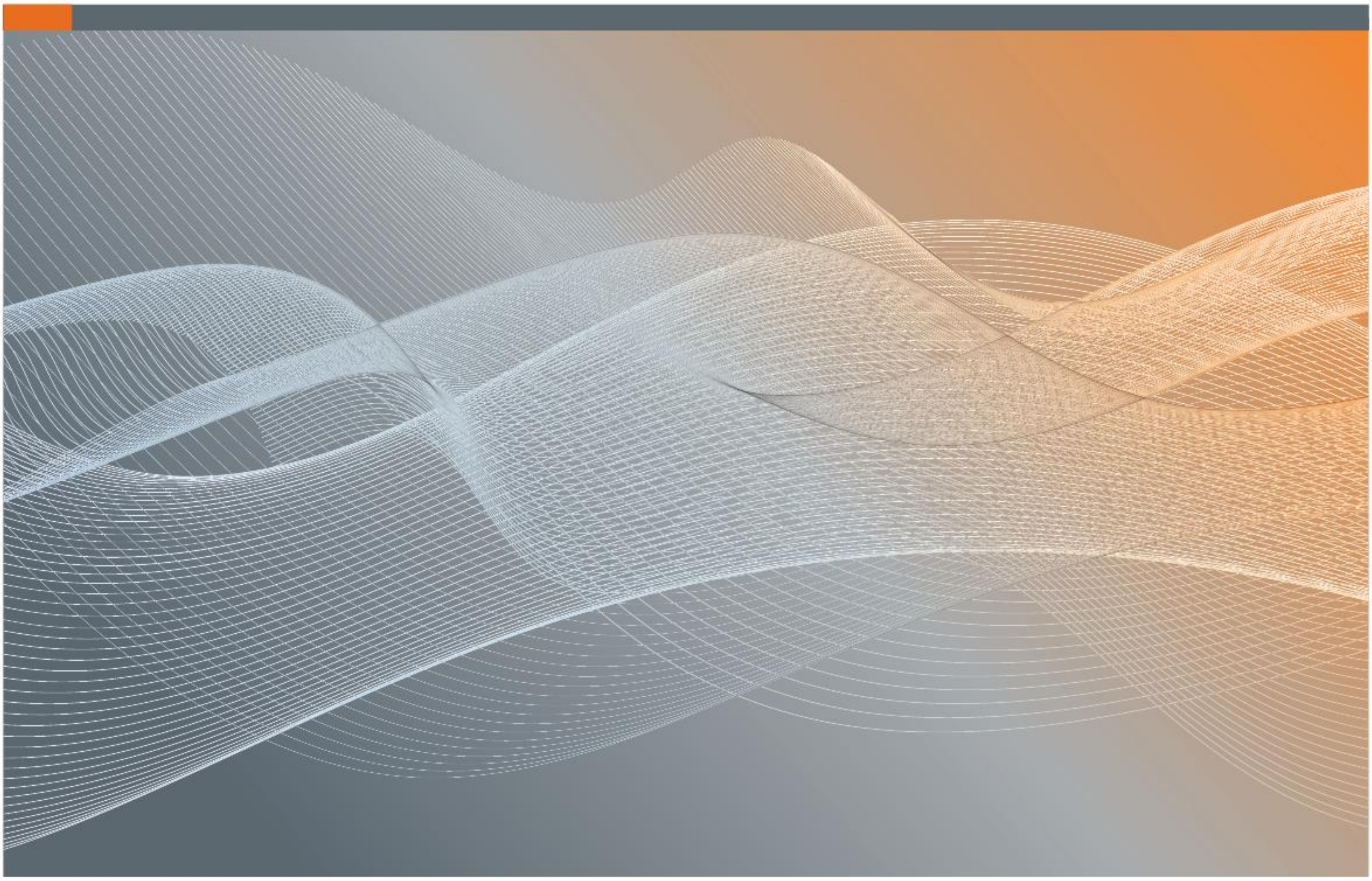
Australian Government
Department of Defence

EDTAS on Quantum Computing: Technology Opportunities Quick Look Report



Defence Science and Technology Group

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Defending Australia and its National Interests
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EXECUTIVE SUMMARY

Quantum computing (QC) technologies are developing rapidly in Australia and across the world, with potentially substantial and broad ranging implications for Defence and National Security.

On 22–23 June 2022, Defence Science and Technology Group (DSTG) hosted a 2-day symposium to explore current and future directions of QC technologies through the Emerging and Disruptive Technology Assessment Symposium (EDTAS).

The EDTAS was attended by over 100 participants from across government, industry and academia. This included Australia's leading quantum researchers; the Chief Defence Scientist (CDS); the Australian Chief Scientist; Defence officials from Australia, the US, UK, Korea, Singapore and Japan; and Australian government representatives.

The 2-day symposium gave a voice to diverse views and perspectives from across the Australian quantum community and canvassed:

- different technology options in each layer of the QC stack, and the potential advantages/limitations they bring
- projected technology development pathways and timeframes (sub-components, technology-readiness-levels, convergences, etc.)
- policy initiatives to promote domestic and international collaboration and competition
- potential future use-cases of QC and associated technologies that may provide innovative solutions to challenging environments.

Through the forum, experts were able to engage with Defence and develop a shared understanding of our national research and development (R&D) strengths, the challenges we face as a nation and Defence's role in supporting the Australian quantum eco-system.

Analysis of the presentations, discussions and workshop content identified a series of key insights, summarised below:

- EDTAS was attended by a core community of leading technical experts, from across industry and academia. Their involvement and contributions to EDTAS demonstrated enthusiasm from the QC sector to engage with Defence and collaborate on Defence-focused R&D challenges. Equally, the CDS's participation at the EDTAS was a show of commitment from DSTG to building productive and collaborative networks with the quantum research community.

- Investment in QC is accelerating with the emergences of significant initiatives in many countries. Unable to match these investments, Australia's edge in some areas of QC may erode with time. Possible response options may include:
    - policies designed to protect local innovation, that also enable collaboration opportunities, especially with countries backed by greater investment
    - prioritising Defence-focused R&D efforts towards capability that offers Defence a unique quantum-advantage.
- The EDTAS heard of the many different hardware platforms being developed and their fundamental challenges. Much uncertainty remains over which hardware platform will prevail as the superior option in the coming decades. This places Australia in a challenging position when considering national investment options.
    - Early and concentrated resourcing towards a narrow set of hardware options is likely to yield a stronger national foundation, but it may result in us losing focus of peripheral technology options that offer unexpected and superior capability.
    - Smaller investments across many different hardware options may enhance the likelihood of Australian R&D success, but would be unlikely to engender technical depth in the field.
    - Delaying investment until the emergence of a globally preferred hardware option may result in Australia being too late to establish impactful research programs that can contribute to the field, and to train, retain and attract the necessary workforce.
- The EDTAS raised a tension between ideologies in how to best grow our domestic R&D within the private sector and balance sovereign capability needs. One approach presented was to attract further international industry into Australia, to drive research competition and guide the development of a highly trained and mobile workforce. By contrast, another approach advocates support for sovereign Australian small-to-medium enterprises, with deeply collaborative networks across the Australian quantum ecosystem.
- A sentiment among EDTAS participants was that the fabrication facilities required for large-scale manufacture of QC hardware will likely require significant financial investment and long lead times to build. Parallels were drawn to cutting edge electronic chip fabrication facilities. Strategies to support the scaling up of different

QC technologies in a globally competitive environment will be a key consideration for growth.

- The quantum R&D sector suffers from a global skills shortage in quantum science and engineering. This deficit will deepen as the field expands with time. For Australia to meet the demand, we must train a future workforce that spans the breadth of fields required to build QC technology (e.g. precision manufacturing, software development, etc.). The magnitude of this problem is significant, considering the specialist skills required for quantum R&D.

Defence's role in the quantum R&D eco-system

Defence is uniquely placed to support the Australian quantum computing research community and encourage research directions that will deliver benefits to Defence capability.

