timing precision for potential applications in radar, communications and quantum computing.[37] Similarly, NSW Smart Sensing Network is investing in quantum and non-quantum sensing technologies to improve water utility networks.

Local verticals

In the longer term, there will be complementarities from scaling quantum technologies with applications in areas such as mineral exploration and biomedical imaging given Australia has significant industries in mining, construction, pharmaceuticals and healthcare. This could provide a commercial pathway for quantum technologies and a first-mover advantage for Australian industries in global markets.

---

[34] The Univeristy of Adelaide (2019). Quantum Sensors to Make Australia Safer. Accessed at < https://www.adelaide.edu.au/news/news106202.html>

[35] The University of Queensland (2019). Unmanned Vehicles to Take Quantum Leap. Accessed at <https://www.uq.edu.au/news/article/2019/01/unmanned-vehicles-take-quantum-leap>

[36] The University of Queensland (2019). Inertial Sensing with a Quantum Gas Phonon Interferometer. Accessed at < https://researchers.uq.edu.au/research-project/37522>

[37] The University of Adelaide (2019). Cryogenic Sapphire Oscillator – The Sapphire clock. Institute for Photonics and Advanced Sensing. Accessed at <https://www.adelaide.edu.au/ipas/our-research/defence-security/cryogenic-sapphire-oscillator-the-sapphire-clock#defence-applications>

Indicative timelines for commercial opportunities

TIMEFRAME	POTENTIAL COMMERCIAL OPPORTUNITIES
Near term (0-5 years)	• Deliver in-field demonstrations of quantum sensing and measurement devices with a return on investment for early industry adopters. This includes atomic clocks, inertial measurement units, magnetometers and potentially quantum radars for applications in industries such as defence, mining exploration and hydrology. • Develop deployable prototypes of quantum-enabled medical imaging technologies such as hyper-polarised magnetic resonance imaging for earlier detection of disease tissue states. **Potential end-users:** Defence, research, mining exploration, hydrology, oil & gas, civil engineering, surveying, healthcare, agriculture, security
Medium-long term (5+ years)	• Manufacture, package and customise field-deployable sensors and imaging technologies (by sizes, weight and specifications) for industries at commercial scale. This may include quantum-enabled bioimaging devices in health care, precision inertial navigation units in GPS-denied environments (e.g. subsea and space exploration), quantum calibration for quantum-based and classical instruments, and portable, room-temperature, high-resolution sensors in mining exploration, surveying and hydrology. **Potential end-users:** Defence, research, mining exploration, hydrology, oil & gas, civil engineering, surveying, healthcare, agriculture, security

CASE STUDY: LuciGem is developing fluorescent nanodiamonds for applications in sensing and imaging[38]

Sydney-based LuciGem is focused on producing nanomaterials such as fluorescent nanodiamonds, fluorescent nanorubies and irradiated nanodiamonds. Nanodiamonds for example have potential applications in quantum-based sensing with higher sensitivity and resolution due to its material and quantum spin properties. This includes detection of magnetic field (nanoscale magnetometry) and temperature variations (thermometry). The properties of nanodiamond also exhibit potential for application in in-vivo imaging or as contrast agents in magnetic resonance imaging. Customers of LuciGem products include the Centre for Nanoscale BioPhotonics (Australia) and Laval University (Canada). LuciGem was established out of Macquarie University and as a team under CSIRO's On-Innovation Accelerator program.

[38] Lucigem (2019) Our Products. Viewed on 22 August 2019, <https://www.lucigem.com.au/our-products/>; On-Innovation (2019) LuciGem. Viewed on 22 August 2019, < http://www.oninnovation.com.au/en/ON-teams/ON-Tribe/Accelerate3/LuciGem>

CASE STUDY: Superconducting devices with potential applications across mining, defence and agribusiness[39]

Superconductors are materials with useful quantum electronic properties when cooled to low temperatures. Its macroscopic quantum effects can be used to make ultra-sensitive magnetic field and radio frequency sensors. CSIRO specialises in novel superconducting devices such as Josephson junctions, microwave and terahertz devices, and superconducting quantum interference devices (SQUID). CSIRO is developing SQUID magnetometers and gradiometers with world leading sensitivity, low noise performance and longevity properties.

Following early collaborations with BHP Billiton and former Canadian mining company Falconbridge, CSIRO commercialised LANDTEM with Australian firm Outer-Rim Developments. LANDTEM is a portable magnetic field sensing system that use SQUIDs to detect mineral ore buried deeper underground. The technology is highly sensitive and can detect magnetic anomalies at greater depths relative to conventional magnetometry. Several companies have operated LANDTEM systems, with one company reporting a 30 percent reduction in mineral exploration costs from its use.

CSIRO is also using similar technologies to develop high temperature superconducting gradiometer sensors to detect undetonated sea floor explosives as part of the US Government's Strategic Environmental Research and Development Program (SERDP). After successful trials in stationary laboratory environments, the sensor is undergoing in-motion trials in preparation for underwater trials. The technology demonstrates potential to help clear landmines, noting that more than 10 million acres of coastal waters are contaminated with undetonated explosives according to SERDP.

CSIRO has also developed high-temperature superconducting electronic technology that can detect electromagnetic radiation at terahertz frequencies (a frequency that is difficult for conventional semiconductor and optical devices to reach). CSIRO has developed this technology as a cryogen-free superconducting detector imaging system and is collaborating with an industry partner on potential applications in areas such as security check points and safety inspections for food and agriculture products.

[39] CSIRO (2015) Superconducting Devices – Manufacturing Flagship. Viewed on 22 August 2019, <https://www.csiro.au/~/media/MF/Files/RS1941_15-00207_MF_Superconducting-brochure-150603.pdf>; CSIRO (2019) Unearthing Mineral Deposits Around the World – Case Study. Viewed on 22 August 2019, <https://www.csiro.au/en/Research/MF/Areas/Innovation/Superconducting/LandTEM>; CSIRO (2019) Detecting Bombs on the Sea Floor – Case Study. Viewed on 22 August 2019, <https://www.csiro.au/en/Research/MF/Areas/Innovation/Superconducting/Detecting-bombs>

2.4 Enabling services and technologies

Australia’s opportunity

Australian industry can capture early revenue streams by providing enabling services and technologies for the global quantum industry. Australian universities are already leveraging their reputation for quantum science research expertise to expand their higher education offerings. Likewise, there is an opportunity for Australia’s quantum experts to provide consulting and advisory services to governments and businesses as they explore their quantum readiness and opportunities to invest in quantum technologies.

Why Australia

Research and education strengths

Australia’s world-class quantum research sector presents the opportunity to develop hubs for education and training in quantum science, technologies and engineering. Examples includes the University of Queensland’s Masters of Quantum Technology launched in 2019 and the NSW Government-backed Sydney Quantum Academy initiative. With executives in mind, the University of Melbourne run a short course on quantum information processing.

