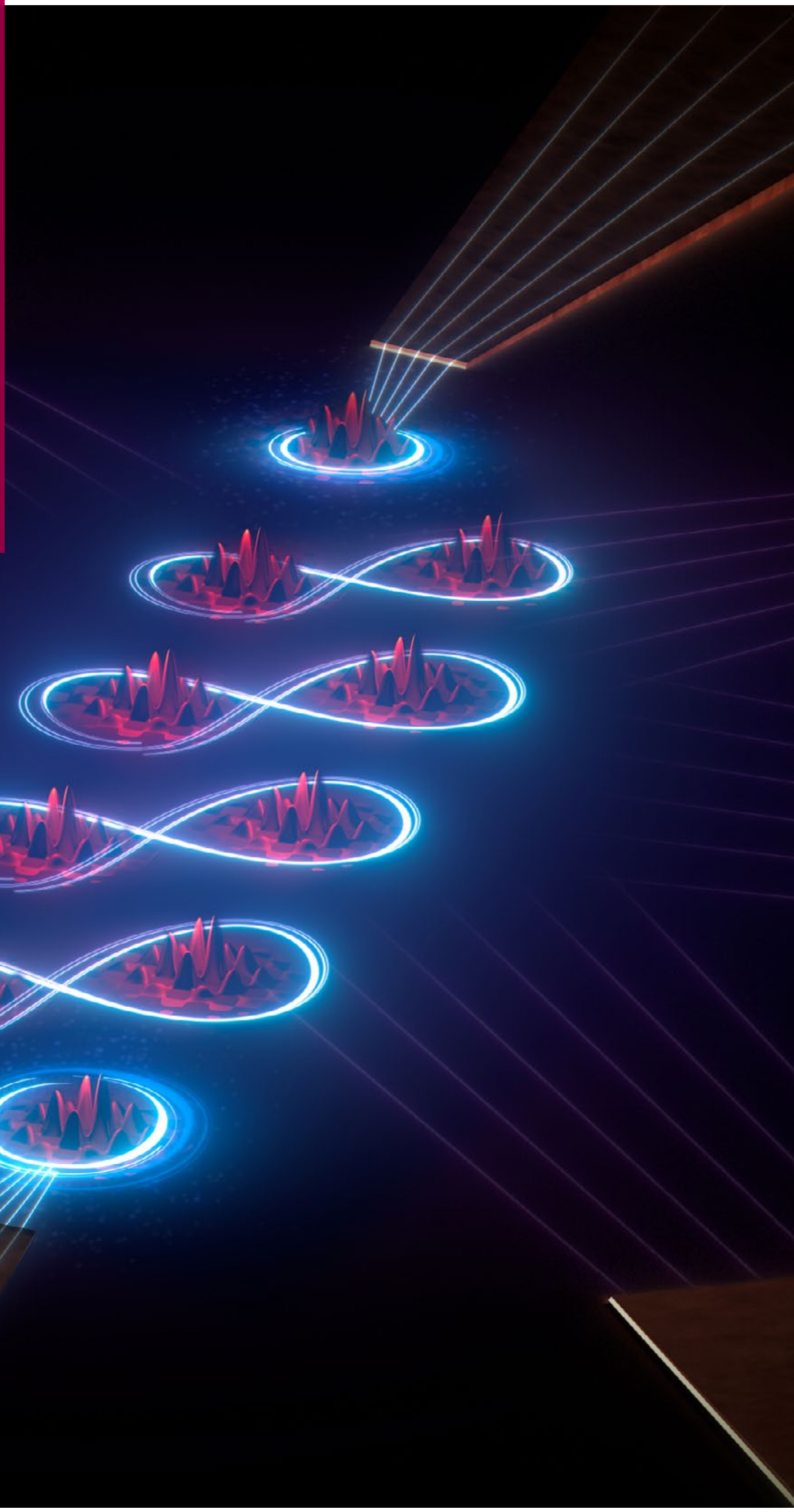
THE AUSTRALIAN NATIONAL FABRICATION FACILITY

ANFF

WHITEPAPER

DELIVERING THE QUANTUM PROMISE

A handbook for businesses to engage with the Australian quantum ecosystem.



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EXECUTIVE SUMMARY

The second quantum revolution is upon us. Its comprising technologies exploit the concepts of quantum mechanics and promise a paradigm shift to the role played by technology in business and industrial processes; these can be broadly categorised as quantum sensing, quantum computing and quantum communications.

As a result, the rising quantum economy presents an opportunity for Australian businesses to develop competitive advantage by envisioning industry-specific solutions that use quantum technologies. The purpose of this paper is to raise awareness about the local quantum economy and infrastructure network that nurture early-stage ideas, and to identify pathways to create a tailored 'Quantum Readiness' plan for businesses that intend to take advantage of the second quantum revolution.

This paper delivers a qualitative outlook on the Australian quantum ecosystem through a high-level explanation of principles of technologies developed by Australian companies, concurrently embedding that information in the context of real-world technology in development. While the applications of quantum sensing and communications discussed in this paper could be realised in the near term, path to achieving practical applications in quantum computing is plagued by factors that affect system stability. As progress is being made to mitigate the effects of instability through methods like 'quantum control', this paper takes the opportunity to discuss the types of technology platforms that enable quantum computing and potential applications that are being considered to tackle global challenges.

> **"It's not necessary to be a quantum engineer to get involved. Just as many of us use computers to make our work more productive every day but can't explain the physics of computer processing at any level. The same holds true for quantum technologies."**
>
> Jane Fitzpatrick, CEO, ANFF

Australia has a world leading position in the race to develop quantum solutions and has a reputation for 'punching above its weight' compared to its international counterparts. This could be attributed to sustained investment by government in critical research infrastructure and projects, that form the bedrock for the broader quantum ecosystem to thrive and flourish. This paper also acknowledges the role played by local supply chains and several government initiatives including the 'National Quantum Strategy' in supporting the growth of the quantum sector. While Australian researchers and innovators have demonstrated practical applications of quantum technologies, the onus of further growing this sector must equally rest on the prospective end-user of quantum technologies by proactively engaging with the ecosystem to develop a fit-for-purpose quantum strategy.

This paper emphasises the importance of preparing for the uptake of quantum technologies and concludes by providing practical ways in which all Australian companies can understand the developing set of technological solutions and its adoption for competitive advantage. It is imperative that the broader economy is prepared to take advantage of this long-term investment to create a highly developed and economically diverse Australia.

CONTENTS

1. PREPARING FOR THE SECOND QUANTUM REVOLUTION

The Industrial Revolution transformed the business landscape in the 18th and 19th centuries when production moved from hand-made to mechanised systems. As part of this transformation, classical mechanics played a vital role in supporting industrialisation by providing the scientific framework necessary for designing, analysing, and improving machines and industrial processes. Its principles and mathematical models were instrumental in driving technological advancements during the Industrial Revolution and laying the groundwork for our modern industrial society.

In the early 20th century, the world commenced its transition into the information age which was led by advancements in the first quantum revolution that arose from the understanding of the behaviour of atoms, molecules, and subatomic particles. For example, the development of semiconductor devices like the transistor was a result of exploiting our understanding of the behaviour of electrons which could be described using quantum mechanics. While classical mechanics is a well-established theory that works effectively at macroscopic scales, quantum mechanics is the foundation of modern physics and provides a more comprehensive and accurate description of the microscopic world. As a result, the first quantum revolution laid the groundwork for subsequent advancements in quantum science and technology, leading to the current second quantum revolution. The second quantum revolution is still in its early stages, and many of its practical applications are yet to be realised. It has however already generated significant interest and investment from governments, academia, and the private sector worldwide. Researchers and engineers are working to overcome challenges such as improving the stability and scalability of quantum systems, reducing error rates, and developing robust quantum algorithms. The goal is to unlock the full potential of quantum science and technology and bring about groundbreaking advancements across multiple fields.

Quantum technologies gained considerable attention and excitement in recent years, owing to significant scientific breakthroughs that demonstrate commercial potential and investor activity. As a result, it inevitably also created hype and misconception that set unrealistic expectations about timeframes in which its potential would be realised. At the same time, it is important to acknowledge the significant contributions delivered by our research community over the last few decades which helped Australia position itself as a leader in quantum technologies. Australian businesses have a unique opportunity to leverage this global leadership position and capitalise on the prowess in quantum technologies that has been locally established through continued investment from the government and relentless perseverance from our researchers. Some of these efforts are being commercialised and are attracting significant private investment to support their growth.

For Australian businesses, this presents a seamless opportunity to establish partnerships with global leaders in quantum technologies to demonstrate use cases that are not only specific to Australia but can also be scaled and exported to the rest of the world. Successful implementation of such partnerships can not only make Australian companies more productive and profitable, but also directly contribute to our national objectives, support research and development, help build sovereign capabilities in quantum technology, attract investment, and directly contribute to increasing Australia's economic complexity and most importantly make Australian companies more productive and profitable.

2. QUANTUM READINESS: AN OPPORTUNITY TO ADOPT NEW QUANTUM SOLUTIONS TO BUILD COMPETITIVE ADVANTAGE

Investing in new technology can offer immense benefits that have the potential to spur innovation, increase productivity, and drive global competitiveness; the quantum technologies on the horizon are no different. These benefits can be realised in both the short and long term and stretch far beyond the bounds of specific industry sectors. There is also a pressing need to expedite solutions for increasingly intricate societal, macroeconomic, and environmental challenges on a global level. This urgency spans various domains, such as the discovery of novel therapeutics with mitigation of financial risks, addressing the climate crisis and the restructuring of supply chains. It is likely that quantum technologies will play a key role in addressing these global issues. According to CSIRO's economic modelling, it is estimated that Australia's quantum technology opportunity in revenue terms could conservatively reach $2.2 billion by 2030 and is projected to contribute $6 billion to GDP by 2045[1].

Advancing artificial intelligence and cybersecurity through quantum

The rapid adoption of Artificial Intelligence (AI) and machine learning by various industries in recent times is a relatable example which demonstrates the value of deploying new technology that can transform businesses. Upon closer observation, it can be appreciated that early adopters and those companies that were involved in research partnerships have been the biggest beneficiaries of this technology transformation to date which has just started to deliver impact to business processes and day-to-day activities. Likewise, quantum technologies have a key role to play in advancing AI and cybersecurity applications. For instance, AI relies on large datasets of accurate information which can be collected with high precision and processed faster with the deployment of quantum technologies.

Industries should become 'Quantum Ready', to take advantage of the new developments that are inevitable as quantum technologies mature.

In today's context, quantum readiness could be as simple as understanding the opportunities, limitations, and maturity of quantum technologies which vary in their operational principle and application in different environments. It is therefore important for businesses to obtain a fit-for-purpose understanding of the type, scale, and robustness of changes that the application of quantum technologies can bring to their specific industry sector, rather than have a generic overview of the underlying physics. This understanding can then be translated into a tangible strategy that outlines the extent to which a business should allocate resources towards preparing for adoption of quantum technologies.

Such a quantum strategy could include activities that:

INCREASE AWARENESS
about quantum technologies and identify opportunities of its applications to address complex business problems

ESTABLISH PARTNERSHIPS
with quantum experts in industry and academia

ASSESS
the requirement for talent and incremental infrastructure upgrades

UPSKILL THE WORKFORCE
to apply quantum technology to business goals

DEVELOP COMPETITIVE ADVANTAGE
by creating a pipeline of new products and services, or improving current ones, that leverage quantum technologies.