With EDTAS as the beginning, Defence aims to develop a clear understanding of the use cases for QC, showcase the benefits of QC for defence relevant applications, and ultimately develop QC-enabled and assured capability for the ADF. This will help build Defence's quantum-IQ, driving us to create concepts of operation and facilitate co-investment in projects and also key related infrastructure, as well as the future workforce needed to grow and sustain this industry.

Defence aims to develop long term relationships with the R&D community and has the risk appetite to sustain the development of future QC applications. Defence's role is likely to include co-ordination and engagement, with international partners to provide requirements as an end-user of quantum technology.

What to next?

Insights captured at the EDTAS will undergo analysis, refinement and prioritisation by DSTG. Some of these will be further explored and tested with Defence stakeholders at the next stage of the EDTAS campaign, the Military Implications Workshop.

The Military Implications Workshop will provide a mechanism for Defence to assess the impacts of quantum computing strategic research opportunities on Defence capability. The outcomes of this activity are intended to inform planning about Defence's future posture and investment.

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1. BACKGROUND

Quantum Computing (QC) has the potential to fundamentally transform Defence capability in the coming decades. Future applications of QC are expected to yield superior capabilities in encryption breaking, database searching, communications, sensing and intelligent decision making. Forecasting the depth and breadth of disruption imposed by QC, however, remains a challenge due to the inherent uncertainty surrounding deep technological challenges in the field and the opportunities these may unlock.

The relatively low technology-readiness-levels (TRL) of QC components and systems have meant that the few proof-of-concept systems that exist are limited in scale and real-world applications. Additionally, the computational advantages offered through each of these systems is application specific, each requiring specific performance characteristics for implementation. These technical challenges, alone, may take decades to resolve and will likely lead to a staged realisation of applications over a range of timeframes.

To grow a quantum-enabled Australian Defence Force (ADF), Defence must position itself to identify and invest in the right quantum computing applications. Historically, Defence's commitment to quantum research has largely concentrated on the areas of quantum for sensing and position, navigation and timing (PNT). In September 2021 Defence reassessed that approach and delivered the *Quantum Computing In Focus* symposium – an event focused on increasing Defence's understanding of QC technologies and the research community in Australia.

QC in Focus emphasised the role of Defence as a unique partner – through both funding research and as a critical early-adopter and end-user for quantum-enabled products. QC in Focus reinforced that Australian scientists are at the cutting edge of quantum development and our research in this important area punches well above our weight internationally. This provides opportunities for the development of significant sovereign, world-class capabilities.

The Emerging Disruptive Technology Assessment Symposium (EDTAS) series was the natural next step in Defence's QC journey. The EDTAS, an initiative under the Next Generation Technologies Fund (NGTF), provides one avenue that Defence Science and Technology Group (DSTG) uses as part of our Technology Foresight program to elicit plausible futures to help drive the development of future strategy and investment pathways.

The EDTAS on QC was held over 2 days during 22–23 June 2022, in Canberra. It was attended by over 100 participants from across academia, government and industry. With DSTG as the lead, the EDTAS was organised and delivered through partnership with external research organisations with demonstrated excellence in the field of QC.

During the symposium, participants considered topics such as the future of QC and associated technologies, how they might be applied, capability concepts, and the drivers, barriers and implications for their adoption. The insights captured help shape Defence strategic understanding of the implications and applications of QC and inform where Australian investment should focus and where collaboration is necessary.

Forming deep and genuine partnerships will be core to achieving quantum-enabled capability for Defence. Through EDTAS, Defence sought to bring together researchers, entrepreneurs, innovators, system integrators, investors and end-users to collaborate in exploring the problem from diverse perspectives. Future stages will explore how to co-design and co-invest in quantum algorithms and applications that offer potential advantages.

2. AIM OF THE QUANTUM COMPUTING (QC) TECHNOLOGY OPPORTUNITIES SYMPOSIUM

The aim of the EDTAS on QC was to:

1. strengthen networking/relationships between Defence and the QC research community
2. create a forum through which the QC community can learn about Defence as a unique and preferred research partner
3. support Defence in gathering QC knowledge for a R&D framework.

To achieve this, the 2-day EDTAS symposium gave a voice to diverse views and perspectives from across the Australian quantum community and canvassed:

- different technology options in each layer of the QC stack, and the potential advantages/limitations they bring
- projected technology development pathways and timeframes (sub-components, technology-readiness-levels, convergences, etc.)
- policy initiatives to promote domestic and international collaboration and competition
- potential future use-cases of QC and associated technologies that may provide innovative solutions to challenging environments.

The symposium comprised 2 main components:

Subject matter expert (SME) presentations and facilitated question and answer (Q&A)

Keynote presentations framed the technological state-of-the-art, projected how technology will develop into the future, and described how key challenges may be met. Keynote presenters were internationally recognised experts in the field of QC. Panel sessions delivered short presentations followed by facilitated Q&A; these enabled rigorous discussion and analysis of important and sometimes contested aspects of QC.

Workshop activities

Workshop sessions provided a format through which SMEs could innovate potential future use-cases and concepts for QC and understand their technology development pathways.

3. OUTCOMES OF THE TECHNOLOGY OPPORTUNITIES SYMPOSIUM

3.1. Panel Sessions

3.1.1. Session 1 – Algorithms and Applications

- Keynote presenter: Dr Jay Gambetta, IBM Quantum
- Panel facilitator: Dr Muhammad Usman, CSIRO
- Prof. Lloyd Hollenberg, University of Melbourne
- Dr Dominic Berry, Macquarie University
- Dr Marika Kieferova, University of Technology Sydney
- Dr Florian Preis, Quantum Brilliance

The panel session on Algorithms and Applications constituted 4 short presentations from the panel members. All 4 members highlighted promising opportunities for the application of quantum computing in Defence related problems. Key messages from the panel session can be summarised as follows:

1. While the focus of the EDTAS event was 2040+, a recurrent theme was that quantum computing will offer plenty of opportunities for application development and benchmarking in the intermediate timeline. As the quantum devices scale up within the next decade, it is imperative to develop both quantum and hybrid classical/quantum algorithms and applications which can lead to tangible benefit for Defence related problems.
2. Quantum error correction will play a crucial role in the longer term to enable broad practicality of quantum computing. In the lead up to this regime, associated software development will be required for quantum, classical and hybrid aspects. Additionally, quantum error mitigation strategies across algorithm and hardware implementation will be critical to optimise applications.
3. Quantum advantage comes in many flavours. Although the common perception is to define quantum advantage in terms of exponential speed-up, more generally quantum advantage can be achieved by designing solutions which are more accurate or robust than their classical counterparts, e.g. in machine learning applications.
4. Quantum algorithm design is fundamentally different from the classical algorithm development. Therefore, it is important to develop quantum education and training

programs beyond the traditional cohort of students with quantum physics backgrounds to establish an Australian quantum trained workforce to advance the field of quantum algorithms and applications.

5. Quantum hardware development has been Australia’s key strength for many years. However, the challenge is to establish world-leading capabilities in quantum software and algorithms that can capture opportunities in the noisy intermediate-scale quantum (NISQ) era. A key enabler for these developments (and for those listed in 1–4 above), and the competitiveness of Australia’s position, is to ensure access to globally state-of-the-art quantum computer hardware.

3.1.2. Session 2 – The full-stack: Competing technologies

- Keynote presenter: Prof. Rodney Van Meter, Keio University (Japan)
- Facilitator: Prof. Michelle Simmons, University of New South Wales
- Prof. Andrew Doherty, University of Sydney
- Dr Charles Hill, University of Melbourne
- Dr Ludwik Kranz, University of New South Wales
- Dr Maja Cassidy, Microsoft

3.1.2.1. Overview

The stack session was focused on discussing the entire quantum computing platform from physical qubits to algorithms applications in a fault-tolerant architecture. There were talks from physical qubit implementations and the necessary classical electronics required for error correction through to architectures and software layers. It was also noted that there is no one definition of what is required for the full quantum computing stack and many proposals have been made ranging from a few layers to more than 10 layers.