Commercial growth

Australia is an attractive destination for education and training in quantum and has established companies to supply scientific instruments and devices for R&D labs developing quantum (and other) technologies. Major infrastructure such as the Australian National Fabrication Facility can provide the Australian quantum industry with access to world-leading micro and nano-fabrication infrastructure.[40] Companies such as MOGLabs and Liquid Instruments have also developed and commercialised optical and laser technologies, and flexible testing and measurement hardware respectively for the R&D market. Companies such as H-Bar are also emerging to provide quantum-related advisory and consulting services.

Strategic complementarities

A strong education and training hub is a critical enabler to the Australian and global workforce in quantum technologies. Advisory and consulting services provides an opportunity for business development and engagement with industry end-users. Similarly, the supply of high-quality instruments and devices for quantum research and translation is another important enabler for industry.

[40] For example, UNSW researchers have used the New South Wales node of the Australian National Fabrication Facility to fabricate a two-qubit logic gate. Source: Australian Government (2016) National Research Infrastructure Roadmap. Viewed on 23 August 2019, <https://docs.education.gov.au/system/files/doc/other/ed16-0269_national_research_infrastructure_roadmap_report_internals_acc.pdf>

Indicative timelines for commercial opportunities: education and training

TIMEFRAME	POTENTIAL COMMERCIAL OPPORTUNITIES
Near term (0-5 years) and ongoing	• Establish Australia as a preferred destination for education and training in quantum science and technology. This includes undergraduate, postgraduate and post-doctoral pathways. This provides an additional source of revenue for the quantum research sector and a pathway to attract and retain the best global talent.

CASE STUDY: Sydney Quantum Academy will attract and develop the next generation of engineers and scientists in quantum computing[41]

The Sydney Quantum Academy (SQA) is a joint-initiative by the University of Sydney, University of Technology Sydney, Macquarie University and UNSW to support the quantum technology workforce. SQA will enable students to collaborate and train between universities, connect students with industry internships and research opportunities, support quantum technology businesses, and promote Sydney as a global leader for quantum computing. SQA will support NSW's growing quantum ecosystem, among the four universities, centres of excellence, and commercial companies (e.g. SQC, Q-CTRL). The NSW Government has since committed $15.4 million in funding to SQA. This brings total investment, with current university and future industry support, to around $35 million. The initiative demonstrates how targeted investments and joint-initiatives can develop Australia's quantum industry.

CASE STUDY: The University of Queensland's Master of Quantum Technology will support industry access to world-class talent[42]

The University of Queensland introduced its Master of Quantum Technology in 2019 to domestic and international students in science, mathematics and engineering. The 18-month program is intended to develop student foundations in quantum physics theory and technologies in areas such as quantum sensing, information, communication, computation, error correction, and noise and error suppression. Students get to access the university's measurement and fabrication facilities in superconducting, opto-mechanical, optical and ultra-cold atomic systems; and connect with various centres of excellence (EQUS, CQC2T, ANFF) and the university's strategic partnerships (including Lockheed Martin, Defence Science Technology Group, and Boeing Research & Technology) on research opportunities. The program is intended to prepare students for careers with public and private start-ups, as well as Fortune 100 companies, in quantum.

---

[41] NSW Government (2019) Sydney Quantum Academy to Create Jobs of the Future. Media Release. Viewed on 27 August 2019, <https://www.finance.nsw.gov.au/about-us/media-releases/sydney-quantum-academy-create-jobs-future>

[42] The University of Queensland (2019) Master of Quantum Technology Course Overview. Viewed on 27 August 2019, <https://future-students.uq.edu.au/study/program/Master-of-Quantum-Technology-5711?year=2019>

Indicative timelines for commercial opportunities: advisory services

TIMEFRAME	POTENTIAL COMMERCIAL OPPORTUNITIES
Near term (0-5 years) and ongoing	• Leverage Australian industry's capability and reputation to offer advisory services to help local and international enterprises and governments to understand and respond to the opportunities and threats that quantum technologies present. Potential customers include defence and government agencies, communications, healthcare, pharmaceuticals, advanced manufacturing and finance in Australia and across the world. Advisory services can provide an additional pathway to early revenue generation, end-user engagement and business development.

CASE STUDY: H-BAR Quantum Technology Consultants is helping governments and industries to understand and navigate the next-wave of quantum technologies[43]

H-Bar Quantum Technology Consultants (H-Bar) brings over 50 years in combined experience and expertise in quantum technology and quantum physics to help governments, businesses and start-ups understand and navigate the next generation of quantum technologies. Their services include consultations, training and investigations to help clients understand the impact of quantum on business needs, build the knowledge base to ensure quantum readiness, and develop an investment framework in quantum technologies.

[43] H-Bar (2019) H-Bar: Quantum Technology Consultants – Quantum Technology is our Business. Viewed on 27 August 2019, <http://www.h-bar.com.au/about>

Indicative timelines for commercial opportunities: enabling technologies

TIMEFRAME	POTENTIAL COMMERCIAL OPPORTUNITIES
Near term (0-5 years) and ongoing	• Scale development and provision of scientific devices, instruments and technologies for organisations undertaking research, development and translation in quantum technology industries. These could include software user interfaces, cryogenics, custom electronics, custom instruments and packaging. Potential customers include quantum research and engineering divisions at universities, governments, defence agencies, start-up companies and multinational companies.

CASE STUDY: MOG Laboratories provides high-performance laser technologies for research institutions in quantum physics and technologies[44]

MOG Laboratories (MOGLabs) was founded in 2007 by University of Melbourne researchers to fill the gap in access to high-performance laser technologies for research institutions in quantum physics. MOGLabs develops scientific instruments such as laser electronics, tunable cateye and Littrow lasers, RF synthesizers, AOM drivers, optical amplifiers and laser wavemeters. RF synthesizers for example have applications in diamond quantum control, laser cooling and trapping, quantum optics and laser spectroscopy. The Melbourne-based company received funding support through the Australian Research Council's Linkage Project and Melbourne City Council's Business Expansion Grant. It has now established sales offices in the United States and Germany.

CASE STUDY: Liquid Instruments is simplifying workflows for experimental measurement and control with flexible hardware platforms[45]

Liquid Instruments provide equipment and instruments to help professionals, scientists, engineers and students to collect data, perform measurements and control experiments. Moku:Lab is Liquid Instrument's reconfigurable hardware platform that provides the functionality of twelve instruments on a single device at lower cost. The device simplifies workflows that would otherwise require multiple equipment for instruments such as arbitrary waveform generator, frequency response analyser, phasemeter, spectrum analyser, data logger and oscilloscope. Liquid Instruments was founded by a team of experimental physicists and engineers from the Australian National University with experience in gravitational wave detector instrumentation and precision measurement.