Quantum readiness should not be misconstrued as gaining expertise in complex scientific concepts or investment in capital intensive resources, rather it must encompass an exploratory attitude to attract talent and establish collaborations that will inform investment opportunities specific to the industry opportunity identified. Embracing quantum technologies and developing a strategic approach can position Australian businesses as leaders in this emerging field, reap the benefits that quantum advancements offer and mitigate potential risks to business processes. Developing a pipeline of high-impact projects that incorporate quantum technologies would also appeal to investors, who recognise its potential in transforming industries and creating new markets.

1 Growing Australia's Quantum Technology. 2020, CSIRO.

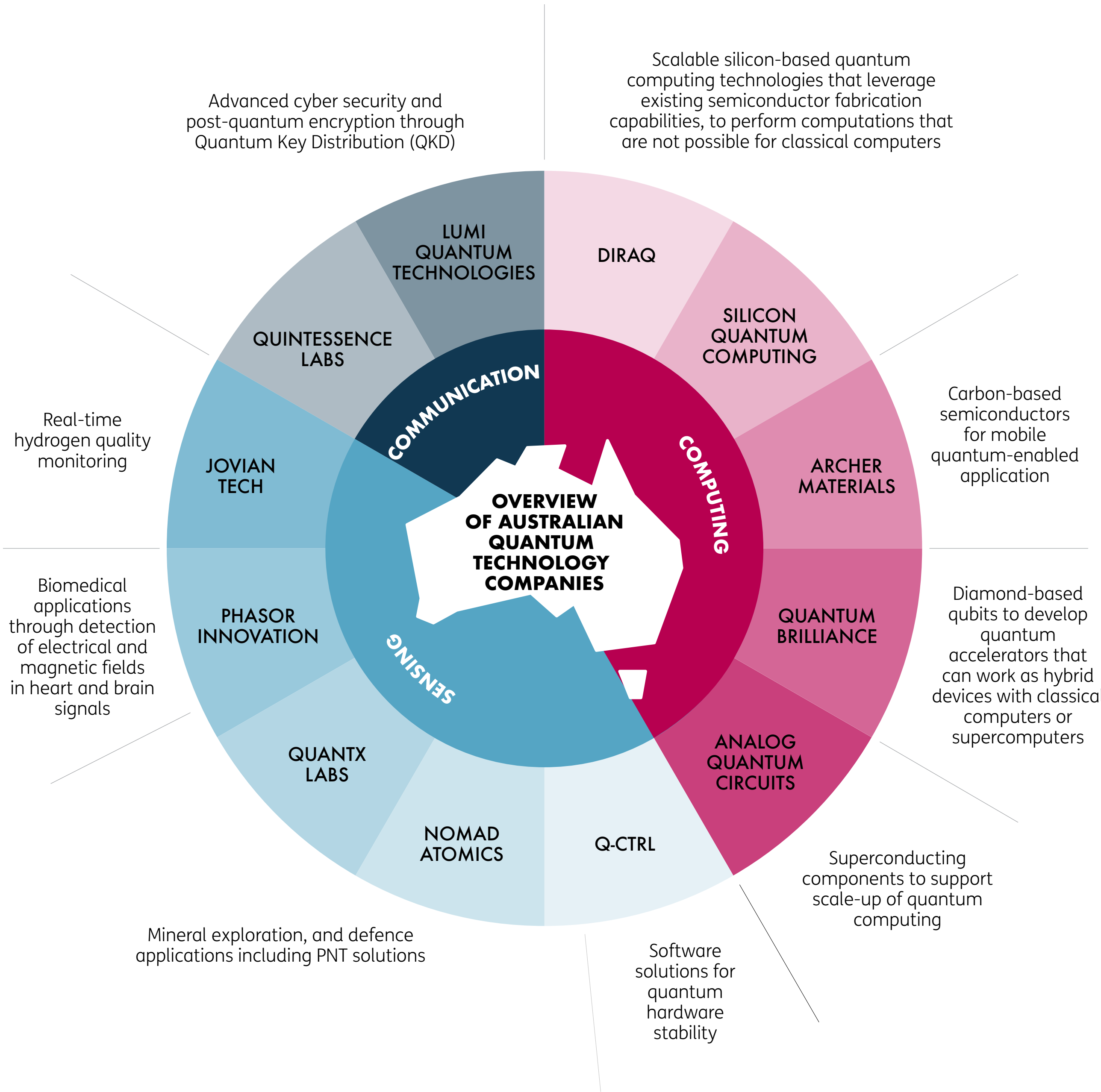
Quantum technologies are at an inflection point and fortunately Australia is home to some of the best minds in quantum research and world-class infrastructure that support fabrication and characterisation of quantum devices. With readily accessible technical resources in our own backyard, Australia's opportunity is immense and can be realised as broader industry adopt these technologies that is supported by a quantum literate workforce. In addition to a strong network of homegrown quantum companies that are industry leaders, we have attracted some of the world's leading companies in quantum to undertake research and development in Australia.

The quantum technologies landscape in Australia is characterised by collaborative innovation and open-access infrastructure that serves as a platform for start-ups, SMEs and large corporations alike, to enable development of quantum applications specific to their industry. It has the potential to create highly skilled jobs, stimulate innovation and 'intrapreneurship', leading to the establishment of a strong talent pipeline. In addition to the economic prospects of onshore development of novel products or service offerings based on quantum technologies, such involvement also aligns with Australia's national priorities. Active participation of Australian industries could therefore bolster sovereign capabilities in quantum technologies as they are adopted to solve problems and provide competitive advantage for Australia on the evolving world stage.

3. APPLICATIONS OF QUANTUM TECHNOLOGY

Quantum technologies can broadly be categorised as sensing, computation, and communications. Among these, quantum computing is still in its early stages of technology development and challenges relating to hardware stability (for minimising error) and scalability (for handling complex problems) are being addressed before real-world applications could be achieved. Technologies that drive the second quantum revolution involve the manipulation and control of individual quantum systems, such as atoms, photons, and electrons which are highly sensitive to environmental factors. In the case of quantum computing such sensitivity causes hardware instability, and scalability under such circumstances does not allow applications to perform with precision and efficiency. Whereas, in the case of quantum sensing such hardware instability is turned from liability into asset and presents opportunities to implement measures for improving sensor performance by exquisitely detecting background interference.

To emphasise the growing wealth of expertise in this ecosystem, and as a reasonable initiation towards quantum readiness, the following sections provide examples of Australian businesses that are leading the world in the application of quantum technologies. While the emergence of practical applications is discussed under quantum sensing and quantum communication, the section concerning quantum computing delves into various approaches of achieving information processing using quantum systems which is an important factor in considering industry specific applications.



3.1 QUANTUM SENSING

Quantum sensors are touted as the quantum technology application that could start a revolution if they are properly deployed. It is also one of the quantum technologies that has demonstrated proof of concept in laboratory, currently ready for industry evaluation in field applications and is anticipated to attain full-scale commercialisation in the next five to seven years. Several Australian companies are already engaging with potential end-users of this technology for field deployment to bring transformative changes to sectors such as mining, clean energy, biomedical imaging, defence, and space. Quantum sensors enable measurement of magnetic fields, rotation, gravity, acceleration, and time with significantly higher precision in comparison to existing systems that are engineered based on chemical or electrical signals. They operate by exploiting the interaction of atoms and light, and the extreme sensitivity of the quantum state of particles to their environment. In the rest of this section applications of molecular sensors, gravimeters, gyroscopes, and magnetometers will be discussed.

3.1.1. Supporting decarbonisation goals with efficiency gains

With governments around the globe setting decarbonisation goals, technologies are being explored to progress towards a net zero future. Hydrogen has emerged as one of the most promising energy carriers that does not have any polluting emissions depending on its production method. However, producing hydrogen at large scale and transporting it to market requires advanced instrumentation to reduce costs and improve safety. Hydrogen exists as two spin-isomers at a molecular level known as *ortho*- and *para*-hydrogen, the ratios of which vary with changes in temperature which affects the thermophysical properties of molecular hydrogen.

For effective use and storage of hydrogen as a fuel, it is important to ensure the optimal ratios of hydrogen isomers and purity is maintained throughout all stages of hydrogen production. Existing methods to monitor these parameters are expensive, time consuming and labour intensive, requiring samples from every batch to be tested in a laboratory to ensure quality specifications. Based on a quantum technology that can sense spin states of hydrogen molecules developed at The University of Western Australia, Jovian Tech has developed cutting-edge instrumentation for the hydrogen energy sector that provides direct and real-time analysis of *ortho* and *para*-hydrogen, in addition to detecting trace impurities in hydrogen stream.

This monitoring plays a critical role in hydrogen production including process optimisation, metering, storage and utilisation. This technology empowers chemical engineers with information to optimise hydrogen production plant operations and lower costs in the hydrogen economy.

In another aspect of decarbonisation, the increasing demand for critical minerals required for electrification and power generation imposes a severe strain on the efficiency and productivity of the mining sector. There is also a growing consensus that the mining industry should aim to reduce the environmental impact of surface mining, ensure safety in underground mining, and improve operational efficiencies. Nomad Atomics, a start-up founded by researchers from the Australian National University, has developed a cold-atom gravimeter which is a quantum sensor that offers real-time measurement of absolute gravity that enables monitoring of mass changes in sub-surface or underground conditions.

This device can be used by resources companies to explore for deeper and smaller mineral deposits, or for more efficient and safer production from underground mines. The technology is also considerably smaller than existing gravimeters, which extends the applicability in field applications. Apart from supporting the resource exploration sector, Nomad Atomics is also looking to develop their technology in carbon dioxide sequestration, land and groundwater management and next generation navigation.

Team Nomad in a customer's underground mine.
Source: Blackbird.vc

3.1.2. Navigation systems for GPS denied environments

Positioning, Navigation, and Timing (PNT) solutions are an indispensable aspect of logistics, telecommunication systems, defence, and exploration activities. Current terrestrial requirements for determining position and direction heavily rely on satellite-based navigation such as the Global Navigation Satellite System (GNSS). Such reliance on GNSS is widely recognised as a vulnerability as their low-powered, unencrypted signals are susceptible to both intentional (jamming and spoofing) and unintentional (equipment failure or effect of cosmic phenomena such as solar emissions) disruption.

Typically, in situations where GNSS is unavailable, Inertial Navigations Systems (INS) are used to perform dead reckoning, a process used to calculate the position of a moving object using a previously determined position by incorporating estimated speed, direction, and time. INS use classical sensors such as accelerometers (motion sensors) and gyroscopes (rotation sensors) which are prone to errors in dead reckoning that affect the accuracy of estimated position that accumulate over time, resulting in loss of position. In circumstances where GNSS is denied such as undersea, underground and outer space navigation applications, high accuracy dead-reckoning can be invaluable and can open new possibilities.

Advanced Navigation, a global leader in ultra-precise, AI-enabled navigation hardware, develops products and custom navigation technologies for sea, land, air, and space. Advanced Navigation has partnered with Q-CTRL (a spin-out from the University of Sydney) in exploring a new research area of applying quantum sensor technology for navigation in dynamic environments. The partnership leveraged Q-CTRL's expertise in optimising quantum hardware and harnessing the extreme sensitivity of quantum sensors to develop a new kind of INS, which is currently the size of a standard refrigerator, using a digital fibre-optic gyroscope as a classical-quantum fused sensor for space exploration in the NASA Moon to Mars mission.