However, at their most fundamental level there were the physical qubits in the quantum hardware chip – the fundamental basis of the computer. Six unique hardware platforms were summarised with their current status and fundamental challenges. On top of these were the classical hardware, software, and user interfaces. Proper architecture (or systems) engineering is required to fully develop a useful quantum computer and requires many different people with many different skills working together. There was robust discussion about whether these layers could be developed independently in a plug and play mode, but it was widely accepted that all hardware companies are building the stack in-house due to both the need and the practical necessity of success. Having full-stack capabilities in-house allows for efficient communication, robust integration of different stack layers, fast turnaround and quick prototyping cycle.

3.1.2.2. Recurring themes

There were a few recurring themes throughout the panel and talks that revolved around obtaining better physical qubit performance. It was made clear that for NISQ-era quantum computing qubit quality is essential for any quantum advantage to be obtained. Therefore, there needs to be significant investment in the design, fabrication, and control (including noise and error mitigation techniques) of physical qubits to reach the strict quality requirements for quantum advantage.

Error correcting schemes are continuously being optimised and refined to allow for noisier qubits for fault-tolerance. It has been well established that quantum error correction is necessary for large-scale quantum computers; however, this comes with significant overheard in terms of the number of qubits and control hardware/software required to run an algorithm. This can also be further reduced by using better physical qubits.

3.1.2.3. Integrating the stack

The quantum stack requires the dedicated effort of many different people over many different disciplines. Importantly, these various fields need to be able to communicate efficiently with each other to quickly progress the field. In Australia, there are full-stack companies (offering full quantum capabilities) and software companies (offering control/algorithms and are hardware agnostic). The overall attitude of the panel and talks was that full-stack companies offer better communication between layers leading to faster development cycles. Companies focused on individual components of the stack, however, have a much more detailed view on their parts, but this requires developing standards such that each layer has well defined inputs and outputs to be able to interface with other layers of the stack.

Full-stack companies within Australia have developed their own in-house quantum stack capability by hiring expertise directly into the company recognising the different architectures, and control needed for their specific platform technology. Whilst creating a forum for standardisation across the quantum stack may assist separate single layer companies to interface with other quantum computing companies, it was not clear that this was the most efficient route to success.

3.1.2.4. Opportunities and challenges

Australia has a tremendous opportunity to expand on its already world-leading expertise in quantum computing across the stack. Australia has exceptional skills in the physical qubit layer with multiple full-stack companies across 3 main platforms: silicon spin qubits, photonic qubits and diamond spins qubits. The challenge for these world-leading companies and research groups is to maintain their position at the forefront of the field as other, larger countries expand into QC research. This will require strong collaborations and fostering of the Australian ecosystem to help lift everyone, particularly in the areas where Australia has strengths. Australia has significant expertise in quantum control and theory. Combining this theoretical expertise with the different hardware platforms in a concerted effort will further Australia’s opportunities to develop sovereign quantum capabilities.

A significant challenge facing the entire quantum industry, which can be particularly detrimental to Australia, is the skill shortage in quantum engineering. This may require investment in training within Australia to develop a new generation of quantum engineers. However, we also note that this training can be delivered directly in some of the start-up companies rather than through the traditional academic route.

3.1.2.5. Australian strengths and weaknesses

Australia is a world leader in silicon, photonic and diamond-based quantum computing hardware. Australia is also a world leader in quantum algorithms and control, verification, and validation. Australia therefore has the technical expertise to build sovereign capabilities across the entire quantum computing stack. What Australia lacks is the larger resources of Europe and the US, where complete supply chains exist to assist in the development of the quantum computing stack. The resources required extend from personnel to materials, to cryogenic systems and hardware.

3.1.3. Session 3 – Strategy, policy and programs

Panel session 3 was designed to facilitate a conversation about how government strategy, policy and programs could evolve from where they are today to support the types of aspirations and applications for QC of tomorrow. Strategy, policy and programs were discussed in 2 parts with an initial panel of experts discussing the Defence context, followed by a second panel discussing the whole-of-government context.

3.1.3.1. Panel 3A – Defence panel

Panelists:

- Facilitator: Duncan Tailby, Program Lead Quantum Information Science, Defence Science and Technology Group
- Prof. Michelle Gee, Chief Technology Officer, Innovation and Strategic Research, Defence Science and Technology Group
- Dr John Burke, Principal Director for Quantum Science, US Department of Defense
- BRIG Ian Langford, Head Land Capability, Australian Army

The Defence focused panel brought together a range of views and equities on Defence's role in the QC innovation pathway. Key themes discussed are summarised in the sections below.

3.1.3.2. Technology regulation

Collaboration and partnerships are central to the development of QC, however, it was raised through the Q&A that stringent government regulations designed to protect intellectual property (IP) and national capability may be stifling collaborative R&D. The designation of quantum technologies as 'sensitive' could mean that without a dual-use application, partnerships with Defence may become prohibitive for small quantum technology companies.

Science and technology (S&T) exchanges, including bi- and tri-lateral exchanges (e.g. via AUKUS) may alleviate the challenges imposed by regulations. There is an appetite within both Australian and US government to effectively partner and collaborate on QC R&D. AUKUS may provide the mechanism to overcome some of these regulation challenges.

With respect to export controls, QC represents a unique challenge. Compared to other S&T fields, QC is rapidly advancing in many different directions. Because it's not obvious how to effectively enact export controls in this area, a nuanced approach and culture of agility – that enables regular reviews of effectiveness – may be necessary.

3.1.3.3. Defence investment in QC

As presented by the Australian Chief Scientist, the quantum computing sector has received multi-billion dollar investment of public money by several nations to build national capability (e.g. US USD$1.5B, Europe USD$7B, China USD$15B – although it is unclear over which timeframe). The sheer value of these figures and rapid growth in investment signifies an international competition with an urgency to develop frontier Quantum R&D.

It is unclear how much of an effect the economic catastrophe imposed by COVID will have on the scale of future QC investment. One thing that is certain, is that as public funding becomes more contested, the need for logic, application and narrative will become increasingly important for winning Defence investment.

3.1.3.4. Expected Defence impact and utility of QC

The impact of full-scale QC has been recognised as high/existential upon future militaries (both through a capability and threat lens). This can be evidenced by the initiation of research programs in the US Department of Defense into understanding how QC will implicate cryptographic protocols – despite a single functional QC still not having been developed yet. While the uncertainty around additional implications remains high, other potential applications are predicted to include enhanced military decision-making or superior last-mile logistics planning capabilities.

3.1.3.5. Defence's role in developing a national QC eco-system

To build sovereign QC capability, Australia needs a complete eco-system, from fundamental research in universities all the way through to start-ups and primes. Defence's role in supporting the development of a national eco-system is exemplified by programs and initiatives that are designed to stimulate Defence-focused innovation and collaboration:

- Defence Innovation Hub
- Rapid proto-typing initiative
- Next Generation Technologies Fund (NGTF)
- Office of the Defence Industry Support (ODIS)
- D.START

Defence can offer a low-risk pathway for QC research which supports 'mission-directed' R&D ideally providing practical outputs of quantum in-action to fill capability gaps. Through collaboration with Defence, researchers will gain context for where technology gap exists and how dual-purpose quantum computing technology may provide a solution.

By becoming highly engrained in the national quantum eco-system, Defence can provide unique opportunities to grow Australian industry and encourage the formation of an Australian prime, so that critical capabilities can be built on-shore.

3.1.3.6. National vs Defence technology roadmaps

In 2021 the Australian government announced the development of a national strategy for Quantum Technologies to be led by the Department of Industry, Science and Resources (DISR). Defence's analytical activities for guiding posture and structuring investment (like EDTAS) may also inject useful insights into the national strategy for how capability gaps can be met on a national level.

A complementarity between Defence 'roadmaps' and national strategies has been demonstrated in the US: the National Quantum Initiative set out to enhance fundamental research and workforce development; while the US DoD focused on applications that could deliver a capability advantage. The 2 programs work in tandem to train up an educated workforce that could then feed into Defence's application-focused R&D programs. Australia is in a promising position to emulate this approach.