[44] MOGLabs (2019) A Research Lab Beginning – About Us. Viewed on 27 August 2019, <http://www.moglabs.com/about-us.html>; The University of Melbourne (2019) MOGLabs – Precision Laser Technology for Quantum Physics Researchers. Viewed on 27 August 2019, <https://research.unimelb.edu.au/partner/case-studies/licensing-and-spin-outs/moglabs>

[45] Liquid Instruments (2019) Moku:Lab. Viewed on 27 August 2019, <https://www.liquidinstruments.com/hardware>

Satyendra Nath Bose and Albert Einstein, depicted using Bose-Einstein Condensates and a microscope.
Credit: Tyler Neely and Patrick Self

3 Challenges and risks for the quantum industry

In an increasingly competitive global environment, capturing the long-term commercial opportunities that quantum technology can enable will not be easy. The following sections of the discussion paper summarise the key challenges and potential risks associated with quantum technology development that stakeholders in the quantum technology sector will need to address. High level summaries of these challenges and risks are provided in Table 4.

Table 4: Challenges and risks for Australia's quantum industry

CHALLENGES →	RISKS →
Coordination and collaboration International peers are increasing their coordination and building strengths that challenge Australia's current position. **Workforce capacity** A thriving quantum technology industry will require Australia to continue to train, attract and retain world class talent in a competitive global landscape. **Infrastructure availability** Access to world class equipment and infrastructure is essential for Australia to maintain its quantum R&D strengths and expand its ability to protype and manufacture quantum technologies. **Research translation** Australia has a poor record of retaining and commercialising intellectual property developed in its universities. **Limited deep-technology investment** Compared to its global peers, Australia has a limited amount of capital available for deep technology investment.	**Development uncertainty** Scientific, technical and engineering barriers may be more challenging to overcome than expected, delaying the potential value creation of quantum technologies **Unrealistic expectations** Quantum technology development will require sustained effort. Excessive media hype and inflated expectations may lead to an investment bubble and damage long term investment in quantum technology development. **Material and component supply** Consideration of the entire supply chain for quantum technologies is essential to manage production risk, such as the limited availability of key materials (e.g. rare-earth minerals) or component manufacturing capabilities. **Health and environment** It is essential that the quantum technology supply chain is environmentally beneficial. Risks associated with carbon emissions, material toxicity, and waste and recycling must be appropriately managed. **National security** Potential national security risks, including emerging cybersecurity concerns, must be proactively managed. Industrial security, e.g. the management of insider threats, is also a key risk that requires government consideration. **Export and trade controls** Export controls must be commensurate with risk to ensure continued global collaboration and innovation. **Unintended consequences** Emerging risks that are not yet understood can be explored and managed through responsible innovation practices.

3.1 Australia's challenges

We welcome your feedback on the following questions:

3.1.1 Do you agree with the summary of Australia's challenges? Please provide a brief rationale for your response.

3.1.2 Are there any additional challenges that should be considered?

The consultation process suggested several systemic challenges that may restrict the ability to grow Australia's quantum technology industry.

Coordination and collaboration

The scale of initiatives and investments made by international peers means that Australia must be increasingly strategic and targeted in research and translation efforts to capture long-term commercial opportunities in quantum technologies. Failure to achieve this will result in decreasing international competitiveness.

Stakeholders have noted that:

- Australia is yet to articulate a long-term strategy and clear investment priorities for the sector. This contrasts with regions such as the US, the UK, the EU, and China which have outlined national strategies and investment commitments to quantum technology development.
- Insufficient national planning and coordination can hamper the effectiveness of quantum-related initiatives such as workforce development, investment in shared-infrastructure, and collaboration programs (both domestically and internationally).
- Collaboration between universities can be stifled by university attitudes towards shared funding and intellectual property management.
- A balance needs to be found between multinational investment into local research, and national investment into local research.
- There are concerns regarding the implementation of defence trade controls that are not fit for purpose and unintentionally restrict beneficial international collaborations.

Workforce capacity

Improving the capacity of Australia's quantum technology capability and talent pool will be a significant challenge for the sector. As global companies seek to scale, competition for talent with expertise in quantum-related R&D, hardware and software engineering and business skills has become increasingly intense. Continuing to develop, attract and retain talent is essential to maintain Australia's capacity to capture long-term opportunities in quantum technology development.

Stakeholders observed that:

- Many Australian graduates in quantum go on to work for start-ups and multinational companies overseas. While this is excellent for individuals and the global industry, it is an opportunity cost for Australia.
- Immigration policy and work-study visa programs can deter global talent from pursuing postgraduate study and careers in quantum in Australia.
- The continued lack of gender diversity in STEM fields means that a large portion of the talent pool may be overlooked.[46]

[46] Australian academy of science (2019) Women in STEM Decadal Plan. Viewed on 10 October 2019, <https://www.science.org.au/files/userfiles/support/reports-and-plans/2019/gender-diversity-stem/women-in-stem-discussion-paper.pdf>

- Australia's quantum research strengths are often built around the deep-domain expertise of a small number of experts. This creates capability-risks and challenges to scale without strategic workforce development and planning. [47] Australia's size dictates that it cannot invest in all areas but needs to focus on building strengths in key areas with demonstrated competitive advantage.
- In addition to developing Australia's quantum technology R&D workforce, upskilling people with relevant capabilities will be essential to progressing the sector. This includes engineers and computer scientists, but also senior decision makers in end-user organisations.

Infrastructure availability

Access to equipment and infrastructure is an important enabler for industry. It is also an important drawcard that can attract researchers, students, start-up companies and multinational partners.

Stakeholders have highlighted that:

- Quantum technology development is capital intensive and expensive. Start-ups and research groups often face difficulties to accessing needed infrastructure and equipment.
- There is higher risk of fragmentation and underinvestment in equipment and infrastructure relative to international peers due to Australia's size and geographic dispersion.
- Australia has well-regarded quantum centres of excellence across major cities but risks ceding its leadership position if future capital requirements are neglected.
- Local industry does not currently have the infrastructure for manufacturing and packaging of quantum devices and components at commercial scale.[48]

Research translation

Australia has a long history of contributions to global research and IP development across many industries, but a poor record of retaining and commercialising intellectual property developed in its universities. For example, Australia made important scientific contributions to the development of computing, solar-cells and wireless networking, but failed to capture the significant commercial opportunities that followed.