As this technology is refined and gets widely adopted for applications in other sectors, the SWaP-C (size, weight, power consumption and cost) is likely to reduce to the extent where the size will be less than one quarter of its current size. The potential for this technology will enable continued precise navigation without requiring recalibration or correction using external references such as satellites, magnetic fields, base stations, or stars. This represents an enormous step change in INS that will be revolutionary in applications sensitive to GNSS spoofing/jamming and those that rely on long-term inertial navigation where GNSS is denied.

Quantum sensing device.
Source: Q-CTRL

Recently, Q-CTRL and Australia's Department of Defence announced a partnership to develop quantum sensors that will deliver the ability for vehicles to position accurately over long periods when GPS is unavailable or untrustworthy, opening new frontiers for defence operations. This further emphasises the ability for quantum sensors to make a real-world impact in the short term and demonstrates the development of home-grown technology into sovereign capability. Additionally, it also positions Australia as a strong peer among our closest technology-sharing partners in defence such as the US and UK.

> **"Defence recognises that quantum sensing has the potential to fundamentally transform Defence capability. Partnerships of this kind demonstrate our capacity to translate innovative concepts into capability, delivered by a world-class Australian deep-tech company."**
>
> Emily Hilder, Interim Head
> Advanced Strategic Capabilities Accelerator

3.1.3. Detecting movement and object detection in inaccessible locations

Quantum magnetometers such as directional magnetic field sensors are also emerging as an alternate solution for navigation in GNSS signal denied environments. Phasor Innovation, in partnership with academics from the University of Melbourne and RMIT University, has developed a quantum diamond magnetometer that can sense the direction and strength of Earth's magnetic field to create a 'magnetic map' for navigation without the need for GNSS. These diamond-based quantum sensors are created by disrupting the orderly crystal lattice arrangement of carbon atoms with nitrogen atoms, resulting in a nitrogen-vacancy centre. This enables these sensors to operate at room temperature in ambient unshielded conditions and the magnetic field sensors are stable over time. In the context of medical science, the sensitivity of vector magnetometer technology allows detection of far smaller electrical and magnetic fields which can be translated to clinically relevant applications to sense heart and brain signals.

Another compact ultra-high performance quantum magnetometer system is being developed by QuantX Labs, in collaboration with the University of Adelaide. The technique used in their systems involves controlling and reading out the quantum states of rubidium atoms in a vapour cell using a frequency tuned laser diode. The device provides extreme magnetic field sensing that can be used in defence applications in detection of submarines, underwater mines, underground tunnels, munitions, buried IEDs and space applications such as geospatial intelligence and mineral exploration. QuantX Labs is also known for the development of a Cryogenic Sapphire Oscillator or Cryoclock – the world's most precise clock delivering microwave and radio-frequency signals in a reliable and autonomous package that has applications in quantum computing and advanced PNT capabilities. While QuantX Labs now work closely with the University of Adelaide to commercialise their research, some of their technology was initially developed at the University of Western Australia. Building on the success of the Cryoclock, a recent $750,000 funding from Australia's Department of Defence will support the development of a secure and resilient PNT system for defence applications, and synchronisation of two Cryoclocks which is critical for new radar architecture.

3.2. QUANTUM COMPUTING

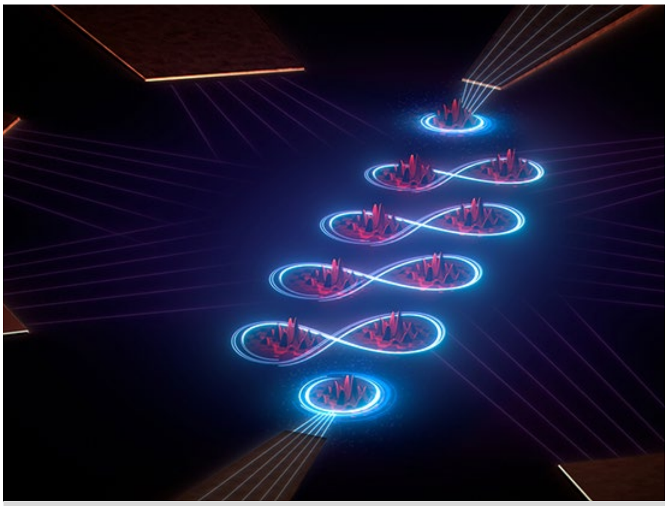
While still in the early stages, quantum computing holds promise for solving problems that are intractable for classical computers, offering transformative capabilities across multiple industries and scientific disciplines. This is due to the fundamental distinction in the way information is processed by quantum computers, which is in qubits (quantum bits) which can be both 0 *and* 1 at the same time, whereas classical computing represents bits as either as 0s *or* 1s. This leads to an exponential rise in the number of calculations that can be performed in a given time using the same number of (qu)bits. Industries will witness new opportunities for gaining an edge as progress in quantum-enabled hardware, software, and algorithms aligns and results in substantial performance gains over classical computing. While the full potential of quantum computing may not be realised in the near term, there are already valuable demonstrations of its power in place.

> **"Given the transformational nature of this type of computing, not pursuing it is a bet that industry can't afford not to make."**
> Jeremy O'Brien, Co-Founder and CEO PsiQuantum

3.2.1. Leveraging semiconductor infrastructure to scale silicon-based qubit technology

In healthcare and biotech, quantum computing can accelerate drug discovery by simulating molecular interactions and optimise patient care by analysing large datasets to enable healthcare professionals to improve accuracy of prediction in treatment outcomes. In 2022, Silicon Quantum Computing (SQC) gained recognition for their world's first quantum integrated circuit manufactured at the atomic scale. This quantum chip was operated as an analogue quantum processor to simulate a well-understood molecule, polyacetylene. Development of this capability to its full potential could provide opportunities to develop new treatments for various diseases. SQC was Australia's first quantum computing company pioneering a globally unique atom-based manufacturing technology to build a commercial-scale quantum computer.

SQC is a spin-out company from the University of NSW (UNSW) that manufactures all its devices in a dedicated on-site atomic-scale fabrication line developed over the past 20 years, leveraging approximately $150 million worth of infrastructure at UNSW. The company aims to double their operations by 2028 to deliver a 100-qubit quantum processor and aims to develop an error corrected quantum computer by 2033 that can demonstrate useful solutions across various industry sectors. SQC aims to apply the current quantum processing capabilities to solve problems in material science which can translate to near-term, real-world impacts. This will be done in parallel to the development of the hardware and software needed to fully realise the potential of their system.



Simulation of polyacetylene molecule using world's first quantum integrated circuit.
Source: Silicon Quantum Computing

In the finance sector, quantum computing has the potential to enhance security and fraud detection, as well as enable faster transaction processing and risk assessment. Commonwealth Bank of Australia and Telstra Corporation are shareholders in SQC and have been industry partners in the ARC Centre of Excellence for Quantum Computing and Communication Technologies (CQC2T) since its inception in 2014. This demonstrates the forward-thinking nature of leading Australian businesses eager to explore the potential of quantum computing and associated technologies.

It is believed that at least one million qubits are required to achieve a useful quantum computing application; however, maintaining the integrity of the quantum information as it is stored and processed remains a significant industry challenge when scaling up. Diraq, the most recent quantum spin-out from UNSW, is a world leader in building quantum processors using electron spins in Complementary Metal-Oxide Semiconductor (CMOS) quantum dots. Diraq's technology is based on controlling electron movement and its spin state using radio-frequency pulses, where individual electrons are trapped in devices made using the most advanced semiconductor fabrication technology. The electron spin state, whether up or down, will represent a qubit in the 0 or 1 state. By integrating a large number of transistors on one chip, Diraq hopes to minimise the infrastructure that is currently needed to run a quantum computer, making it more efficient, and more accessible.

While the company was formally established in 2022, Diraq's technology is being built on a family of patents filed since 2014 which enables Diraq to manufacture at scale using existing silicon chip manufacturing facilities. According to Diraq's technology roadmap, a one million qubit quantum hardware chip can be expected by the end of this decade.

3.2.2. Approaches for quantum computing at room temperature

One of the major hurdles in scaling up quantum computing is the need for large cooling systems that are required to ensure the stability of quantum state in order to reduce errors. This not only results in increased power consumption but also makes it difficult to deploy the devices in field applications. By harnessing the properties of Nitrogen-Vacancy (NV) centres, which are a defect in the diamond crystal lattice, long electron spin coherence time (up to one millisecond) can be achieved at room temperature, or in lay terms, more stable qubits at room temperature. Quantum computing established through this phenomenon is controlled via radio frequency, microwave, optical and magnetic fields, where clusters of nitrogen and carbon-13 act as the qubit and the NV centre acts as the quantum bus that mediates readout from qubits and permits their interoperability.

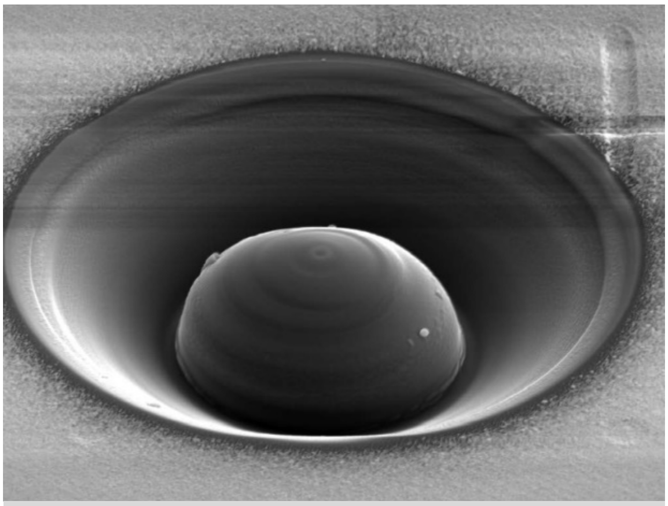
CASE STUDY:
ENHANCING THE EFFICIENCY OF GREEN HYDROGEN PRODUCTION

As our ability to make more powerful devices by linking more qubits improves, quantum computing could unlock breakthroughs in material science, climate modelling, and optimisation of energy systems through efficient grid management. The membership agreement between Fortescue Future Industries and Qlimate is a great example of a partnership that set out to explore quantum solutions in the field of green hydrogen. Qlimate is an initiative by an Australian-led company PsiQuantum that is building the world's first fault-tolerant quantum computer. Joining Qlimate is the initial stage in FFI's broader strategy to create algorithms that address computational limitations in modelling Proton Exchange Membrane (PEM) technology and pulse electrolysis. These technologies are crucial for enhancing the efficiency of green hydrogen production. FFI aims to leverage quantum computing to develop and expand green hydrogen ventures, thereby contributing to a more sustainable future.

While German researchers pioneered this technology for various quantum applications, it could not be scaled beyond a handful of qubits due to challenges with precise fabrication of NV centre arrays that are separated by a few nanometres. Quantum Brilliance, an Australian-German startup that was spun out of the Australian National University in 2019, is overcoming this barrier to scaleup by deploying atomically-precise fabrication methods based on designer surface chemistry and lithography. This technique draws inspiration from similar techniques used for silicon that were pioneered in Australia.