3.1.3.7. Panel 3B – Whole-of-government panel

Panelists:

- Facilitator: Duncan Tailby, Program Lead Quantum Information Science, Defence Science and Technology Group
- Brett Cooper, FAS Global Business and Talent Attraction Taskforce, GM Investment, Austrade
- Prof. Jim Rabeau, Director Quantum Technologies Future Science Platform, CSIRO
- Camille de Burgh, GM Technology Policy and Engagement, DISR

The whole-of-government panel discussed the broader national level strategies and policies needed to realise Australia's quantum technologies potential. Key themes discussed are summarised in the below sections.

3.1.3.8. Funding and investment

Global trends in quantum technology investment show a small number of national hubs starting to emerge. Chief among these are the US, Japan, China, and Europe. The trend shows investment is initially led by government, followed by larger capital investments by private industry.

The size of the global quantum technology market is forecast to be A$8.6 billion by 2027, and growing rapidly with 50.9% compound annual growth rate over 2021–2027. Australia is committed to capturing a portion of this market, and has committed A$111 million to boost quantum technology commercialisation, along with A$1 billion pledged by the Labor government for critical new technologies.

Australia's quantum technology ecosystem cannot grow without foreign capital investment. Every modern industry in Australia has relied on overseas capital to expand and realise its potential, and now is the pivotal time for these investments to be made in the QC sector.

3.1.3.9. Proactive government involvement

In all countries that have established quantum technology industry clusters (with the possible exception of the US), government has led the way with early investments and served a coordinating role. Examples include the UK's NQTP, Germany's Quantum Valley, Q-STAR in Japan, and the US QED-C. The quantum industry is a highly competitive space, and active whole-of-government effort is vital to competing with the rest of the world.

Japan's approach has been to establish a new industry council in strategic alliance with government, where government facilitates linkages and guides industry players towards strategic goals such as making Japan a key quantum hub. China and Korea are examples of top-down directive approaches. Irrespective of the method, Government needs to be actively involved in the Australian quantum ecosystem.

Among Commonwealth organisations, Austrade Global Business and Talent Acquisition Taskforce naturally has a marketing role, but is also seeking to bring in companies to help build the quantum ecosystem.

CSIRO aims to play a bridging role across the ecosystem from research to application between government, academia, industry, startups, and end users. CSIRO's role is to conduct basic research into quantum science, support and deliver education and awareness campaigns, and pursue external engagement opportunities. Its business units are exploring cross-discipline use cases for quantum technologies, aiding universities in finding the problems they can solve for industry through quantum technologies and informing industry of potential quantum solutions.

DISR has a major role in coordinating and leveraging collective efforts across federal and state domains. Quantum technologies are a priority, and DISR aims to promote Australian quantum technology and build demand; strengthen Australian strategic industry capability; stem the brain drain; mobilise the quantum community for the national interest; and raise awareness of security implications and interests.

3.1.3.10. Attracting talent

The Australian government recognises that key challenges to the Australian quantum industry include:

- access to workforce and talent
- continued growth in foreign investment.

Austrade is currently working closely with a small number of world leading quantum firms to establish a presence in Australia, and the Labor government has pledged A$3 million to fund quantum PhD studies, as well as A$1 million in support for national collaboration on quantum research.

DISR and Government broadly are also aware of the incentives for Australian quantum startups to move to larger markets such as the US, and acknowledge the urgency in needing to support local industry at this time. Cognisant of Australian industry concerns with inviting foreign competition, the field should not be considered through the lens of a zero-sum game, rather more participation from global players will build up the scale, breadth and momentum of the Australian quantum industry to unlock further opportunities for all.

3.1.3.11. Building relationships

The Australian government is eager to kick start national collaboration in quantum and build genuine partnerships across all sectors of the quantum ecosystem. These relationships can be transnational, with similarly-minded countries such as Japan offering a good opportunity for engagement.

In the complex landscape of the current quantum ecosystem, functioning relationships require trust between end users, firms, government, and others. CSIRO's mechanisms of internal SMEs regularly interacting with industry in their domains can be a pathway for the quantum context as well, and DISR is also looking at how to build the bridge between companies looking to use or invest in quantum. The industry certification and standards will also be key components, however, it is still too early.

Relationships also need to have clear value exchange communicated between parties, especially with the long gestation period for quantum technologies at this stage. In addition to de-risking, there also needs to be effort in highlighting groundbreaking future use cases that engage the imagination.

3.2. Experiential Futures Workshops

The second major component of the symposium was the futures workshops. These were used to immerse participants in a 2050 timeframe and have them generate innovative concepts for future QC technologies and capabilities.

Syndicate groups comprised diverse SME representation (e.g. from academia, industry and government) to ensure cross-pollination of ideas and group diversity.

3.2.1. The Scenario

To guide conceptual thinking about future QC use-cases and their development pathways, participants were presented with a scenario, based on a future space weather event. Through creative media, participants were immersed in the year 2024, where a large solar flare had occurred in our region, causing major disruption.

Details were provided regarding the impact to Australia at the time of and 4 months after the incident. This presented a set of environmental challenges that QC use-cases would have to operate under or would provide a resolution to solar flare implications. After initial consideration of the scenario through the first breakout exercise, participants were asked to imagine the year 2046 where a second space weather event was imminent. In this phase of the scenario, development of use-cases was influenced by the ability to prepare for the incident, using potential learnings from 2024.

Under this scenario environmental challenges included direct impact on:

- radio communications
- energy
- space infrastructure.

Societal impacts included:

- shutdown of trade and large-scale loss of supply
- credit lines ceased
- protests
- increase medical need (physical and mental health).

Political implications included:

- need for greater food security
- concerns of digital and technology reliance

- demand for accessible healthcare
- investment in protective measures.

Participants were tasked with developing QC-enabled future use-cases, through the lens of this scenario, and in the context of themes described in Section 3.2.2.

3.2.2. Themes

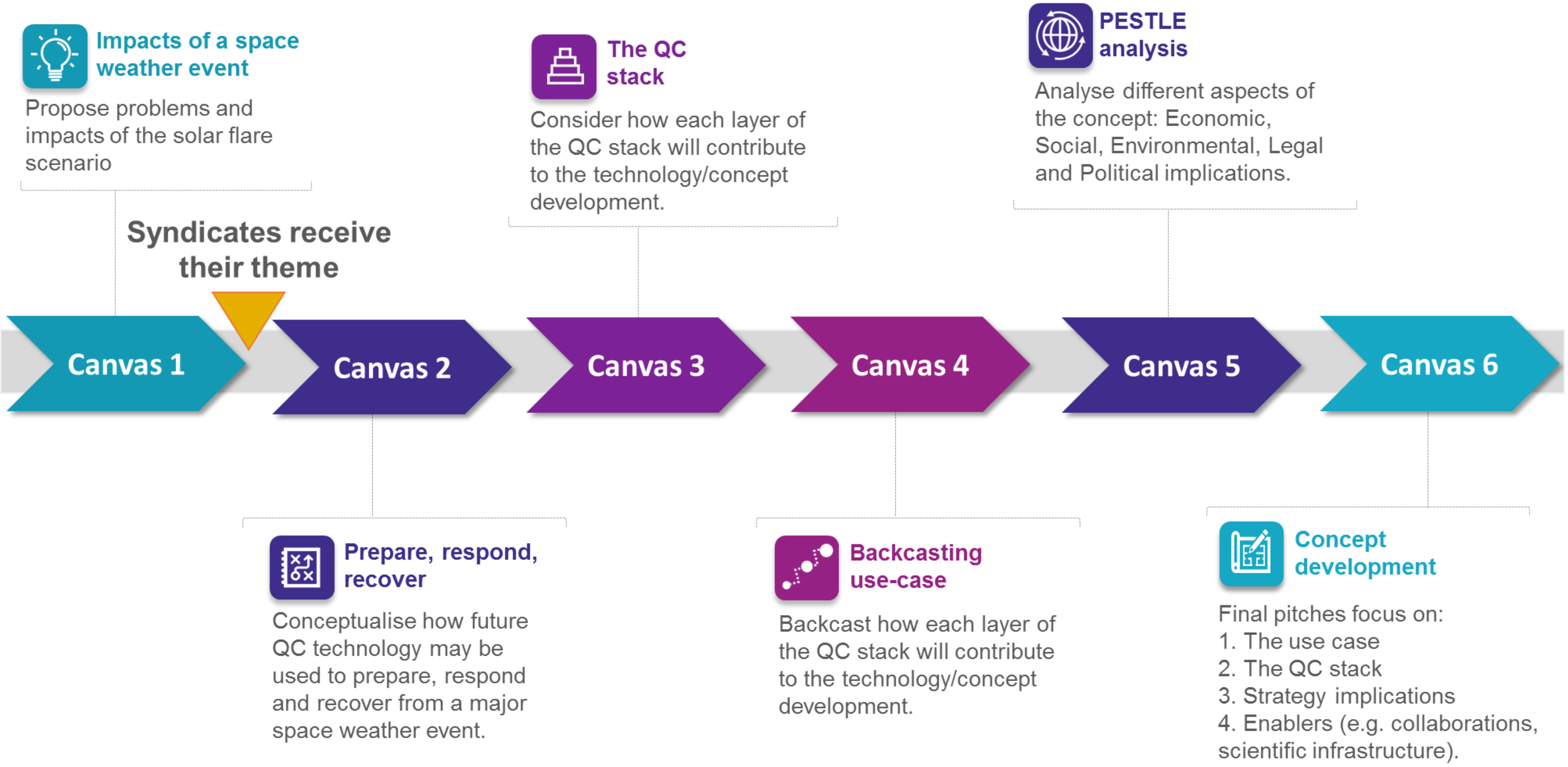
A key objective of the QC EDTAS was to identify how QC technology opportunities may influence strategic planning, guide longer-term investments and support a national research agenda. Four application-focussed themes were applied to workshop activities in order to tease out diverse views and perspectives for how this may be achieved.