Stakeholders have noted that:

- Successful translation in quantum requires appropriate IP management, an ecosystem of suppliers and customers, access to capital.
- Some university IP management practices can hinder local commercialisation due to exclusive (and potentially inappropriately valued) licensing to global companies. Creator owned IP models, as demonstrated by the University of Waterloo, may create better incentives for commercialisation. [49]
- Pairing deep-science expertise with commercial mindedness is critical for engagement with end-users and identification of commercial opportunities.
- Failing to achieve the above risks ceding commercial opportunities to competitors who

[47] Australia's quantum research output is much smaller than that of China or the United States. Despite Australia's strong quantum R&D capabilities there are areas where Australia has limited capacity. For example, Australia only has a small number of researchers with expertise on the two dominant quantum computing physical architectures: trapped-ion and superconducting. This represents a potential disadvantage if these architectures continue their dominance into the future.

[48] At present, the Australian National Fabrication Facility (ANFF) network provides Australia's quantum sector with access to micro and nano-fabrication infrastructure for research and prototyping. For example, UNSW researchers have used the New South Wales node of the Australian National Fabrication Facility to fabricate a two-qubit logic gate. Source: Australian Government (2016). National Research Infrastructure Roadmap. Available at < https://docs.education.gov.au/system/files/doc/other/ed16-0269_national_research_infrastructure_roadmap_report_internals_acc.pdf>

[49] University of Waterloo. Intellectual property. Viewed 8 October 2019, <https://uwaterloo.ca/research/waterloo-commercialization-office-watco/intellectual-property>

deeply understand end-user needs and innovate accordingly.

Limited deep-technology investment

Australian investment firms lack the same appetite as US counterparts for investing in complex and early stage technology. While Australia's quantum technology start-ups have attracted some investment from companies such as Telstra, CBA and Westpac, industry will face challenges to translation and commercialisation of quantum technologies without continued investment in and appetite for deep-science and technologies.

Stakeholders have noted that:

- There is a growing appetite for deep-tech investment in Australia led by funds such as Main Sequence Ventures and Square Peg Capital.
- Some US funds see Australian start-ups as a good value proposition with low valuations compared to their Silicon Valley counterparts.
- However, relative to global peers, Australian multinationals and investors are typically more reluctant to invest in deep-tech projects that have higher risk-reward profiles by nature.[50]
- Australia currently ranks 19th globally on venture capital deals on a per GDP basis, which reflects the country's relatively lower appetite for early-stage investments.[51]
- Addressing this challenge may require an investment-culture shift, as well as more demonstration projects with clearer expected returns on investment.
- Government efforts to support scaling of start-ups and SMEs are valuable. For example, governments can increase strategic use of procurement to support the growth of Australian SMEs.[52]

Other challenges

Other Australian challenges that have been suggested by stakeholders and discussed in previous reports include:

- Perceived isolation of Australia, when there is limited difference in distance between many global hubs (e.g. the distance between California and major European cities).
- Lack of awareness around the depth of Australian strengths in comparison to international competitors.
- Limited local market size dictates that for a technology to be successful it must integrate global export into the development plan.

[50] Main Sequence Ventures (MSV) for example was established to help address the shortage of deep tech investment in Australia through management of the CSIRO Innovation Fund. At the time of writing, MSV is the only Australian venture capital firm that has invested in Australia's quantum sector.

[51] Cornell, Insead & WIPO (2019). Global Innovation Index 2019 – Australia Country Profile. Available at <https://www.globalinnovationindex.org/analysis-indicator>

[52] As recommended by Innovation and Science Australia (2017) Australia 2030: Prosperity through Innovation. Viewed on 10 September 2019, <https://www.industry.gov.au/data-and-publications/australia-2030-prosperity-through-innovation>

3.2 Commercialisation risks

We welcome your feedback on the following questions:

3.2.1 Do you agree with the summary of possible risks associated with commercialisation of quantum technology in Australia? Please provide a brief rationale for your response.

3.2.2 Are there any additional risks that should be considered?

The consultation process identified risks that may develop and hinder the growth of the quantum technology industry. Most of these risks are not unique to Australia, but they are important for industry and governments when making decisions and investments related to quantum technology. If Australia can overcome a risk more effectively than an international peer, it may help build a new competitive advantage.

Development uncertainty

Uncertainty in the timing of scientific and technical milestones leads to subsequent uncertainty when planning for when, how and which quantum technologies will impact or benefit industries within the next 20 years. For example, the quantum computing community remain uncertain on which physical architecture will dominate. Existing challenges around quantum control, decoherence and scalability require resolution to enable useful applications.

Unrealistic expectations

The commercial applications of quantum technologies are currently subject to considerable global media attention and international investment interest. There is a risk that speculative bubbles may form based on misinformation and unrealistic expectations, damaging long term investment strategies in place by governments and established companies. Similar trends have been observed in internet stocks in the late 1990s and more recently with cryptocurrencies in the 2010s. While there are some short-term opportunities, it is essential to recognise that the development of many quantum technologies will require sustained long-term effort.

Material and component supply

Supply shortages for the specialised materials (such as rare earth metals) and components required to implement quantum technologies will create costly delays and slow commercialisation activities. For example, the niobium-titanium and niobium-nitride alloys used in some superconductors are expensive imports to Australia. The specialised dilution refrigerators required for many quantum technologies are also in limited supply.[53] Lack of access to required materials introduces supply chain risks, slowing the development lifecycle of quantum hardware and components and inhibiting scalability in Australia.

Health and environment

Inputs into quantum technologies may create broader health and environmental risks; all emerging quantum technology should aim to have in the least neutral impact, and ideally positive benefit, on the environment. This includes all ecosystem impacts associated with production and use, such as environmental toxicity and energy consumption.

National security

Quantum technologies may be of importance to national security in the longer term. For example, quantum computers being used to break current

[53] MIT Technology Review (2019) We'd have more quantum computers if it weren't so hard to find the damn cables. Viewed on 2 October 2019, <https://www.technologyreview.com/s/612760/quantum-computers-component-shortage/>

best-practice (public key cryptography) cybersecurity solutions. This may create significant risks to government, defence, critical infrastructure, healthcare and major industries. Quantum technologies for sensing, positioning, navigation and timing are also being explored for military applications. Proactively preparing for these risks (and the related opportunities) and developing Australia's sovereign quantum technology capabilities will be of strategic importance.