Quantum Brilliance has also invented chip-scale microprocessors that miniaturises and integrates electrical, optical, and magnetic control systems of diamond-based quantum computers. Collectively, this enables simultaneous scaling-up of qubits with scaling-down of total size, weight and energy requirements of diamond-based quantum computers, leading to the development of quantum accelerators which can be used in parallel with classical computers. By 2025, Quantum Brilliance plans to launch their 50-qubit quantum accelerator which promises a leap forward in the simulation of Molecular Dynamics (MD), and signal and image processing for autonomous and intelligent technologies in edge computing. MD simulations have applications that include drug design, chemical synthesis, and energy storage where structure, conformations, and interactions with solid interfaces of biomolecules are studied.

In another approach to process quantum information without the requirement for extremely low temperature systems, Archer Materials is developing qubits using a carbon-based semiconductor. The material dubbed a nano-onion, is a round graphite-based nanoparticle with an onion-like shell structure approximately 50 nanometres in diameter. This forms the basis for their flagship 12CQ qubit chip architecture where qubit states are defined by the spin state of electrons that are spread over these carbon spheres. The stability of the qubits demonstrated was sufficient for operating quantum logic calculations at room temperature. Archer Materials is an ASX listed company (ASX: AXE), that has patented the 12CQ quantum chip across several jurisdictions in the world including Australia, US, UK, South Korea, Japan, France and Germany. Archer recently announced that their qubit material has been engineered to mimic a high-vacuum environment that enables quantum functionality in air (rather than vacuum).



Micro-optic half-sphere structure on diamond that provide higher-fidelity readout from qubits.
Source: Quantum Brilliance

This approach has the potential for technology translation to industrially scale 12CQ qubit chip architecture using standard semiconductor foundry methods. The aim of Archer's revolutionary 12CQ chip technology is to develop this novel material into a viable qubit architecture that will allow for mobile quantum-enabled applications capable of operating at room temperature and make them available for everyday electronics.

3.2.3. Achieving practical applications from quantum computing

Despite the significant breakthroughs achieved across various quantum architecture and candidate materials, the development of industry-specific solutions using quantum computing is plagued by hardware instability. The quantum state of particles, the foundation of all quantum technologies, is susceptible to various forms of interference such as electromagnetic signals, earth's magnetic field or vibrations from the environment which are broadly described as 'noise'; these result in the loss of quantum coherence (stability). This means that an algorithm performing multiple operations across a large number of qubits in a noise prone environment can lead to an erroneous output. It is therefore paramount that problems relating to noise and error are addressed to maximise hardware efficiency in leading towards 'Quantum Advantage' where a quantum computer can perform a particular computation significantly faster or efficiently than even the best classical computer.

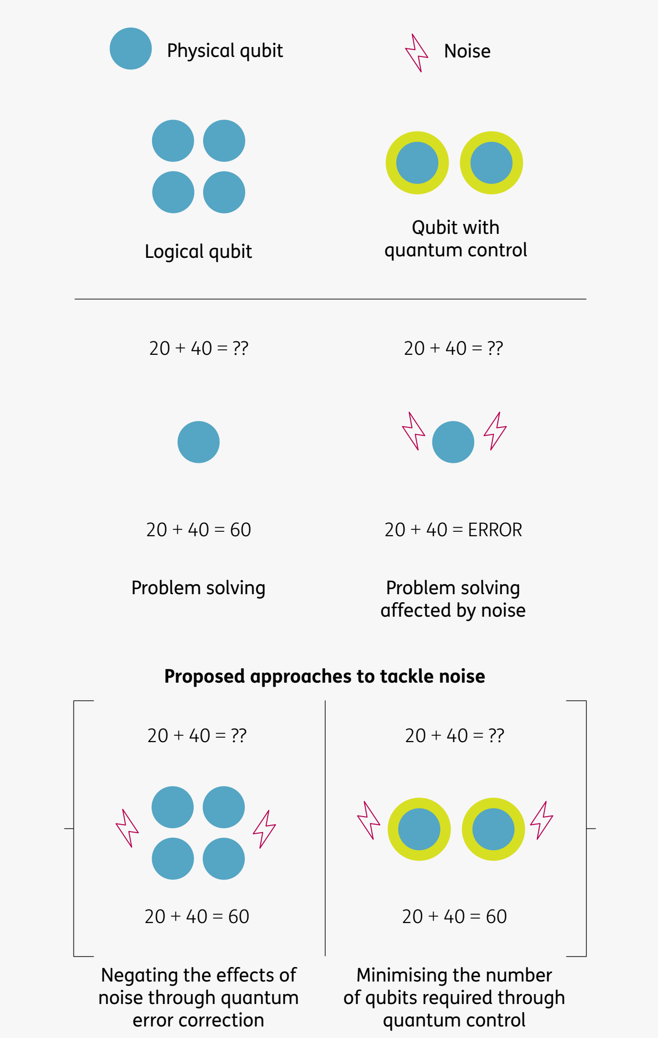
The current state (as of 2024) of quantum computing characterised by size-limited and error-prone hardware is referred as the Noisy Intermediate-Scale Quantum (NISQ) era. Development of sophisticated algorithms including quantum error correction has identified complex problems that could potentially be solved using NISQ machines, which has increased the likelihood of achieving Quantum Advantage without waiting for the arrival of fault-tolerant quantum computers (Quantum Era).

In summary, quantum computers have the potential to positively impact various sectors irrespective of the approach taken towards the fabrication and scale-up of qubits, and the time is now ripe to establish collaborative partnerships with quantum technology companies to turn this potential into industry improving solutions.

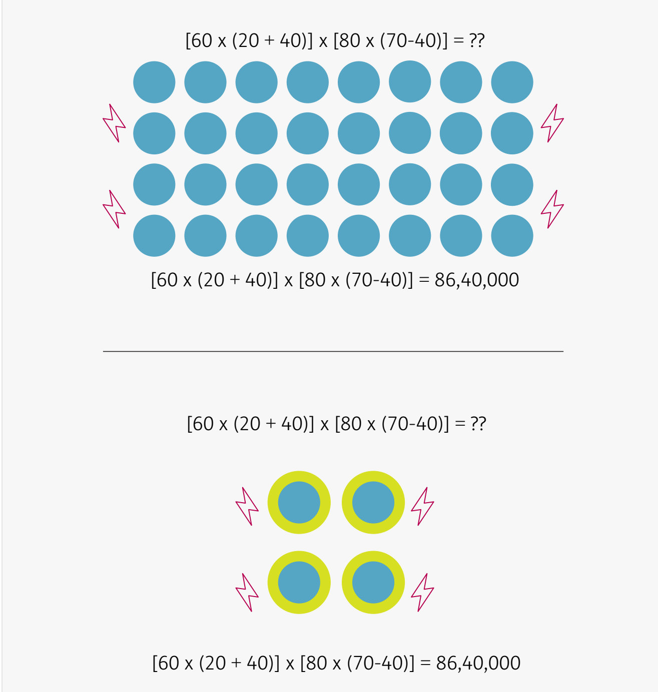
QUANTUM ERROR CORRECTION AND QUANTUM CONTROL

Quantum Error Correction (QEC) is an algorithm developed from validated mathematical approaches used for classical devices that are deployed in extreme environments where the likelihood of errors is high. QEC implementation is a possible way to negate the effects of noise and fix errors in quantum computing. QEC operates by distributing quantum information stored in a single qubit across other supporting qubits to protect the integrity of the original information, to form a logical qubit. As a result, the number of physical qubits required to perform a computational task increases proportional to the noise, which in turn scales up the need for logical qubits with increasing complexity of problems being solved. However, deploying QEC alone as the solution for hardware stability could be resource intensive and challenging for scalability.

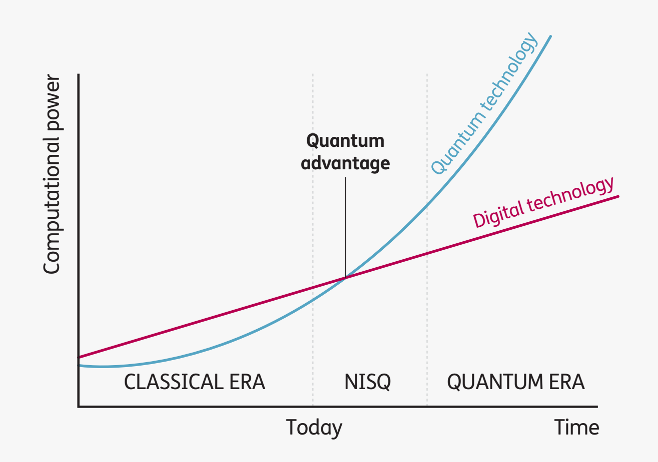
A promising approach is the development of a 'quantum control' firmware which can stabilise qubits against noise and decoherence which in combination with QEC algorithm can reduce the need for additional qubits required to perform useful quantum computation. Quantum control is a discipline that is concerned with the manipulation of quantum devices to create desired behaviours when they interact with external environments. Quantum control permits a form of "error virtualization" which allows the manipulation of the hardware's error properties before applying QEC encoding. This leads to several benefits such as lower error rates, more consistent errors across devices, more stable hardware against slow changes, and more suitable error statistics for QEC assumptions.



Role of QEC and quantum control in addressing noise and reducing the number of physical qubits required.



Benefit of quantum control for solving larger-scale problems. As the problem size increases, quantum control requires fewer logical qubits than QEC.



Quantum advantage in NISQ era implies some problems are better solved by quantum than classical computing.
Source: Black Opal, Q-CTRL

3.3. QUANTUM COMMUNICATION

Quantum Communication enables the transfer of qubits between quantum devices and establishment of secure communication networks, which is a crucial infrastructure requirement as other quantum technologies mature. Application of quantum communications can extend from establishing a resilient cryptographic system which is available today in the form of Quantum Key Distribution (QKD), to the development of highly secure Quantum Internet (QIN).

With increasing dependence on technology for critical business processes and increasing sophistication of cyberattacks, robust cybersecurity protocols are paramount for most organisations worldwide to protect against threats to national security, financial and personal data. As qubit fabrication scales-up, the subsequent development of a Cryptographically Relevant Quantum Computer (CRQC) will render most contemporary public key cryptography (based on large prime numbers) insecure. Combined with rapidly improving artificial intelligence and machine learning capabilities, the threat of CRQC decrypting sensitive data is more imminent than ever. This also applies to previously harvested and stored public key encrypted data, that can be decrypted when quantum computing becomes accessible.

3.3.1. Quantum Key Distribution (QKD) as a means to advanced cybersecurity

Secure quantum communication systems such as QKD are deployable today. It uses the quantum properties of light (photons) to generate and share secure random keys for encrypting and decrypting data, rather than mathematics. QKD is a point-to-point protocol that uses specialised hardware where information is transmitted over an optical link. QKD can detect and mitigate eavesdropping attacks, and the data transmitted with QKD-protection are unlikely to be intercepted or decrypted by adversaries.

There are two main approaches to QKD that leverage the wave or particle characteristics of the quantum information carrier, e.g. light photons. When information can be encoded onto the amplitude and phase characteristics of a laser and measured with relevant detectors, it is known as Continuous Variable QKD (CV-QKD). Quintessence Labs (QLabs), a spin-off company from The Australian National University and currently headquartered in Canberra, is a global leader in quantum cybersecurity and a frontrunner in the development of QKD technology. QLabs' quantum safe cryptography solution integrates a CV-QKD device as part of their full technology solution that generates, shares and manages encryption keys. The architecture is compatible with current telecommunication encoding, transmission and detection techniques, and provides the ability to use standard fibre connections as well as allowing daylight operation over free space optical link. Realising the potential of QKD and associated technologies, Westpac Banking Corporation has invested in QLabs.