The 4 themes explored were:

- **People and Platforms**
    - The theme focusses on the design and evolution of platforms, their systems, and the role of people, to build resilience in dynamic operating environments.
- **Sensing and Sense-making**
    - The theme encompasses the range of concepts and capabilities to sense the environment and undertake sense making of complex systems.
- **Intelligent Decision Making**
    - The theme focusses on the ability to improve situational awareness and understanding to enhance decisions in complex dynamic environments.
- **Cyber and Communications**
    - The theme examines how information, computing, networks and communications can be hardened and more resilient.

3.2.3. Structure of the Workshops

There were 6 components to the workshop activities. The different canvases participants completed throughout the symposium enabled exploration of different aspects of their proposed use-case. Figure 1 describes the workshop component of the EDTAS.



Impacts of a space weather event

Propose problems and impacts of the solar flare scenario

Prepare, respond, recover

Conceptualise how future QC technology may be used to prepare, respond and recover from a major space weather event.

The QC stack

Consider how each layer of the QC stack will contribute to the technology/concept development.

Backcasting use-case

Backcast how each layer of the QC stack will contribute to the technology/concept development.

PESTLE analysis

Analyse different aspects of the concept: Economic, Social, Environmental, Legal and Political implications.

Concept development

Final pitches focus on:
1. The use case
2. The QC stack
3. Strategy implications
4. Enablers (e.g. collaborations, scientific infrastructure).

Figure 1. Syndicate workshop activities. After canvas 1, syndicates received 1 of the 4 themes (people and platforms; sensing and sense-making; intelligent decision-making; or cyber and communications) through which to develop their use-case around.

3.2.4. Analysis of the Syndicate Outputs

Thematic analysis of syndicate ideas identified a series of trends, contentious ideas and wildcards. A summary of these is given in the below section, and the detailed ‘raw’ outputs are provided in the Appendix (A.5).

3.2.4.1. Challenges

Challenges to the realisation of QC are broad and varied:

- **Societal (including education)**
    - Greater attention needs to be given to adequately identifying and considering potential societal challenges to the technology’s realisation.
    - More STEM in schools, including early physics education, is needed to ensure that an adequately trained workforce can support the growing quantum sector.
    - Quantum literacy of the broader population will enhance buy-in from the public.
    - Privacy and consent issues may arise, particularly if QC is used to analyse large and diverse datasets (potentially including personal information).
- **Environmental**
    - Manufacturing of QC may require mining of finite and rare minerals.
- **Political**
    - There may be a need in the future for the introduction of metrics to national QC power, similar to metrics assigned to other national status elements such as GDP. This metric will signal who the high-tech nations are.
    - International agreements may reduce the burden to collaboration in quantum R&D.
    - A unifying narrative is required that brings academia, industry, and government together. This will help prioritise investment and outline the intention to develop and support key technology hubs.
- **Infrastructure**
    - There is an urgent need to plan for the development of infrastructure if Australia intends to build sovereign capability (this includes power, communications networks, foundries, and reliable materials supply chains).

    - Energy will be a major consideration in delivering QC. An overarching professional body to maintain standards and advise government will be required.
- **Regulatory**
    - Trade rules to secure consistent supply, foundries, and partnerships will be essential to realisation and sustainment of QC.
    - Streamlined IP and revised export control laws will remove the barriers to partnering and forming start-up companies.
- **Workforce**
    - There is an imperative for people outside the quantum physics community to be included (e.g. chemists, computer scientists, electrical engineers), and similarly, that these communities become 'quantum aware'. There needs to be strong translation between industry to academia, and convenient ways to transition between academia and industry.
    - As the quantum workforce becomes more highly sought after, globally, Australia will be challenged to retain skilled personnel.
- **Economic**
    - QC is 'high risk, high payoff' technology. This will require an entrepreneurial investment approach and tolerance of failure. Public investment can reduce risk barriers imposed on small companies.
    - Pursuance of grant funds, streamlined foreign capital investment, and sustained economic pathways will be required for QC development.
    - Government incentives may be used to drive industry transformation and talent retention.
- **Sovereignty**
    - A 'sovereign compatible' capability is required, whereby all elements of the technology are not confined to one particular country, but perhaps through an 'allied network' and collaborative partnerships between countries.

3.2.4.2. Opportunities

Key opportunities that syndicate groups identified are described below. These are described within the context of their themes.

People and Platforms

The key opportunity within the People and Platforms theme arose from utilising QC to design advanced materials. Set against the scenario of an imminent solar flare, there were 3 specific types of materials to design.

- Prepare: Shielding material against electromagnetic pulse, heat, and other dangers
- Respond: Materials resistant to damage and/or can capture that energy and store it
- Recover: Self-healing materials

The following were identified as critical enablers in the design of advanced materials using QC:

- Outreach and education (quantum literacy) starting at school age
- Energy efficiency for QC and material production life cycle
- Collaborative global community
- Foreign investment review board and export controls with non-restrictive tailored approaches
- Greater support for manufacturing infrastructure

Sensing and Sense Making

The key opportunity within the Sensing and Sense Making theme was autonomous search and rescue systems. This could be achieved utilising hybrid quantum and classical simultaneous localisation and mapping (SLAM) powered by hybrid quantum-classical computing. The second proposed use-case described the development and deployment of a ubiquitous quantum biosensor network for large-scale monitoring of environment.

The following were identified as critical enablers in the design of quantum-enabled sensing and sense making applications:

- There is an overwhelming need to continue to grow and mature STEM in industry.
- Policy initiatives addressing the ethical use for QC for sense-making (e.g. will QC-enabled ‘sense-making’ be high quality enough for evidence in judicial courts, or for military targeting?).
- Streamlined foreign capital investment may expedite the pathway towards technology development and deployment.

- Because sensing and sense-making will likely be conducted on hybrid classical-quantum systems, there's a need to continually improve classical computational capability.

Intelligent Decision Making

The key opportunity arising out of the Intelligent Decision-Making theme was environmental modelling and the development of digital twins. These models would be trained on highly diverse data sources (potentially from distributed sensors in the internet of things). A QC (likely coupled with high-performance classical computers) would analyse the data and refine models. These digital twins would be used to protect critical infrastructure in the event of a solar flare and optimise recovery.

Environmental modelling will require:

- distributed multi-modal sensors to capture diverse data sources
- advanced communications networks to transmit the data
- distributed classical and quantum computers to analyse the data.