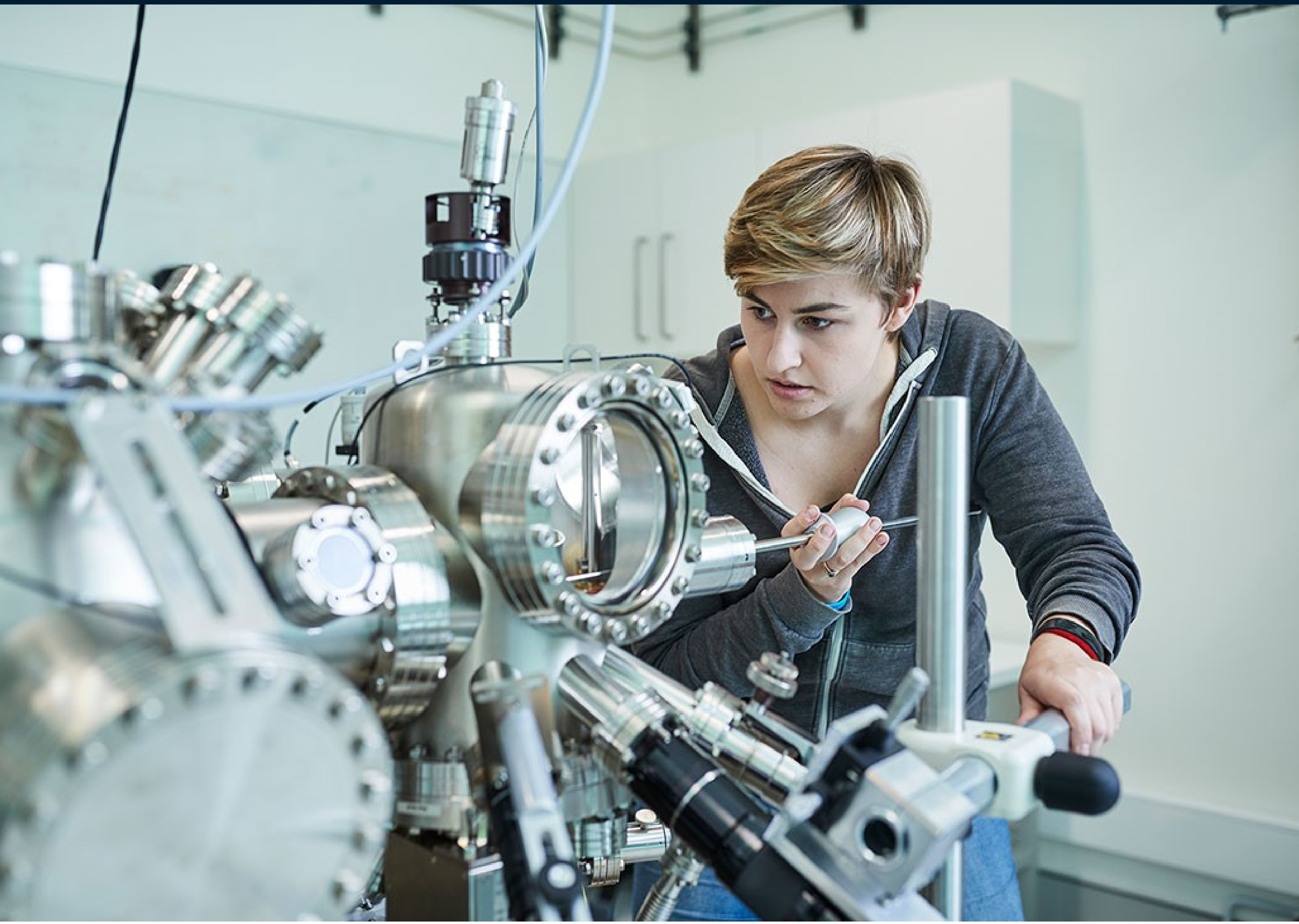
Export and trade controls

Stakeholders shared diverse views on the defence trade controls for quantum technologies. While all agreed that they play an important role in protecting IP and national security, many expressed concerns that inappropriately contextualised technological export controls have the potential to stifle collaboration and innovation. This needs to be balanced with a recognised need for controls, with stakeholders noting that if Australia develops any reputation as a risky place to do business then there is a possibility that allied countries will look elsewhere for collaboration. It is important that export control restrictions are informed by evidence and broad consultation to ensure that they are fit for purpose.

Unintended consequences

Emerging technologies can present previously unknown risks. Transformative technologies often have undesirable effects on industries that are unable to successfully adapt and transition under periods of disruption, which can lead to significant economic instability. Risks may also arise from a systemic bias or unexplored malicious applications. Important social and ethical considerations may be deprioritised to rapidly demonstrate a quantum technology application, as is being discovered with incomplete and biased data used to build artificial intelligence (AI) systems.[54]

[54] Buolamwini J and Gebru T (2018) Gender Shades: Intersectional Accuracy Disparities in Commercial Gender Classification. Proceedings of Machine Learning Research. 81(2), 1–15.



PhD student Georgina Carson working on a scanning tunnelling microscope.
Credit: CQC^2T

4 Enabling actions

We welcome your feedback on the following questions:

4.1 Do you support the enabling actions listed? Please provide a brief rationale for your responses.

4.2 Are there any additional themes or enabling actions that should be considered?

4.3 What are the highest priority actions that could be undertaken to enable sustainable commercial growth in Australia's quantum technology sector?

Capturing quantum technologies opportunities will not happen without significant effort and planning. Australia faces competition from international peers like the United States, European Union, United Kingdom, Canada and China, with the scale of investment from these countries out-pacing Australia. Because of this, Australia must be strategic and targeted in research and translation efforts to capture long-term commercial opportunities in quantum technologies. Australia must continue to leverage its strengths, address existing challenges, and be increasingly coordinated in the investments and enabling actions it pursues. Importantly, quantum technology remains a long-term effort and continued R&D to address technical and engineering barriers is essential to creating commercial opportunities.

Consultations with stakeholders has emphasised the need for a strategic national focus, enabled by collaboration, capability development, industry readiness, and demonstration projects. Sustained investments and actions under these enabling themes could allow and encourage Australia to build on prior foundations and lead the frontier on quantum technology development and commercialisation. In the longer term, these themes are expected to enable Australia to capture strategic benefits in the form of greater breakthrough science, economic growth, national security and improved collaboration, underpinned by more certainty regarding investments (Table 5).

The remainder of this section summarises identified enabling actions for stakeholders in Australia's quantum technology sector.