Another approach to QKD is known as Discrete Variable (DV-QKD), where information can be encoded in the physical properties of single-photons and measured with single-photon detectors. An emerging start-up called Lumi Quantum Technologies (LQT), which was initially supported through the Defence Innovation Network, is developing Australia's first QKD device that uses a hexagonal Boron Nitride (hBN) crystal lattice as the single photon emitter. They are also part of the research team at the University of Technology, Sydney that discovered the first quantum emitters in 2D materials that operate at room temperature based on defects in hBN. LQT demonstrated that single photons emitted from hBN source could be detected in sunlight, opening the potential for establishing long distance secure quantum communication networks, which is particularly useful in defence and space technology applications.

TACKLING CYBERSECURITY IN THE QUANTUM ERA

As a measure to address the threat posed by quantum computing, Cybersecurity & Infrastructure Security Agency (CISA) of the US Government established a Post Quantum Cryptography (PQC) initiative. PQC, also known as quantum resistant cryptography, refers to new cryptographic algorithms to create encryption keys that are not based on the integer factorisation or discrete logarithm problems. PQC uses complex mathematics that is considered difficult for both classical and quantum computers which can interoperate with existing communications protocols and networks. While PQC is recognised as a low-cost practical path to maintaining the properties of secure communications in the context of a CRQC, its algorithms have not yet been standardised or subjected to scrutiny to the level of public key cryptography. It is anticipated that the National Institute of Standards and Technology (NIST) will publish PQC standards in 2024. PQC is being closely monitored by the Australian Signals Directorate (ASD) to evaluate the parameters for PQC standardisation efforts to deliver updates to ASD-Approved Cryptographic Algorithms. ASD will also continue to monitor alternate methods of securing communications in the presence of a CRQC, such as QKD.

Quantum communication technologies are still in their early stages. Current opportunities exist for developing hardware required for building the Quantum Internet, such as quantum repeaters that can boost qubit strength during transit and hardware that supports quantum teleportation where the quantum state of particles is inferred between locations, without the particle being transmitted. Embracing quantum communication systems is likely to become a necessity in the near term, as safeguarding sensitive information and protecting critical infrastructure from cyber threats is paramount for ensuring a secure digital future for all.

4. GROWTH OF THE AUSTRALIAN QUANTUM SUPPLY CHAIN

Quantum technologies have come a long way from being considered a theoretical concept to demonstrating quantum phenomena that can be harnessed for real-world applications. As a result, this has led to the emergence of start-ups that create innovative technologies to boost the quantum sector. It has also opened up new possibilities for collaboration among businesses in quantum-related fields to develop products or services that will support a sustainable quantum economy.

4.1. LEVERAGING INDUSTRY PARTNERSHIPS TO CREATE NEW SOLUTIONS

Quantum control is an area that is being advanced by Q-CTRL by providing specialised resources for both quantum technology end users and hardware manufacturers to improve performance of quantum processors. Q-CTRL plays an important role in sustaining the growth of the quantum ecosystem through partnerships both in Australia and internationally. It focuses on developing software-based methodologies that not only enable useful field applications of quantum technologies for diverse industry sectors, but also provide a significant performance boost to quantum sensors and quantum computers. For example, Q-CTRL has integrated its error suppression technology into IBM's Quantum Services. While this integration benefits end-users of quantum computing by improving the reliability of results obtained from algorithms processed through NISQ hardware, it is also a demonstration of the role played by an Australian startup in the international supply chain.

In the near term, integration of quantum algorithms within machine learning programs presents the opportunity to feed classical data sets into a quantum computer to make quantum information processing accessible. These quantum machine learning algorithms have been demonstrated on small-scale or special purpose quantum devices where the problems or desired outcomes have been clearly articulated. Aqacia is a machine learning start-up that provides state-of-the-art AI solutions to complex quantum and classical problems. It uses a neural network-based technology capable of simultaneously optimising up to thousands of parameters in complex processes, which can be configured for deep learning for pattern recognition.

Aqacia plans to harness powerful deep learning approaches to enable and accelerate quantum technologies and is pioneering applications for key industries such as wind power generation and in quantum computation and quantum communication. Aqacia is also one the companies that has connections with CQC2T, and their services are being procured by SQC downstream of their hardware to develop machine learning tools focused on accelerating quantum computing chip development.

Similarly, Diraq's partnership with Perceptia Devices, enabled through Cooperative Research Centres Project grant funding, reinforces the need for businesses to work closely with quantum technology companies to create and strengthen the local supply chain in this sector. Perceptia Devices is a design services provider focused on high-speed and ultra-low-power mixed-signal semiconductor designs. This project will focus on developing a cryogenic Quantum Control Unit (QCU) which will integrate with Diraq's Quantum Logic Unit (QLU) to create a truly scalable Quantum Processing Unit (QPU).

As quantum technologies mature, the need for high-speed signal processing capabilities will play an increasingly vital role in the development of error corrected quantum systems and design of practical algorithms. In the case of solid-state quantum computers high performance electronics such as amplifiers, attenuators, circulators are critical to send and receive signals. As quantum technologies scale, there will be an increasing need for integrating these devices on-chip. Analog Quantum Circuits (AQC) is developing a fabrication process that shrinks the footprint of the critical, micro-electronic superconducting components needed to build large-scale quantum computers by a factor of one million which will support development of smaller and more efficient quantum computers. AQC is the first Australian quantum technology company based in Queensland, and the first superconducting quantum technology hardware startup in Australia. AQC is based on research in superconducting microwave devices, which was supported by the Australian Research Council through Future Fellowships and the ARC Centre of Excellence in Engineered Quantum Systems (EQUS).

4.2. NEW CUSTOMER SEGMENT FOR ADVANCED MANUFACTURERS

Manufacturers with niche capabilities have a unique opportunity to capitalise on the growth of the local quantum ecosystem and become a part of the global supply chain for the sector. For example, Lintek established an Australian-based precision manufacturing capability that specialises in producing microwave and high frequency printed circuit boards backed by their innovative, patented, high vacuum deposition process. By eliminating the typical process of etching thick copper, Lintek can produce boards with highly accurate features and predictable impedance characteristics. Consequently, this process produces structures that are highly advantageous in radio frequency and microwave circuit manufacturing as they closely resemble original design simulations.

Such capability can play a key role in developing quantum architectures for high-speed signal processing required for quantum computing and quantum control. Similarly, capabilities in precision micromachining are also known to support the fabrication of components required for quantum computing. NH Micro presents an interesting example where their in-house capabilities used in watch making for their parent company Nicholas Hacko could also support the fabrication of waveguides for quantum circuits.

Bluglass (ASX:BLG) and Redback Systems, spin-out companies from Macquarie University, have found applications for their products in the development of quantum technologies. Bluglass manufactures Gallium Nitride (GaN) laser diodes using their proprietary Remote Plasma Chemical Vapour Deposition (RPCVD) manufacturing technology that is typically used to develop biomedical, robotics and display technologies but are now being considered for development of novel quantum sensing applications. Whereas the high-resolution spectrometers manufactured by Redback Systems are finding use in characterising the wavelength of single photon sources used in full stack photonic quantum computers.

As highlighted throughout this paper, the Australian research ecosystem has been the key enabling factor for the rise of a quantum industry in our country. Supported by such a strong bedrock, Australia has also been at the forefront in this field by offering academic programs in quantum technologies and has therefore positioned itself as a leader in generating a highly skilled, quantum-literate workforce that is paramount for the industry to flourish. Consequently, the wealth of research expertise and access to talent has attracted other leading global quantum technology companies to Australia. Some of these companies are Rigetti, Infleqtion, Quantum Motion, and technology giants including Google, Microsoft and IBM who are working on their proprietary quantum technology. This also opens the opportunity for Australian manufacturers to work with international companies to develop solutions that could be tested locally in Australia, with the potential to scale globally.

5. FOUNDATIONS OF THE AUSTRALIAN QUANTUM INDUSTRY

When it comes to developments in quantum technologies, Australian researchers are globally renowned for making breakthroughs in the field; Australia is often referred to as a country that punches above its weight. Such technological prowess has positioned Australia as an indispensable partner among its allies, as the benefits of quantum technologies are being realised. The success so far could be attributed to the Australian Government's sustained investment in early-stage and forward-thinking research over the past few decades that built national capacity through focus on expertise, infrastructure, and workforce that support the development of quantum technologies.