To enable environmental modelling the following is recommended:

- political and economic buy-in
- development of standards and agreements
- improved and optimised manufacturing and supply
- quantum workforce and establishment of small-to-medium enterprise
- development of centralised quantum computing.

Cyber and Communications

The key opportunities arising from the Cyber and Communications syndicates included:

- multi-scale quantum networks capable of:
    - secure and full-bandwidth communications network using quantum link verification
    - superior Earth observation capabilities through use of a quantum-controlled telescope
    - blind quantum computing using homeomorphic encryption to/from server.

A second concept described development of quantum-assured communication networks between allied nations during response and recovery. Within this use-case, quantum optical networks secured by shielded end-points would allow for continuous transfer of information with verification of authenticity through quantum verification algorithms and analysis of content (misinformation analysis). A universal quantum computer based on photonic qubits is core to this system.

Key enablers for these concepts, included:

- establishing a high-tech workforce
- a uniform national approach to moving IP from universities to application
- establishing photonic and electronic foundries with guaranteed industrial access.

3.3. Collaboration in Quantum Computing Research

Quantum computing is extraordinarily difficult and the process relies on ultra-precise manufacturing using ultra-pure materials to control quantum phenomenon at the atomic scale. What’s more, quantum computers need quantum algorithms that take full advantage of the special properties of quantum computers to realise gains over their classical cousin. For these reasons collaborations in quantum computing have been key to achieving success in the field. Below is a brief description of select examples of collaborations within Australia’s quantum ecosystem:

3.3.1. Examples

University of Melbourne + IBM

First started in 2017, University of Melbourne joined IBM’s Quantum Network to start the first quantum hub in Australia. Researchers, students and IBM staff all collaborate together to work on some of the biggest problems in quantum computing. The research hub is led by Professor Lloyd Hollenberg from the University of Melbourne. Teams at the quantum hub created the accessible Quantum User Interface (QUI) that is currently used for research and teaching across the globe.

University of Western Australia + Pawsey Supercomputing Centre

The UWA/Pawsey Quantum Computing Centre for education (UP-QCC) collaboration seeks to empower the next generation of quantum thought leaders through a collaboration program. Through the program, 25 undergraduate students from UWA will access and experiment with SpinQ desktop quantum computers, under the guidance of renowned quantum physicist Professor Jingbo Wang and her team. This will program will help to develop a quantum mindset among current and future researchers.

SQC + Silex Systems

A partnership between 2 Australian companies to create a supply chain for silicon quantum materials.

RMIT + La Trobe + Quantum Brilliance

A research hub to consolidate expertise in diamond quantum materials and train the next generation of researchers.

Quantum Brilliance + Pawsey Supercomputing Centre

A multiyear partnership that has resulted in Pawsey Supercomputing Quantum Innovation Hub and deployment of a quantum computer inside the Pawsey whitespace. In addition, this collaboration hosted the first cohort of the Pawsey Pioneers Program bringing together Trellis Data, Quantum South, University of Melbourne and University of Western Australia to work on large scale quantum simulations.

CQC2T and EQUS

These 2 ARC research groups bring together 10 leading research institutes to tackle problems from fundamental research, physical devices to quantum algorithms.

Army Quantum Technology Challenge

A yearly challenge put on by the Australian Army to explore quantum technologies on the battlefield. The challenge attracts consortium of academics and private companies showing how quantum technology can be utilised for Defence.

3.3.2. Challenges

Despite the success so far in the broader quantum ecosystem to form partnerships and promote collaboration, the sector does face several challenges.

IP Considerations

Many Australian research institutes have extremely strict IP protections around work generated by their researchers. IP clauses are often complex and are non-standard across institutes, making multi party collaborations difficult. The difficulty of IP can also deter the commercialisation of research.

Infrastructure

Despite Australia's global advantage for quantum research, we have very few facilities that are well tooled for commercialisation of research. This includes a lack of pilot production facilities, test environments and collaboration hubs (NOTE: the Morrison government announced such a hub). The lack of infrastructure makes it difficult for partnerships and collaboration aimed at commercialisation to be formed in Australia, with many players looking overseas for support.

Quantum Awareness and Talent Attraction

A major barrier to collaboration with non-quantum industries is the lack of quantum awareness and education in the Australian economy about the possible impacts of quantum computing. Due to small local talent pools, it is difficult for Australia's non-quantum industry to hire the talent needed to build the internal business capabilities that would allow them to collaborate with Australia's quantum ecosystem.

Security Regulations

Security regulations placed on quantum technologies may limit whom parties can collaborate with (examples include foreign investment controls, defence import/export controls and certification programs like DISP).

3.3.3. Opportunities

Significant Industry Opportunities

One of Australia's biggest advantages in quantum computing is access to a large economy with multiple industries that stand to directly benefit from quantum computing. Mining, petrochemical, agriculture, pharmaceutical, defence and our growing aerospace industry are all prime partners for future collaboration in quantum computing with both universities and the private quantum sector.

Sophisticated Software Industry

Much like classical computers, quantum systems require software and firmware to do useful tasks. Over the past decade Australia has shown we have a very capable software engineering industry. Tapping into this established industry to form collaboration and pipelines for talent is a massive opportunity for quantum in Australia.

Two ARC centres + CSIRO + over 10 world class universities

Australia already has a world class academic quantum ecosystem. Expanding these networks would allow for greater collaborations across areas of expertise not covered by these groups. These networks also have considerable talent, equipment and knowhow that could be further utilised to accelerate Australia’s quantum goals.

Two Tier 1 Supercomputers – NCI + Pawsey

Although counter intuitive, classical supercomputers are vitally important in the development of quantum algorithms and applications. Australia having access to 2 top tier facilities significantly lowers the barriers to entry for collaboration across Australia for the creation of quantum applications. Using simulation supercomputers can de-risk quantum software development and reduce production timelines.

4. WHAT NEXT?

Insights captured in the Technology Opportunities Symposium will undergo analysis, refinement and prioritisation by DSTG. Some of these key insights will be explored and tested with Defence stakeholders at the next stage of the EDTAS campaign, the Military Implications workshop, planned for October 2022.

This prioritisation process will consider how QC use-cases and their associated technology ‘stack’ elements may impact Australian Defence and National Security in 2040.

The Military Implications workshop will provide a mechanism for Defence to assess the impacts of QC strategic research opportunities on Defence capability. The outcomes of this activity are intended to inform planning about Defence’s future posture and investment towards QC.

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- The Next Generation Technologies Fund
- Dr Cathy Foley, Australia’s Chief Scientist
- Defence officials who attended from the US, Republic of Korea, UK, Japan and Singapore
- Attendees at the Technology Opportunities Symposium: representatives from across Government and the ADF, scientists, enterprising entrepreneurs and industry partners.

APPENDIX A.

A.1. The EDTAS model and conduct of the Technology Opportunities Symposium

DSTG undertakes foresight and futures studies to better understand the strategic landscape of key technology themes. These studies allow Defence to anticipate future emerging and disruptive technologies and novel capability concepts and uncover the important research challenges and opportunities that lie ahead, which require awareness or action by government, academia and industry.

Each EDTAS theme is explored via 3 phases:

- Phase 1 – Problem Definition: Identifies the key stakeholders, potential applications, capability implications and key issues of the technology theme and recommendations for the conduct of subsequent phases.
- Phase 2 – Technology Opportunities: Explores a broad technology theme, its associated advances, breakthroughs, and trends and defines capability opportunities that could be achieved with technology advances.
- Phase 3 – Military Implications: Explores future Defence capability needs and how emerging technology might be used to ensure an enduring capability advantage for Defence.

A.2. EDTAS participants

The technology opportunities symposium was attended by a wide range of quantum computing SMEs and policy professionals. Over 80 participants joined the EDTAS in-person, and over 20 virtually. This included representation from 10 Australian universities, 17 industry corporations, 8 government organisations (including international ones) and representatives from 6 countries (Australia, US, UK, Japan, Republic of Korea, Singapore).

A.3. EDTAS partnerships

DSTG partnered with 3 Australian research consortia to support the design and delivery of the EDTAS on Quantum Computing.