Table 5: Summary of enabling themes and strategic benefits

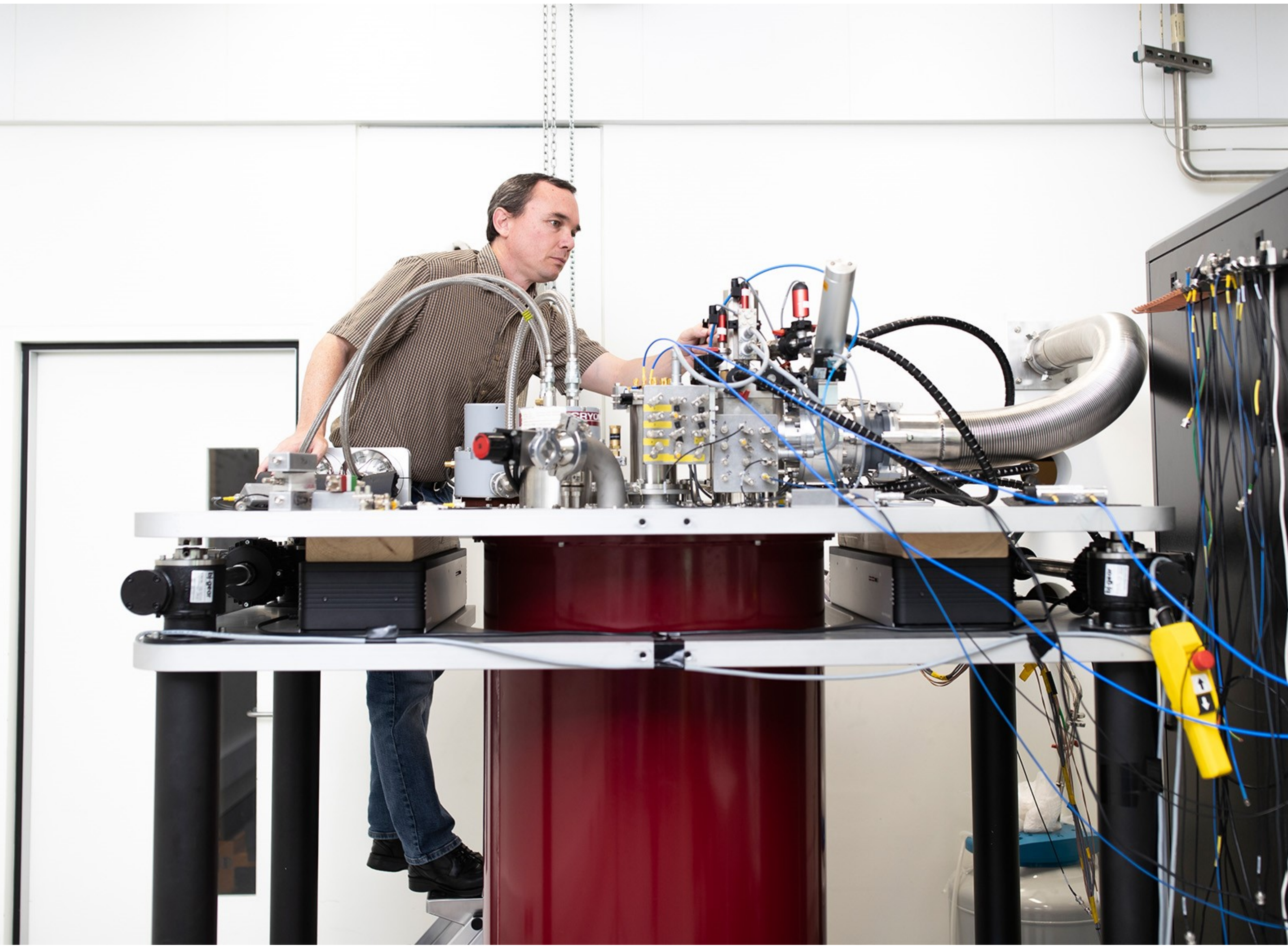
ENABLING THEMES	**Focus:** Develop a national vision and strategy that identifies and supports commercially competitive Australian-led quantum technology initiatives. **Capability:** Strengthen education, training and career pathways to attract, develop and retain talent. **Collaboration:** Enhance cross-disciplinary collaboration and invest in shared infrastructure to enable world-class research. **Demonstration:** Accelerate demonstration projects with commercial benefits and enhance Australia's precision fabrication capacity. **Readiness:** Invest in sovereign capabilities and quantum-readiness to capture early revenue streams and position Australia for the next generation of technologies
STRATEGIC BENEFITS	**Certainty:** A clear strategy supports local and foreign R&D investment. **Science:** Pursue breakthrough science to address global challenges. **Growth:** Create future source of economic and productivity growth. **Security:** Contribute to national and global security. **Leadership:** Ensure ongoing Australian leadership in a potentially transformative area of technology.

4.1 Focus

Objective: Develop a national strategy that identifies and supports commercially competitive Australian-led quantum technology initiatives.

ACTIONS	SUGGESTED LEAD	POTENTIAL SUPPORT
Develop a national strategy based on areas of global leadership within the Australian quantum technology landscape and communicate long-term strategic priorities, commitments and direction to Australia's quantum industry.	Government	All
Identify ongoing funding support streams and opportunities, including government, industry, and VC initiatives.	Government, Industry, Private investors	All

Dilution Fridge Lab: Dr Matthew House working in the Cryogenic Dilution Fridge Lab at UNSW Sydney.
Credit: CQC^2T



4.2 Capability

Objective: Strengthen education, training and pathways to attract, develop and retain talent.

ACTIONS	SUGGESTED LEAD	POTENTIAL SUPPORT
Undertake consultations with research organisations, Australian Defence and early industry partners to map and forecast workforce needs to ensure strategic capability development and growth (rather than ad-hoc or reactive).	Education	All
Ensure that quantum science and technology postgraduate programs have strong pathways to opportunities in Australian research, start-ups and defence. Design postdoctoral research opportunities with industry linkages and spinoff potential in mind.	Research, Industry, Government	All
Encourage development of the skills and knowledge required to enable commercial scale-up of hardware manufacturing in Australia. Examples of necessary expertise include designing for manufacturability of devices, process improvement, lean manufacturing, and ISO accreditation.	Education, PFRAs, Government	All
Initiate technology entrepreneurship mentoring programs with experienced industry leaders (such as Silicon Valley leaders with deep technology commercialisation experience).	Government, Industry, Research	All
Continue to review and improve visa, international study-work and migration policy to fast-track retention of top global talent in physics, computer science and engineering.	Government	Industry, Research
Continue to support and improve postgraduate programs in quantum technology that blend quantum science, computer science and engineering systems with projects in research and industry.	Research	Government
Review physics curriculum in high school and first year undergraduate programs to determine if exposure to quantum science and technology is adequate. This may increase reach and foster passions for quantum at earlier ages, supporting workforce development in the long term.	Government, Education	Industry, PFRAs
Engage in targeted marketing and recruitment to grow a critical mass of talent in quantum technologies for Australian research and industry.	Government, Research	PFRAs, Industry
Ensure tertiary quantum education programs and institutions have access to the state-of-the-art quantum software and hardware to support learning and attract talent (both students and staff).	Education	Industry, Government

4.3 Collaboration

Objective: Enhance cross-disciplinary coordination and collaboration to ensure strategic national direction. Invest in shared infrastructure to cost-effectively enable world-class research.