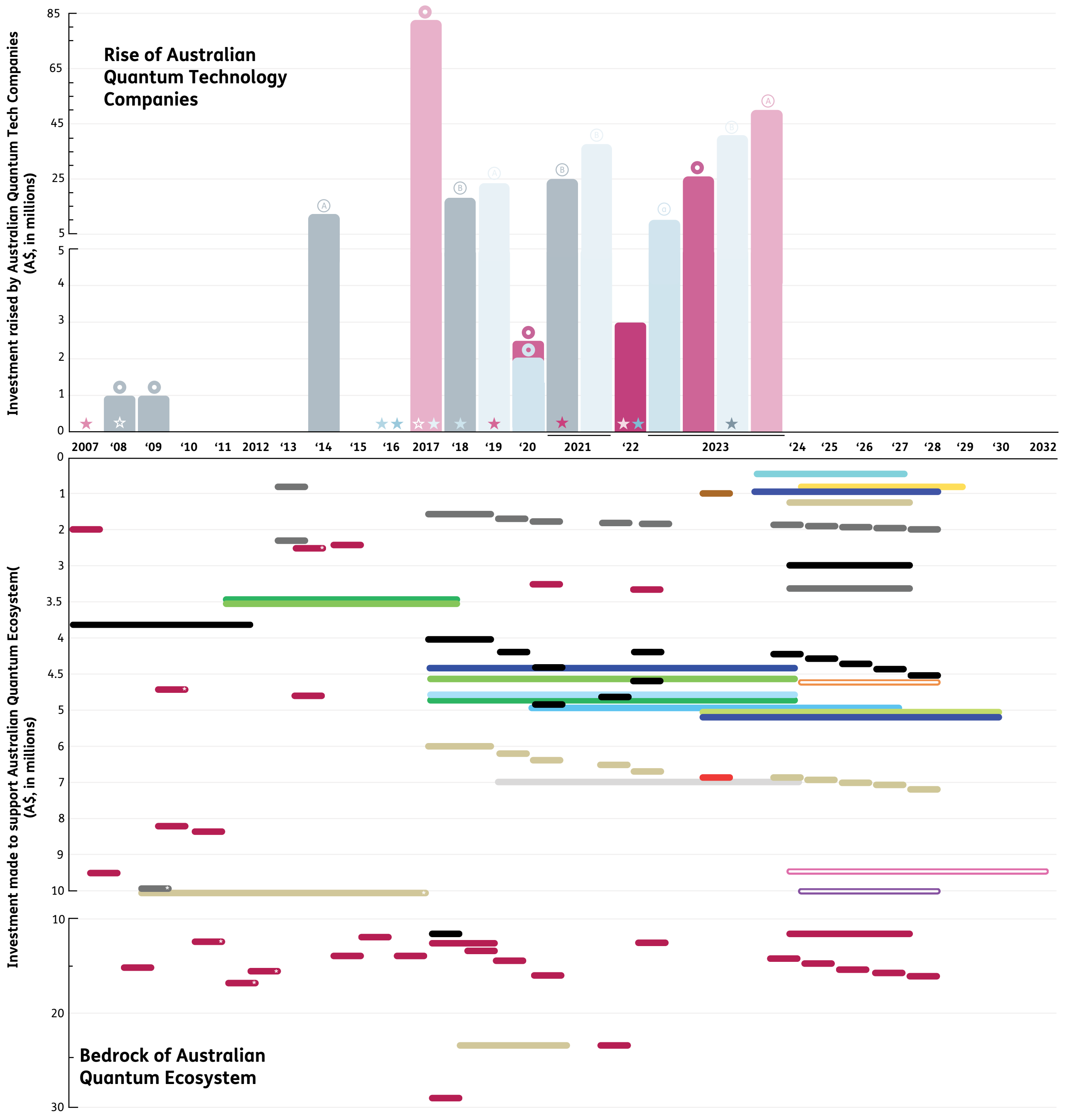
5.1. NURTURING A GENERATION OF TALENT WITH VISIONARY INVESTMENTS

The initial groundwork for research in quantum technologies was laid through funding programs awarded by the Australian Research Council (ARC) that supported research activities at our universities through the establishment of Centres of Excellence (CoE) such as CQC2T and EQUS. These CoE played a vital role in demonstrating fundamental concepts in quantum theories that are now critical for developing commercial applications, some of which are now led by start-ups spun out of these centres. More recently established CoE such as Future Low-Energy Electronics Technologies (FLEET), Transformative Meta-Optical Systems (TMOS), Gravitational Wave Discovery (OzGrav) and Quantum Biotechnology (QuBIC) are taking the next steps in developing novel applications that take advantage of principles driven by quantum technologies and are capable of transforming their respective industry sectors (Appendix 2).

In parallel, since 2007 the Australian Government has been making significant investments toward establishing open-access research infrastructure through the National Collaborative Research Infrastructure Strategy (NCRIS). Among NCRIS projects, the Australian National Fabrication Facility (ANFF), Heavy Ion Accelerators (HIA), Microscopy Australia, and Pawsey Supercomputing Research Centre (Pawsey) have been instrumental in providing access to critical infrastructure and equipment to researchers from both academia and industry (Appendix 3). The shared use of these capital-intensive facilities has catered to a diverse range of research projects, allowing experimentation with various materials and processes that would otherwise not have been possible or been limited to specific groups of users. By providing access to facilities and expertise for prospective users and reducing the timeframe involved in establishing such facilities, this approach has not only maximised the return on investment from these capabilities but also paved way for accelerating the process of developing some of the most promising quantum technologies. For example, prior to launching Diraq, its founder Prof. Andrew Dzurak's research group created the first SiMOS quantum computing chip with ANFF providing crucial input. In particular, the capability to grow high-quality silicon dioxide in high temperature furnaces plus access to nanometre-precision electron beam lithography has enabled them to construct world-class qubit devices. In another instance, as an industry user Quantum Brilliance has benefited from the use of HIA facilities towards prototyping of diamond quantum computing devices. As a further advancement, the diamond-based quantum accelerator developed by Quantum Brilliance has been integrated with Pawsey's Setonix supercomputer as the world's first demonstration and test of a hybrid model of quantum and classical computing. These examples are clear demonstrations of how national research infrastructure served as an important springboard for novel technologies to sprout and flourish, while attracting significant investments and creating jobs as they mature in this burgeoning industry sector.

Through both NCRIS and CoE programs, Australian universities have played a vital and indispensable role in growing the quantum ecosystem through their intellectual capital financial contribution, hosting critical research infrastructure, and by serving as a breeding ground for high-quality talent to thrive. For example, a recent announcement by the University of Sydney indicating the establishment of a 'Future Qubit Foundry' is a testament to such sustained investment as it will support both industry and researchers alike[2]. With a $7.4 million investment towards facility expansion, the initiative is aimed at leveraging the university's research leadership in advanced quantum technologies and position itself at the forefront of next-generation design of qubits. Most importantly, investment in such infrastructure is vital to train the quantum workforce needed and confirm Australia's position in the global quantum supply chain.

2 Future Qubit Foundry to keep Australia at the forefront of quantum tech. 2023. University of Sydney



Company Name	Funding Status
Archer Materials	ASX listed
Analog Quantum Circuits	Seed
Nomad Atomics	pre-Series A
Silicon Quantum Computing	Series A
Q-CTRL	Series B
Quantum Brilliance	Seed
Quintessence Labs	Series B
Diraq	Series A, Undisclosed
Jovian Tech	Undisclosed
Lumi Quantum Technologies	Private/Grant funded
Phasor Innovation	Undisclosed
QuantX Labs	Private/Grant funded

Investments directly related to growth of quantum sector

- CoE- CQC2T
- CoE - EQUS
- CoE - QuBIC
- National Quantum Collaboration Initiative
- Australian Quantum Graduates Program
- Australian Quantum Growth Centre
- Quantum Computing Commercialisation Fund
- Sydney Quantum Academy
- Critical Technology Challenges Program
- Qld Quantum & Advanced Technology Strategy
- Industry Doctoral Training Centre - Quantum Tech Applications

Projects that support critical infrastructure and research support for growth of quantum sector

- CoE - OzGrav
- CoE - FLEET
- CoE - TMOS
- Semiconductor Sector Service Bureau
- Australian National Fabrication Facility
- Microscopy Australia
- Heavy Ion Accelerators
- Pawsey Superconducting Centre

Representation of NCRIS investment in lead organisations based on publicly available data. NCRIS Projects are highly collaborative and involve over 400 delivery partnerships. As per the 2023 NCRIS Guidelines, the Lead Organisation is the grantee.

*Funded through Education Investment Fund Super Science Initiative.

Funding awarded
Funding announced

★ Year founded
Ⓐ Series A
ⓞ pre-Series A
● Seed round
Ⓑ Series B

Refer appendices for details about quantum technology companies, Centre of Excellence (CoE) and research infrastructures.

5.2. PIONEERING INNOVATIVE INITIATIVES FOR GROWING THE QUANTUM ECONOMY

In addition to supporting the continued impact of NCRIS facilities, in some cases initiatives at the state government level have made significant contributions to the growth of the local quantum ecosystem. Particularly, the NSW Office of Chief Scientist and Engineer has pioneered initiatives such as the establishment of Sydney Quantum Academy (SQA), Semiconductor Sector Service Bureau (S3B), NSW Smart Sensing Network (NSSN) and the Quantum Computing Commercialisation Fund (QCCF) which are part of a holistic approach for growing the quantum industry. The QCCF offered competitive funding with the objective of progressing quantum computing hardware and software towards commercialisation, and the aim of helping companies move along the TRL scale, increase the technical maturity of their technology, and enable them to attract large-scale private investment. Under QCCF, Diraq, Q-CTRL, and Quantum Brilliance were collectively awarded $6.8 million to accelerate commercialisation of quantum computing project.

While sustained infrastructure investment has been key to the growth of the Australian quantum sector, it also nurtured world-class expertise and the development of a skilled workforce. Several professionals trained in Australia are creating impact around the globe in research and industry positions in the quantum sector. With a vision to grow Australia's quantum economy, organisations such as SQA play a crucial role in establishing collaboration between industry, government, and universities to provide best opportunities for graduates trained in quantum technologies. Along similar lines, the South Australian government has partnered with the state's major universities to establish an Industry Doctoral Training Centre (IDTC) in the application of quantum technologies that will facilitate collaboration between research and business, develop innovations for translation to market, and support greater mobility of graduates between research and industry. This is particularly important for the growth of the quantum sector, as there is significant interest in exploiting the advantages of quantum technologies to specific industry sectors.

On the other hand, S3B has been established to support and grow the semiconductor sector by facilitating access to Electronic Design Automation (EDA) tools, supply chain brokerage, fabrication services, packaging and testing services as a strategic and functional semiconductor market intelligence capability for Australian businesses. Semiconductors and their manufacturing methodologies are a critical enabler for quantum technologies, that are used to create qubits as well as the hardware required to control quantum processes. The above-mentioned capabilities required for development of the semiconductor sector also intersect with the requirements for the growth of quantum industries, particularly the technologies that are involved in manipulating silicon as the substrate material for creating qubits. It is also likely that qubits fabricated through other approaches such as photonics or superconductors that do not rely on semiconductor processing technologies, will also benefit from semiconductor-based hardware implementations for control electronics. Additionally, S3B promotes access to micro-credentialled training programs to address skills gap identified in the industry, which in turn can be extended to benefit the quantum sector.

5.3. ENSURING AUSTRALIA'S LEADERSHIP IN THE QUANTUM ERA

Independent to all the above initiatives, CSIRO, Australia's National Science Agency has also been playing a vital role in facilitating the growth of the quantum industry in Australia. The Quantum Roadmap titled "Growing Australia's Quantum Technology" released by CSIRO in 2020 generated significant interest among industry groups as the report outlined the $4 billion economic opportunity that lies ahead for Australia, and the technical prowess it could endow to various industry sectors such as health, mining, space and defence[3]. The report also detailed the inherent challenges that needs to be addressed to materialise such opportunities. Foreseeing a long-term opportunity enabled by Australia's research excellence in quantum technology, CSIRO collaborated with the World Economic Forum in 2022 to develop the first guidelines for the responsible use of quantum computing and ensure quantum produces equitable outcomes for all Australians. In addition to the continued investment and work in quantum technologies, CSIRO is building capability and expertise through its Quantum Technologies Future Science Platform to push the limits of applications in quantum software and algorithms, devices, simulation and quantum biology.

In May 2023, the announcement of the National Quantum Strategy outlined the Australian Government's plan to grow the quantum industry in Australia[4]. The strategy offers reassurance to the growing quantum ecosystem with a long-term vision and guidance in identifying opportunities that would enable broader industry to take advantage of benefits that could be achieved through the implementation of quantum technologies. Based on the strategy, a $60 million investment will be made to grow the quantum ecosystem through the establishment of an Australian Centre for Quantum Growth and Critical Technologies Challenges Program (CTCP). These funding mechanisms are aimed at nurturing industry interest in quantum technologies and application-oriented research, further

3 Growing Australia's Quantum Technology. 2020, CSIRO.

4 National Quantum Strategy. 2023, Australian Government Department of Industry, Science and Resources.

helping catalyse the demand for quantum technologies and enabling Australian companies to capture a share of the emerging global market. Additionally, the Australian Department of Industry, Science and Resources (DISR) has funded Sydney Quantum Academy (SQA) to manage National Quantum Collaborative Initiative (NQCI). The initiative aims to develop a plan to enhance national collaboration and interconnection in workforce development across Australia's quantum ecosystem and create a pipeline of quantum skills while ensuring Australia retains specialised talent.

The Queensland Government has been a long-term investor in quantum technologies through co-investment in national centres of excellences namely EQUS and CQC2T since 2003. Its Department of Environment and Science in 2023 launched a $76 million Queensland Quantum and Advanced Technologies Strategy to harness the state's expertise in quantum technologies, focused on supporting the translation of quantum science into useful real-world applications and complement the broad national effort underway to build Australia's sovereign capability in quantum technologies[5].