In March 2022, an open call went out seeking applications to partner with DSTG in the co-development of the programme including shaping themes and identifying thought leaders to deliver presentations.

Three partners were selected to support the EDTAS. Their roles and responsibilities are briefly described below.

Partner 1

Partner 1 comprised a consortium of institutions, including The University of Melbourne, IBM Quantum and Quantum Brilliance. Partner 1 was responsible for the identification and organisation of appropriate representatives to speak at the *Algorithms and Applications* section of the symposium. Partner 1 prepared the summary and overview of *Algorithms and Applications* keynote and panel session, which is provided in Section 3.1.1.

Partner 2

Partner 2 was the ARC Centre of Excellence for Quantum Computation and Communication Technology (CQC^{2}T) – headquartered at UNSW Sydney. Partner 2 was responsible for the identification and organisation of appropriate representatives to speak at *The Stack: Competing Technologies* section of the symposium. Partner 2 prepared the summary and overview of *The Stack: Competing Technologies* keynote and panel session, which is provided in Section 3.1.2.

Partner 3

Partner 3 comprised a consortium of institutions, including RMIT University, La Trobe University, Quantum Brilliance, H-bar Consultants and Pawsey Supercomputing. Partner 3 was responsible for the identification and organisation of a dinner speaker during the EDTAS event. Partner 3 prepared a summary of *The importance of collaboration in QC R&D,* which is provided in Section 3.3. Partner 3 will continue to work with DSTG in conducting an activity aimed at student innovation and STEM pipeline stimulation.

A.4. Syndicate themes

Syndicates received one of four topics to guide their brainstorming activities and future use-case development. A detailed description of each of these topics is provided below.

A.4.1. Topic 1 – People and platforms

The theme focusses on the design and evolution of platforms, their systems, and the role of people, to build resilience in dynamic operating environments. For example the enhanced ability to design novel materials through chemical simulation. These may be biological materials that are designed to improve speed of chemical discovery (e.g. medicines, chemical countermeasures, agricultural agents, etc.); or they may be non-biological and used to build superior technology (e.g. room temperature superconductors, high temperature materials, etc.). Quantum machine learning could enhance the speed of chemical and material discovery. Optimisation and modelling may augment the ability of people and platforms to survive and act in dynamic environments.

A.4.2. Topic 2 – Sensors and sense-making

The theme encompasses the range of concepts and capabilities to sense the environment and undertake sense-making of complex systems. This may include designing, deploying, optimising and processing data from novel and diverse sensors coupled together. Potential benefits could include improved high and low detection limits and increased stand-off detection. Advanced sensors will likely benefit from reduced SWAP-C features. Sense-making may leverage distributed, hybrid and mesh concepts to increase functionality and processing capabilities. Sense-making could also include novel signal and information processing techniques to interpret and understand raw sensor data. New computer architectures and methodologies might improve detection and positive identification of weak signals in cluttered environments.

A.4.3. Topic 3 – Intelligent decision-making

The theme focusses on the ability to improve situational awareness and understanding to enhance decisions in complex dynamic environments. The ability to interpret data and provide viable solutions may become exponentially faster in some cases. Quantum machine learning, modelling and optimisation could provide enhanced speed and accuracy for decision-making tasks.

A.4.4. Topic 4 – Cyber and communications

The theme examines how information, computing, networks and communications can be hardened and more resilient. Quantum-enhanced modelling of networks will assist in detecting intrusions, optimising performance or adapting to failures. Quantum-based networks could be supported by quantum computers that can route and fully exploit quantum data at a global or local scale.

A.5. Syndicate Concepts/Use-cases

Each syndicate in the experiential futures workshops developed a concept for new technologies within the context of their allocated technology topic (e.g. People and Platforms; Sensing and sense-making; Intelligent decision making; and Cyber and Communications). Short summaries of the concepts developed by each syndicate are provided below, in Tables 1–9.

A.5.1. People and platforms

Table 1. Future QC technology concept 1.

Syndicate name:	***Whovian Skywalker's***
Use-case	QC for advanced material design. QC will enable simulation of theoretical novel materials and analysis of their properties. QC will also assist in finding effective methods for synthesising these materials. These materials will be used for: • Shielding (EM reflective, refractive or absorbing) • Building resilient components (i.e. circuits that are less impacted by EM) • Self-healing components (i.e. significantly faster and cheaper to repair, perhaps without any external input) Major weakness is the need to simulation algorithms and software – this is a long way off and not a very active field of research at the moment.
The-stack	• The use case is physical size ambivalent • Qbit scale of 107+ required • Cloud or QC supercomputer (i.e. large centralised QC capacity)
Strategy	• QC workforce development • Partnerships – private + public, Government + academia • QC materials design methods and algorithms • Hardware development – qubits, cryo CMOS
Enablers	• QC professional body + lobby group • QC multidisciplinary education and hiring (i.e. not enough QC educated people are hired by research groups in other fields) • Development of VC and Entrepreneurial culture (esp. acceptance of failure in Aus. Start-ups) • Accepted QC standards and protocols

Table 2. Future QC technology concept 2.

Syndicate name:	***Androids dream of electric sheep***
Use-case	Design of novel materials to improve system resilience. Examples may include room-temperature superconducting shields, switchable electromagnetic materials, radiation and energy capture materials, self-healing materials and advanced battery materials and designs.
The-stack	***Algorithms and applications:*** • Better simulation algorithms (VQE) • Verification of results ***Software, compilation and control:*** • Quantum error correction codes • Quantum/classical compiler • Integrated libraries ***Hardware:*** Classical (cryo) control electronics and cooling infrastructure (cryostats, materials) ***Qubits:*** High-fidelity (coherent) qubits, possibly topically protected, perfect materials Qubit real-estate (size, power, fan out) ***Networking and integration:*** Smooth integration of stack Quantum interconnects (modular, distributed)
Strategy	***Technology development:*** flexible, specific foundries for mass manufacture

	Algorithms and applications: demonstrate capability on simple problem before tackling more complex problems. High level, abstract material simulation language (DSL) ***Software, compilation and control:*** Optimised compilers and reduced QEC overhead. ***Hardware:*** dense, interconnected chips; modular architecture with communication via entanglement. ***Qubit:*** high fidelity, towards high temperature operation ***Strategy, policy and programs:*** government to foster a collaborative community.
Enablers	***Social:*** outreach and education (quantum literacy) starting at school age ***Environmental***: energy efficiency for QC and materials production; lifecycle of materials. ***Political:*** collaborative global community, global political stability; support low TRL research. ***Other technology:*** material supply (^{3}H, ^{28}Si); laboratories; manufacturing facilities. ***Legal:*** foreign investment review board and export controls to become non-restrictive and apply fast, tailored approaches. ***Economic:*** strategically patient venture investment; greater support for manufacturing infrastructure.

A.5.2. Sensing and sense-making

Table 3. Future QC technology concept 3.

Syndicate name:	***Quantum Fireflies***
Use-case	The concept was a novel method to grow quantum bio-sensors that would be ubiquitous (like growing yeast). The sensors need not be resilient, because if the sensors were destroyed in a flare event, they could easily be regrown in a distributed manner. The bio-sensors would be part of a human monitoring/augmentation system that would enable assessment of individual and population health. This data could then be used in strategic planning to increase resilience, guide/optimise response that would lead to a faster recovery in the event of a significant solar flare event.

The-stack	• The sensors would require quantum design and optimisation of bio-molecular systems. • The distributed sensor network would be enabled by ubiquitous quantum networks and large scale quantum data analytics. • Bio-compatible qubits (like NV nanodiamonds) created via biological fabrication.
Strategy	• Develop a bio-technology policy that would create a social license that would address the potential threat to widespread adoption of human augmentation. • Develop a roadmap for quantum bio-sensor design and fabrication. If this is an exceptionally beneficial capability, a Manhattan Project style approach could be applied to align public, private and academic resources. • The availability and analysis of data at individual through to population level would be a significant benefit to the nation.
Enablers	• Government vision and long term commitment to fund quantum research and commit to sovereign quantum manufacture. • Identification and communication of the individual and corporate benefits of supporting this concept would be required to gain buy-in and commitment. • A program and associated funding to attract and train multi-disciplinary researchers to work in quantum. This would result in 'cross-pollination' and generate benefits in unrelated areas. • Funding, a lot of funding.