ACTIONS	SUGGESTED LEAD	POTENTIAL SUPPORT
Formalise a quantum technology network within Australia to strategically coordinate development efforts. This should include representatives from government, research institutions, industry and end-users. The US Quantum Economic Development Consortium may provide an appropriate model.	Government	All
Establish quantum information science and technology hubs/clusters to attract talent and enhance collaboration on fundamental quantum research challenges and commercialisation opportunities.	Research, PFRAs, Government	Industry, end-users
Organise national collaborative activities and events to strengthen networks, enhance collaboration, identify strategic opportunities, engage with industry, and de-mystify quantum.	Government, PFRAs	All
Strengthen incentives and funding for cross-disciplinary research, translation and commercialisation projects. This is critical as quantum opportunities draw on complex science and engineering across varied-disciplines (e.g. computer science for quantum computing, chemistry for quantum simulations).	Government	All
Increase defence collaboration and coordination with the quantum research sector. This could include co-funded PhD positions, workshops, and collaborative projects.	Government, PFRAs, Research	All
Continue to support existing shared research infrastructure. For example, ANFF provides essential capabilities that enable quantum technology research.	Research & Government	All
Invest in developing platform technologies and shared infrastructure and equipment with cross-disciplinary applications. Fields that share needs with quantum include artificial intelligence, imaging and diagnostics, advanced manufacturing, drug development, materials design and nanotechnology.	PFRAs & Government	Industry

4.4 Demonstration

Objective: Accelerate translation and demonstration projects with commercial benefits. Enhance Australia's precision fabrication capacity to enable prototyping of advanced quantum technologies.

ACTIONS	SUGGESTED LEAD	POTENTIAL SUPPORT
Investigate mechanisms to encourage targeted investment in demonstration and commercialisation of quantum technologies. This could include co-funding or matched investment between venture capital and government partners; or hosting quantum competitions.	Government, Research	All
Continue to explore and implement public-private partnerships and government procurement strategies that foster investment in demonstration projects and support emerging deep-technology SMEs. Programs should ensure that there is funding for small and large projects, with pathways to access finance options if projects demonstrate commercial potential.	Government	All
Undertake further work to scope and develop Australia's precommercial advanced and precision manufacturing capability. This could include consideration of the business case for establishing a sovereign precision integrated circuit fabrication capability (like the nanoelectronics and chip R&D manufacturing capability established at IMEC, Belgium).	Government, PFRAs, Research, Industry	All
Explore opportunities to partner and collaborate with international institutions and investors in translation and demonstration projects with stronger commercial prospects. Priority partners may include countries with major research and investment programs, including the US, Germany, UK, Canada, Switzerland, Japan, France, Singapore, China, Netherlands and Hong Kong.	Research	All

4.5 Readiness

Objective: Invest in sovereign capabilities and quantum-readiness to capture early revenue streams and position Australia for the next generation of technologies.

ACTIONS	SUGGESTED LEAD	POTENTIAL SUPPORT
Embed responsible innovation practices into quantum technology research and development to better understand and address any unknown ethical, social or environmental risks.	Research, Industry	All
Continue to undertake consultation with researchers to ensure that the implementation of trade control regulations appropriately mitigates national security risks without creating undue impacts on R&D and collaboration.	Government	Research
Undertake additional campaigns to de-mystify and manage expectations surrounding quantum technology for Australian industry, and for the general public in the longer term as well. Stakeholders and investment partners should understand that quantum technologies are long-term investments.	All	All
Formalise channels to connect the quantum industry with potential end-users to identify and scope research and demonstration projects with greater commercial potential.	All	All
Develop and communicate guidance and standards to help government and industry transition into a post-quantum world. This includes identification of near-term research and investment priorities related to quantum security. Priority stakeholders are likely to include government, defence, healthcare, communications and finance.	PFRA's, Standards bodies, Industry	Research
Collaborate with global peers to develop international standards and metrics for quantum technologies to help customers and investors understand the technologies that they are buying into. Further research and appropriate regulation are essential to develop safe, beneficial and environmentally-friendly technologies for society.	Government, Standards bodies, PFRAs, Industry	All
Continue dialogue between and education for relevant stakeholders on quantum technologies and export controls to enable outcomes that balance research, commercial and security priorities	Government, Research, Industry	All
Foster dialogue with international governments and partners to understand practical strategic and policy responses to the long-term ethical, social, environmental and political risks that may arise with the next generation of quantum technologies.	Government	Universities

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[55]
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[56]	• The National Quantum Technologies Programme has invested more than £1 billion since its establishment in 2014.[57]

[55] Local currency unless specified.

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

[57] 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".[58]	• Canada has invested more than $1 billion in quantum research over the past decade.[59] • 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. [60] • In 2017, the Canadian government provided the Canadian Space Agency (CSA) with $80.9 million funding for emerging technology research, including in quantum technologies.[61]
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.[62]	• The local government has reportedly invested $10bn to establish a National Laboratory for Quantum Information Sciences in Hefei.[63]
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.[64]	• The Quantum Flagship has been allocated €1b of funding over 10 years

[58] 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.

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

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

[61] 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

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

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

[64] 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.[65]	• 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.[66]	• 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.

[65] 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.

[66] 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

Please refer to the updated overview of Australia’s quantum landscape in CSIRO (2020) Growing Australia’s Quantum Technology Industry, available at www.csiro.au/quantum.