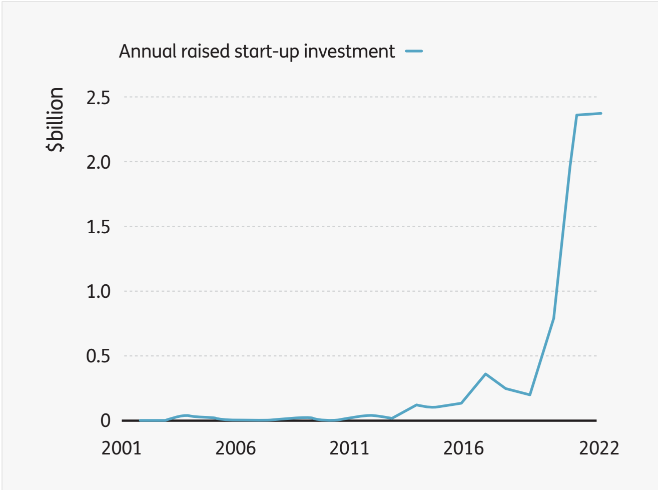
5.4. A STRONG INVESTMENT LANDSCAPE FOR QUANTUM DEVELOPMENT

As quantum technologies developed by Australian startups mature and their need to scale up becomes imminent, the capital required for growth of such startups will be crucial for the collective success of the quantum sector. According to the National Quantum Strategy, Australian quantum companies already attract significant venture capital investment compared to our international competitors, capturing a 3.6% share of global venture capital for quantum from 2017 to 2021. Blackbird, Breakthrough Victoria and Main Sequence Ventures (MSV) are some of the venture capital firms that dominate investments in Australian quantum technology ecosystem. Blackbird has led a $10 million pre-Series A round for Nomad Atomics with participation from Right Click Capital and have also been involved in a US$450 million Series D round for PsiQuantum.

Whereas Breakthrough Victoria, an investment company established by the Victorian Government that manages a $2 billion investment fund, invested $29 million in US-based global quantum leader Infleqtion (previously ColdQuanta). This will help establish an Asia-Pacific quantum computing and technology facility at Swinburne University of Technology known as the ColdQuanta–Swinburne Quantum Technology Centre. In early 2023, Quantum Brilliance announced an $18 million fundraise from investors such as Breakthrough Victoria, MSV, Investible, Ultratech Capital, MA Financial, Jelix Ventures, Rampersand and CM Equity. CSIRO founded MSV which was established in 2017 to address the 'valley of death' between research and commercialisation, and has raised more than $1 billion as of 2023 and are known for investing in early-stage deep tech startups. Advanced Navigation, Quintessence labs, Q-CTRL are some of MSV portfolio companies that were founded in Australia and have now garnered an international reputation as industry leaders for developing quantum sensors, QKD and quantum control, respectively.

Globally, with growing interest in quantum technologies, investments in quantum startups have rapidly accelerated in recent years (US$2.35 billion in 2022). Analysis by McKinsey & Co has highlighted the opportunities offered by the adoption of quantum technologies, estimating industries such as automotive, chemicals, financial services and life sciences could potentially gain up to US$1.3 trillion in value by 2035[6].

In the Australian context, there could be more opportunities for new startups as research breakthroughs are translated to commercial outcomes. So far, the contribution of Australian investment companies mentioned above in the local quantum ecosystem is a reflection of investor confidence in the progress of quantum technologies and its future commercial potential.



Global quantum technology investment landscape over the years.
Source: McKinsey&Co, based on data recorded in Pitchbook

5 Queensland Quantum and Advanced Technologies Strategy.2023. Queensland Government Department of Environment and Science.
6 Quantum Technology Monitor, 2023. McKinsey& Company.

6. EMPOWERING AUSTRALIAN BUSINESSES TO IMPLEMENT QUANTUM STRATEGY

The success of any new technology lies in its adoption by broader industry sectors and the benefits it can offer in terms of improving productivity. Ongoing activities in the quantum sector promise to be the platform technology that will drive the next generation of scientific advancements having profound impacts on our daily lives. As our researchers and startups strive to push the limits of quantum technologies and demonstrate their practical applications, the onus to secure first mover advantage lies equally on the prospective end users to deploy a technology adoption strategy in anticipation of mature quantum applications relevant to their industry sectors. Australian businesses that aspire to implement quantum technologies as part of their business processes are an important stakeholder to the Australian quantum ecosystem that can enable our quantum sector in directing research efforts toward industry challenges.

While we've just scratched the surface in understanding the commercial potential of quantum technologies, there are still plenty of opportunities to be unlocked as industry-specific applications emerge. With the next generation of quantum technologies making their way into commercially relevant products in quantum sensing and communications, a significant mindset shift is required from the broader community to move on from the bandwagon of discussing 'hype vs reality' to start exploring the opportunities with reasonable critical evaluation. Below are a few ways in which businesses can start their journey toward quantum readiness and be able to envision their industry-specific quantum strategy.

6.1. UPSKILLING WORKFORCE WITH QUANTUM LITERACY

Although several universities offer programs in quantum technology which create an invaluable pipeline of workforce for the future, there is an immediate need to impart knowledge about the working principles of quantum technologies to subject matter experts across industry sectors. For example, introducing concepts of quantum computing to a molecular biologist can empower them to design algorithms that can accelerate the process of drug discovery using systems that use qubits, or introducing the concepts of QKD can empower a cybersecurity professional to design protocols that withstand sophisticated cyberattacks. Learning platforms such as Black Opal, developed by Q-CTRL, is designed to make learning quantum computing accessible to everyone and it delves into basic concepts of quantum technology through to advanced programming tasks. These skills can play a vital role in establishing meaningful partnerships with quantum experts as the chance of engaging at a technical level will be higher.

CASE STUDY:
CENTRE OF QUANTUM TECHNOLOGY – TRANSPORT FOR NSW

As a government organisation, Transport for NSW (TfNSW) leads by example through the development of a vision and roadmap that aims to establish TfNSW as a global leader in transport quantum technology[7]. Through its roadmap, TfNSW aims to gain clearer insights about potential applications of quantum technology in transport which could include intelligent traffic control, dynamic scheduling, real-time response, predictive maintenance scheduling and disaster response, with the overall goal of resource optimisation and improving its customer experience. Although these solutions cannot be readily implemented, through this initiative TfNSW is well-positioned to understand the possibilities specific to their industry and allocate resources towards infrastructure upgrades required for the deployment of quantum technologies when they are available in a few years. TfNSW plans to implement this vision with the creation of a Centre of Quantum Technology, establishing a Quantum Expert Advisory Panel and recruiting a Director of Quantum Technology who will lead this initiative. By envisioning a purpose-driven quantum strategy, TfNSW has set an ideal example which other organisations and businesses can follow and tailor a plan to take advantage of the potential benefits of quantum technologies specific to their industry sector.

7 Quantum Technology Innovation. 2021. Transport for NSW

6.2. ESTABLISH PARTNERSHIPS WITH QUANTUM EXPERTS

Australian businesses are fortunate to be able to leverage expertise locally from both homegrown quantum companies and international players who are leading this game changing technology and have the unique opportunity to be part of the second quantum revolution. Organisations such as SQA have a well-established network within the quantum ecosystem with both academic researchers and industry partners. Businesses can leverage this network to offer internships to a diverse pool of PhD and undergraduate students studying quantum or quantum related disciplines to explore solutions for difficult industry challenges through application of quantum technologies.

Furthermore, sponsoring a PhD scholarship through SQA or IDTC is an excellent pathway for businesses to establish long-term collaborations with research expertise based in academia. This can also serve as the foundation for partnership opportunities through programs such as the Cooperative Research Centres Projects grant program which can involve another business pursuing development of quantum technologies. Such relationships are also likely to be supported through initiatives such as CTCP which are being designed to drive greater awareness and uptake of quantum technologies in Australia by creating stronger ties between quantum researchers, companies, and industry.

Another effective way of getting involved with the quantum sector is through partnerships with groups that are focussing on quantum algorithms and software such as the Australian Quantum Software Network or the Centre for Quantum Software and Information at the University of Technology Sydney. This approach enables prospective users to explore applications of quantum simulation or quantum computing for their business or industrial processes, through the development of custom-built software and algorithms, that could possibly be executed through quantum computers that are available today through cloud computing resources.

6.3. EXPLORE OPPORTUNITIES FOR HARDWARE DEVELOPMENT

With several industry applications emerging through quantum sensing, there is an opportunity for established businesses or startups to consider developing quantum sensing hardware specific for their industry requirements. Organisations such as ANFF provide access to infrastructure required for nanofabrication, and a network of researchers trained in quantum technologies whose expertise can be leveraged to develop novel, purpose-built devices.

Micro-credentials in semiconductor design, implementation concepts and tool training developed through NSW government initiative New Education and Training Model and facilitated by S3B, in partnership with the University of Sydney, could also complement this approach by imparting knowledge to staff in electronics development, which can be applied to certain categories of quantum technologies.

Additionally, S3B can also facilitate relationships across the supply chain, required for scale up of such technologies. For example, with a $3.4 million budget NSSN ventured a project working with Sydney Water and a range of other industry partners in water management to develop a real time, smart sensing application for condition assessment and leak detection on live water networks to prevent catastrophic breaks in critical public infrastructure. This project was also one of the early adopters of methodologies developed by co-founders of Nomad Atomics that demonstrated field applications of quantum sensing and its integration with other smart sensing technologies. Such an approach offers organisations the opportunity to de-risk their investment in R&D, and at the same time create novel intellectual property assets that can be applied as solutions to similar problems around the world.

In conclusion, the successful implementation of quantum technology in Australian businesses requires a proactive and strategic approach. It is also important for businesses to independently evaluate any proposed quantum technology solution to gain an understanding of realistic timelines and project outcomes. By upskilling the workforce, establishing partnerships with quantum experts, exploring opportunities for hardware development, and leveraging government initiatives, Australian businesses can position themselves at the forefront of the quantum revolution and reap the benefits of this transformative technology.

APPENDIX 1: LIST OF AUSTRALIAN FOUNDED QUANTUM COMPANIES

Quantum technology	Name	Headquarters	Year founded	Funding status[8]	Affiliation[8]
Computing	Analog Quantum Circuits	Brisbane	2021	$3M, Seed	UQ, EQUS
	Archer Materials	Adelaide	2007	ASX listed	N/A
	Diraq	Sydney	2022	Undisclosed, Series A	UNSW, CQC2T
	Quantum Brilliance	Canberra	2019	$29.4M, Seed	ANU
	Silicon Quantum Computing	Sydney	2017	$133M, Series A	UNSW, CQC2T
Communication	Lumi Quantum Technologies	Sydney	2023	Privately owned, Grants	UTS, Defence Innovation Network
	Quintessence Labs	Canberra	2008	$49.3M, Series B	ANU, CQC2T
Sensing	Jovian Tech	Sydney	2022	Undisclosed	UWA, EQUS
	Nomad Atomics	Canberra	2018	$10M, pre-Series A	ANU
	Phasor Innovation	Melbourne	2016	Undisclosed	University of Melbourne, RMIT
	Quantx Labs	Adelaide	2016	Privately owned, Grants	UWA, University of Adelaide
Infrastructure software	Q-CTRL	Sydney	2017	$110M, Series B	Uni of Sydney, EQUS

8 Values adjusted to AUD, based on publicly available data retrieved from Crunchbase, as of December 2023.

9 Indicates whether the companies were either a spin-out, or had received support, or involved in a research partnership with respective organisations.