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

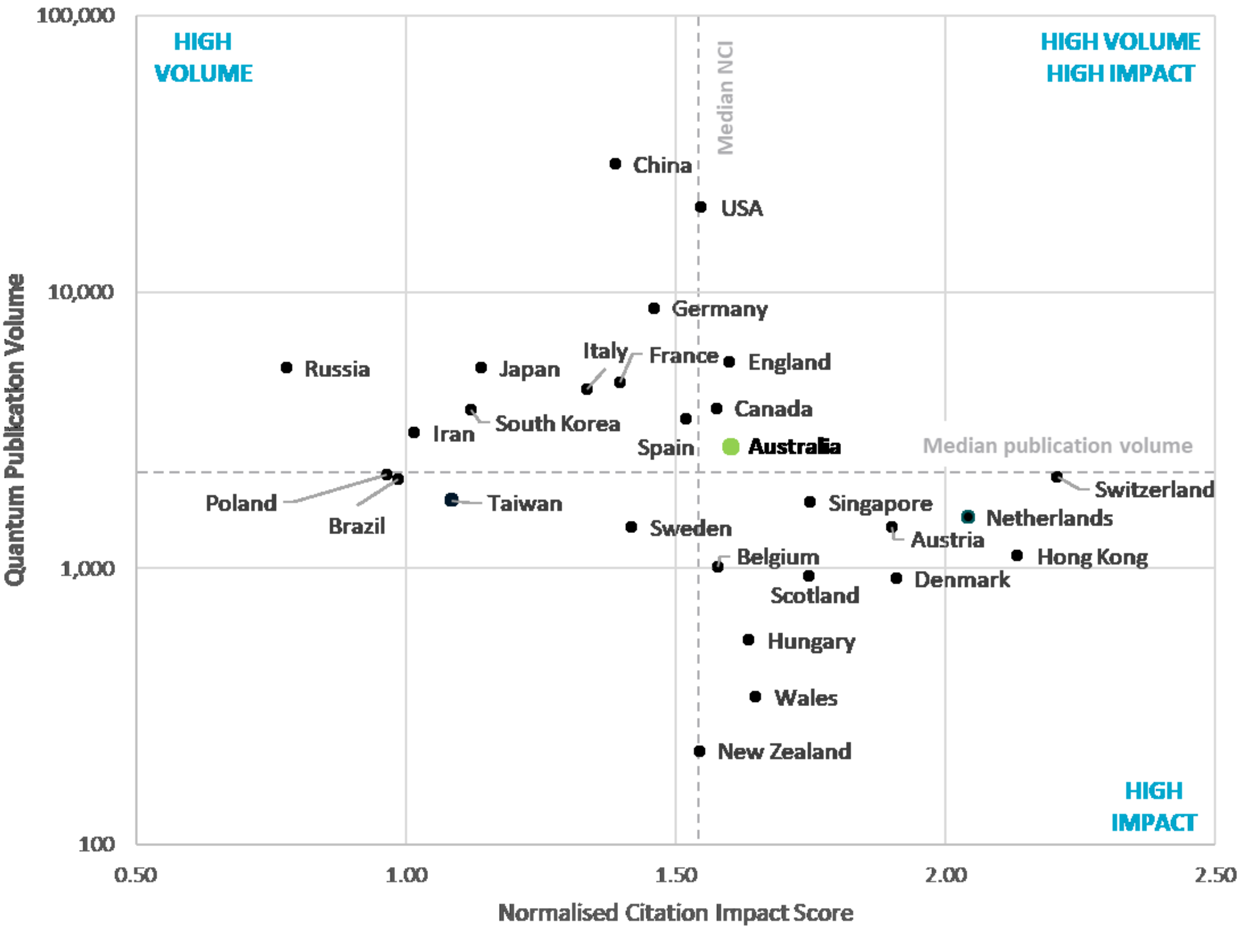
This search returned 269,675 results published between 2001-2018 inclusive. Most of the analysis reported below focuses on the 102,518 documents published in the last five years (2014-2018).

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)[67]

Figure 2: Top countries by quantum science and technology publication count and NCI (2014-2018)[68]



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

[68] 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 6.

Table 6: 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 7.

Table 7: 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[69] and sensing/metrology technologies. In 2017, NG provided an AU$75,000 scholarship to a UNSW researcher focuses on satellite quantum communications research.[70]
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.

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

[70] 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 6) 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[71]

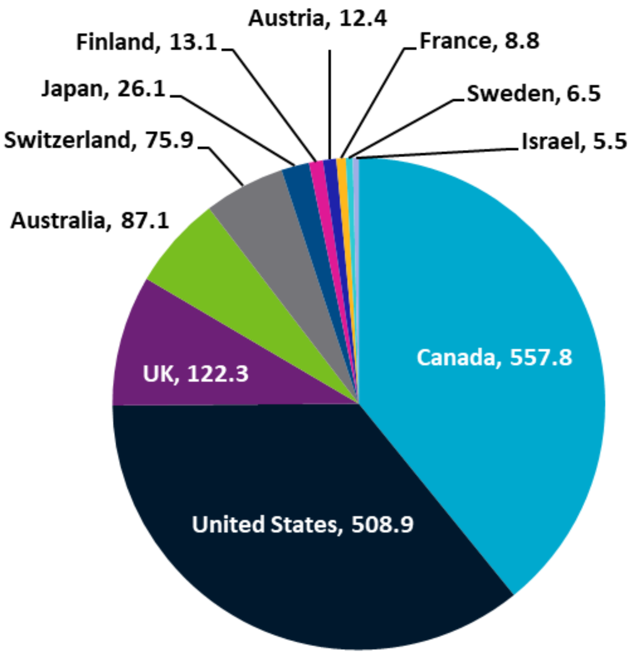
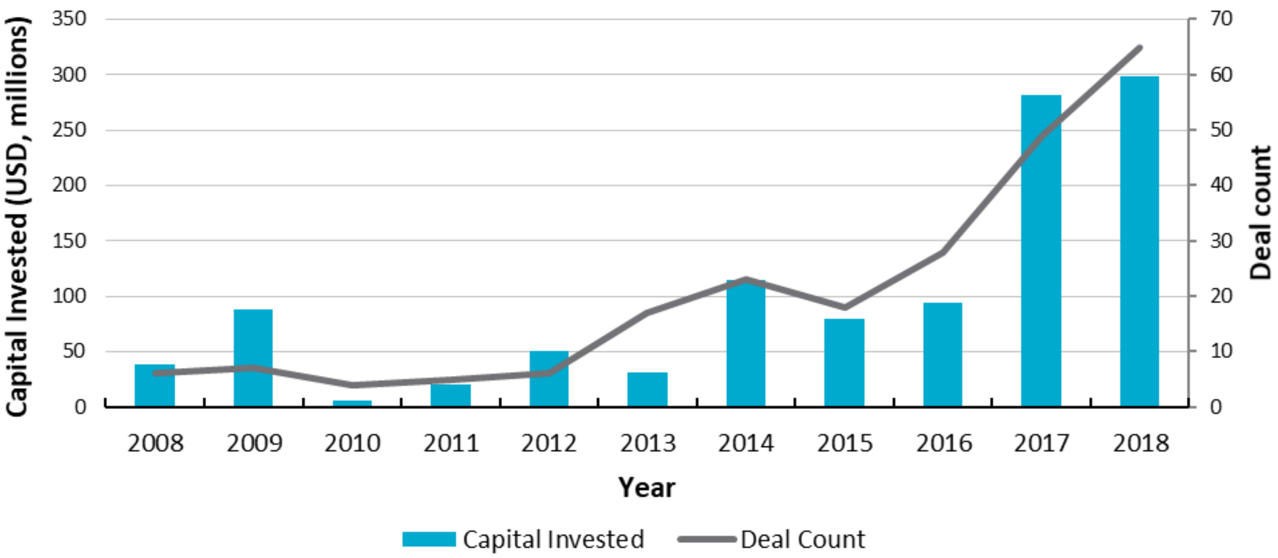


Figure 4: Capital investments in quantum technology companies (2008-2018)[72]



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.

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

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

Developing a single photon source. Credit: Patrick Self & EQUS

As Australia's national science agency and innovation catalyst, CSIRO is solving the greatest challenges through innovative science and technology.

CSIRO. Unlocking a better future for everyone.

Contact us

1300 363 400
+61 3 9545 2176
csiroenquiries@csiro.au
csiro.au

For further information

CSIRO Futures
Dr Shane Seabrook
+61 3 9662 7361
shane.seabrook@csiro.au
csiro.au/futures