APPENDIX 2: CENTRES OF EXCELLENCE SUPPORTING QUANTUM RESEARCH AND DEVELOPMENT

The Australian Research Council's (ARC) Centres of Excellence are prestigious focal points of expertise through which high quality researchers collaboratively maintain and develop Australia's international standing in research areas of national priority.

The Centres of Excellence scheme is an integral part of the ARC's Linkage Program which promotes national and international collaboration and research partnerships between key stakeholders in research and innovation, including higher education providers, government, business, industry and end users. Through these partnerships, the ARC encourages the transfer of skills, knowledge and ideas as a basis for securing commercial and other benefits of research.

Centre of Excellence with focus of applications of quantum technology

Name	Focus
Centre for Quantum Computation and Communication Technology (CQC2T) Funding: • $24.5 million over 7 years, starting 2011 • $33.7 million over 7 years, starting from 2017	To deliver world-leading quantum research to develop full-scale quantum systems – encompassing ultra-fast quantum computation, secure quantum communication and distributed quantum information processing.
Engineered Quantum Systems (EQUS) Funding: • $24.5 million over 7 years, starting 2011 • $31.9 million over 7 years, starting from 2017	To build sophisticated quantum machines to harness the quantum world for practical applications by developing quantum technologies that move beyond the lab towards practical prototypes and commercial applications, including material simulators, diagnostic technologies and geosurvey tools.
Quantum Biotechnology (QuBIC) Funding: • $35 million over 7 years, starting 2023	To develop paradigm-shifting quantum technologies to observe biological processes and transform our understanding of life. It seeks to create technologies that go far beyond what is possible today, from portable brain imagers to super-fast single protein sensors, and to use them to unravel key problems including how enzymes catalyse reactions and how higher brain function emerges from networks of neurons.

Centre of Excellence that leverages quantum technology for their respective fields

Name	Quantum Program
Gravitational Wave Discovery (OzGrav) Funding: • $31.3 million over 7 years, starting 2017 • $35 million over 7 years, starting 2023	Pursuing novel instrumentation research to develop lasers and quantum squeezers, and study quantum state preservation and manipulation.
Future Low-Energy Electronics Technologies (FLEET) Funding: • $33.4million over 7 years, starting 2017	To develop new types of electronic conduction without resistance in solid-state systems at room temperature. These concepts will form the basis of new types of switching devices (transistors) with vastly lower energy consumption per computation than silicon CMOS. Electronic conduction without resistance will be realised in topological insulators that conduct only along their edges, and in semiconductors that support superflow of electrons strongly coupled to photons. These pathways are enabled by the new science of atomically thin materials.
Transformative Meta-Optical Systems (TMOS) Funding: • $34.9 million over 7 years, starting 2020	Focused on engineering new quantum light sources and single photon detectors which have the potential to revolutionise quantum technologies by employing metasurfaces that enable us to precisely control the properties of light at the nanoscale. Quantum metasurfaces will play key role in creating new highly efficient quantum building blocks, that operate at room temperature. These devices have the potential to be faster, smaller, and more energy-efficient than traditional technologies, opening up new modalities and possibilities.

APPENDIX 3: NATIONAL INFRASTRUCTURE UNDERPINNING QUANTUM HARDWARE DEVELOPMENT

The National Collaborative Research Infrastructure Strategy (NCRIS) is a program funded by the Australian Government to provide researchers with access to world-class research infrastructure. NCRIS supports 26 projects and an international membership that cover various fields of research, such as biotechnology, astronomy, marine science, and manufacturing with the aim to foster collaboration and innovation among researchers, industry, and government, and to deliver economic, environmental, health, and social benefits for Australia.

Below are some of the NCRIS projects and their key capabilities that are crucial for supporting the growth of quantum technologies in Australia by providing access to state-of-the-art facilities, equipment, and networks.

A3.1. AUSTRALIAN NATIONAL FABRICATION FACILITY (ANFF)

ANFF was founded in 2007 to overcome hurdles to R&D success by providing open access to micro and nanofabrication equipment for Australia's researchers and industry. ANFF helps to realise research, development, and commercialisation potential of its users by providing access to micro and nanofabrication-related tools and the expertise of more than 120 engineers. ANFF capabilities support the development of a range of quantum technologies including silicon CMOS, diamond nanofabrication and advanced photonics.

A3.1.1. Thin film deposition, including Physical Vapour Deposition (PVD) and Chemical Vapour Deposition (CVD) is used to endow special properties to substrate material, i.e. electrical, optical, mechanical, chemical, that satisfy the needs for specific applications. For example, in the development of superconductor-based quantum sensing or computing devices, thin film deposition plays a critical role in creating Josephson junctions.

A3.1.2. Microwave Plasma-enhanced CVD (MPCVD) is a chemical vapour deposition process which uses a continuous microwave source to create and help to maintain a highly reactive plasma made up of the reacting chemicals and necessary catalysts. MPCVD is useful for depositing layers of diamond and introducing dopants to the carbon structure such as boron that can be exploited towards applications in quantum information systems.

A3.1.3. Epitaxial Growth Facility, with dedicated Molecular Beam Epitaxy (MBE) for compound semiconductors. MBE is useful for developing customised material where crystal structures are grown as one layer of atoms at a time with precise control of atomic concentrations according to specified design. MBE techniques enable development novel technologies by allowing researchers to enhance performance levels of existing materials and create new materials not possible by any other methods.

A3.1.4. Electron Beam Lithography (EBL) can achieve small beam sizes by tightly focussing electron beams which can be used to create very intricate structures for a wide variety of nanofabrication applications, including silicon quantum dot and nanophotonics.

A3.1.5. Etching, including focused ion milling, reactive ion, vapor phase and plasma etching, is a process of selectively removing material from a substrate using a chemical or physical method, often used in the fabrication of microelectronics, MEMS, and nanostructures. For example, focused ion milling could be used to create microscopic structures in diamond with precision at the pre-determined locations of NV centres, that have applications in quantum computing and sensing.

A3.1.6. Fibre Bragg Grating (FBG) is a reflector constructed in a short segment of optical fiber that reflects particular wavelengths of light and transmits all others. It is useful for developing of photonics-based qubits, generating optical frequency for quantum sensing and applications such as entanglement assisted multidimensional QKD.

A3.2. HEAVY ION ACCELERATORS (HIA)

HIA operates world-leading particle accelerators for a wide variety of scientific and industrial applications hosted at the Australian National University and the University of Melbourne. HIA enable researchers to build a fundamental understanding of nuclear physics, develop new medical treatments and tools to fight cancer, build advanced quantum computing technologies, monitor, and protect our environment, and test electronics destined for space. In the advanced manufacturing sector, HIA accelerators are used for precise fabrication of quantum centres (the building blocks of quantum computing), microelectronics, advanced materials fabrication, and prototyping of quantum sensors – through techniques such as ion implantation.

A3.2.1. Ion Implantation enables the introduction of almost any element into any material, and to position the centres close to the surface or deep within the material, makes this approach particularly attractive for research and development in quantum technologies. It plays a critical role in the fabrication of modern electronic and photonic devices, many of which underpin the devices and structures employed for quantum technologies by providing a versatile means of creating electronic and optical quantum centres in materials. Common examples including Phosphorus in Silicon and NV-centres in diamond, respectively. Additionally, facilities at HIA also supports techniques such as doping, electrical isolation, carrier lifetime reduction, layer intermixing and etch rate control. Ion implantation can also be used for fabrication of isotopically-enriched silicon layers through high fluence ^{28}Si ion implantation, providing an alternative means of creating the purified layers essential for silicon-based quantum computers.

A3.3. MICROSCOPY AUSTRALIA

Microscopy Australia empowers Australian science and innovation by making advanced microscopes and expertise accessible to all researchers and industry. Capabilities in quantum sector allow imaging and analysis to the atomic scale, and non-destructive testing of quantum circuitry and hardware to improve fabrication processes.

A.3.3.1. Transmission Electron Microscope (TEM) can reveal the atomic structure and composition of materials, which are essential for designing and optimising quantum devices and also measure the quantum states of electrons and photons, which are the carriers of quantum information.

A.3.3.2. Scanning Electron Microscopy (SEM) is a powerful tool for studying the surface morphology, chemical composition, and crystalline structure of quantum materials. By combining SEM with laser pulses, researchers can manipulate the quantum states of electrons and observe their interactions with photons and matter. This technique can reveal new phenomena and insights that are otherwise impossible to see with conventional microscopy methods.

A.3.3.3. Micro-CT is useful to visualise and analyse the internal structure and geometry of various hardware components involved in development of quantum technologies with high resolution and contrast. Micro-CT is a non-destructive imaging technique that can help to optimise the design, fabrication, and performance of these hardware components by revealing defects, cracks, alignment errors, or other features that may affect their functionality and reliability.

A.3.3.4. Atom probe tomography is a powerful technique for 3D elemental mapping at the atomic scale. It can reveal the structure and composition of nanoscale features in materials, such as quantum dots, nanowires, and superlattices.

A.3.3.5. Cathodoluminescence (CL) and Electron Beam Induced Current (EBIC) are two techniques that can be used to study the optical and electrical properties of materials and devices for quantum technologies. CL can reveal the emission spectrum, intensity, and spatial distribution of light emitted by a sample when excited by an electron beam. EBIC can measure the charge carrier transport, recombination, and collection efficiency in a sample when biased by an electric field. Both techniques can provide valuable insights into the performance and reliability of quantum hardware, such as quantum dots, nanowires, superconducting qubits, and photonic circuits.

A.3.3.6. Atomic Force Microscopy (AFM) is used for characterising the surface properties of materials at the nanoscale. AFM can measure the height, magnetic, electrical and hardness of a sample by scanning a sharp tip over its surface and detecting the interactions between the tip and the sample. AFM can help optimise the design and fabrication of quantum hardware by providing detailed information on the surface morphology, functionality and defects of the materials.

A.3.3.7. Electron Probe Microanalysis (EPMA) is useful for trace element detection and mapping the distribution of impurities, defects, and interfaces that affect the quantum behaviour in quantum technology hardware, such as superconducting qubits, quantum dots, and nanowires. EPMA can help optimise the fabrication and processing of quantum hardware by providing feedback on the quality and performance of the materials and structures. EPMA is a technique that uses a focused beam of electrons to excite characteristic X-rays from a sample. These X-rays can be used to identify and quantify the elemental composition of the sample, especially for trace elements that are difficult to detect by other methods.

A3.4. PAWSEY SUPERCOMPUTING CENTRE (Pawsey)

Pawsey offers service and expertise in supercomputing, data, cloud ervices and visualisation, enables research across a spread of domains including astronomy, life sciences, medicine, energy, resources and AI. Pawsey and National Computational Infrastructure Australia supercomputers also provide modelling to support nano-level research

A3.4.1. HPE Cray EX Supercomputer (Setonix) is a hybrid system of Central Processing Units (CPU) and Graphics Processing Units (GPU) that are engineered to solve massively complex scientific problems. Setonix has been paired with a quantum accelerator developed by Quantum Brilliance, to demonstrate the world's first integration of quantum computing systems in a supercomputing centre and will be used for testing hybrid models of quantum and classical computing.

ANFF

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