Table 4. Future QC technology concept 4.

Syndicate name:	***Ant-Man Charlemagne***
Use-case	Hybrid Simultaneous Localisation and Mapping powered by classical-quantum computing for autonomous search and rescue systems. The envisioned design is teamed air vehicles that can be released following disasters to autonomously conduct search and rescue in environments which differ significantly from known, pre-event terrain. These drones will be at the forefront of first response, dramatically increase efficiency in utilisation of limited rescue assets, while also relaying their collective mapping of the new environment back to coordination centres.

The-stack	***Hardware:*** Array of quantum and classical sensors operating in concert, including quantum gyroscopes, quantum LIDAR, quantum magnetometers, and quantum gravitometers. Edge quantum computing hybridised with classical computing. ***Software:*** Quantum machine learning, sensor auto-calibration, quantum data processing, and data visualisation. ***Network:*** Drone teaming mesh, SLAM data distribution among drones and return transmission to command, and interfacing with the hybrid quantum and classical systems. ***Algorithms:*** The quantum SLAM algorithm, learning-without-training search algorithms, and error correction algorithms for quantum computing. ***Qubits:*** Room temperature qubits to be edge-capable, sufficiently ruggedised to survive challenging environment.
Strategy	• Initiate talent programs to build requisite human capital, establishing dedicated qubit research grants to facilitate necessary breakthroughs in qubit quality. • Development of the traditional manufacturing industry needs to take place concurrently to enable prototyping and fabrication efforts of associated adjacent technologies. • Fund technology research challenges to coordinate research efforts in common direction, and incentivise both competition and collaboration.
Enablers	• Long-term strong leadership will and government commitment to research areas that do not have immediate returns, supported by messaging that gives the social license to utilise these technologies. • Streamlined avenues for accessing foreign capital, more grant funding, and sustainable economic pathways for steady technology development. • Reduced regulatory burden in meeting security needs, intellectual property frameworks that are friendly to researchers and academia, and leveraging hybrid of closed and open-source technology. • Continued research and achievements in traditional technology fields such as material science, improved classical computing, power generation and energy storage, etc.

A.5.3. Intelligent decision making

Table 5. Future QC technology concept 5.

Syndicate name:	***The quantumplators***
Use-case	Quantum Computing is used to reduce damage to and optimise the recovery of the energy grid through the use of a digital twin model that is updated in real-time, based on a very large number of inputs from hybrid information sources. The concept leverages the advantage of QC in conjunction with HPC in accelerated processing of rich information inputs, including from various parts of the IoT. Algorithms are used to optimise the prioritised restoration of power.
The-stack	***Algorithms and applications***: Large-scale modelling of the grid system. Control over the power grid to shut down parts before the event. Assessing the status of energy grid infrastructure. Use of real-time power grid model with simulation of different scenarios for optimised restoration according to prioritisation of power requirements. Rapid response ***Software compilation and control***: Ability to perform quantum error correction for fault-tolerant quantum computing. Efficient transpilation of the algorithm. Rapid calculations and outcomes. Speed of processing and rapid (mili-second level) decisions and response. ***Hardware***: Tens of millions of qubits able to carry out quantum error correction. Edge-processing for sensors, potentially using miniaturised quantum computers. Distributed sensor network that is resilient to the storm. Distributed network of quantum computers for greater resilience. Room-temperature operating QC. Speed of response may be more important than high level of fault-tolerance. ***Qubit***: Physical error rates for all components, gate operations and read-out well below fault-tolerant threshold. ***Networking and integration***: Working with hybrid information sources via a satellite-independent communications network capable of graceful degradation and intermittent syncing.

Strategy	***Technological:*** NISQ applications to AI and optimisation; evolving hardware environment and working towards fault tolerance; developing satellite-independent communications ***Algorithms and applications:*** Modelling grid behaviour (as first point of effort); pre-emptive modelling of the entire scenario and event recovery; modelling weather effects. Digital twin model: incorporating perturbation effects across the entire grid (weather, communications failure, transmission lines, etc.). Prediction, optimisation and control. ***Software, compilation and control:*** Handling ever-increasing number of hybrid inputs without having to re-build quantum chips; interface with supercomputers and data processing centres ***Hardware/Qubit:*** Access to state-of-the-art QC with sufficient number and quality of qubits in fault-tolerant regime. Australian developments in qubits incorporated by strategic partners ***Strategy/policy:*** AU government collaborating with smaller-scale algorithm and software developers for niche applications; bringing together expertise in QC, computer science, and power and energy; addressing supply chain restrictions.
Enablers	***Social:*** Energy security and resilience as part of social conscience; targeting research projects/PhDs towards this; early sponsor and early end-user to drive adoption of technology ***Environmental:*** Emphasis on renewables creates distributed generation points with multiple points of failure, more complex transmission infrastructure; this creates more complex grids ***Political:*** Political imperative following disasters can be leveraged to justify R&D; overcoming short-term, risk-averse nature of politics. Defence/national security – higher level of investment. Leadership in R&D and forum for dialogue with the government. Collaboration, partnership. ***Other technology:*** Low-cost sensors, proliferation of networked devices, IoT, satellite-independent communication network; miniaturisation of QC for edge processing; resilient energy storage - IoT ***Legal:*** Legal framework for ease of transfer of technology/software components through supply chains (strategic partners); ITAR restrictions; data privacy framework to build trust in IoT ***Economic:*** Some of the cost of concept development will be absorbed in the development of renewables-powered grid. Funding for critical TRL points.

Table 6. Future QC technology concept 6.

Syndicate name:	***TARDIS***
Use-case	Use a 'digital twin' to model critical intelligent decision-making in communication-denied environments. Less focus on how to collect data from sensors, more about developing a predictive capability to get an understanding of how your international partners or non-local partners may adapt to a changing situation Can we predict how complex networks, like supply chains, will adopt to the event and optimise our response. This is a massive problem requiring complex optimisation and Artificial Intelligence and would require something on the scale of industrial, high-performance computing that we have now except quantum-enabled and just "better" than what we currently have. This digital twin model will support superior decision-making before, during and after the solar flare.
The-stack	A very difficult problem in AI and optimisation (traditionally an area where quantum computers are thought to have limited potential, with a lot of basic groundwork to be done before quantum computers to be used to in this issue). ***Algorithms and applications*** • Fundamental progression quantum advantage in Artificial Intelligence and OPT • Need a community of people who are educated in a future version of Quantum-enabled heuristics in order to develop such a system ***Software*** • Full quantum programming/software stack that works with a sophisticated quantum + classic high performance computing architecture (e.g. compilers, LLUN, programing languages, instruction sets, libraries need to have existed for at least 10 years prior to undertaking this task). ***Hardware*** • Our group wasn't thinking about interconnected networks but thinking more of a robust/deployable/locally-available computer resource to have access to

	• Require high classical data in and out speeds, complex packaging • Integration with high performance classical computers ***Qubits*** • Need a lot and needs to be error corrected • Require an architecture with high connectivity with classical and quantum compute and quantum RAM
Strategy	This industrial-scale quantum computer on the scale of high performance computing requires fundamental research on software and architecture Develop quantum systems engineering (developing Qubit, hardware, software targets and standards) on a ten-year time-frame Build Qubit foundry(s) based on the information coming out of the SME community Application development is also a multi-year process The time line really dictated our strategy (need key technologies to be manufactured at top peak performance/understanding by ten year, minimum, to reach our goals)
Enablers	1. Assuming infinite money available 2. Goals aligned early in the process 3. Require a large amount of education and talent and communities of scientists and developers who are going to work together (e.g. develop open-source standards for quantum software) 4. Part of that would be an active quantum computing and classical computing ecosystem that works together 5. Agile and enabling regulatory environments 6. Full value chain realised and enables more money to be generated to facilitate this process

Table 7. Future QC technology concept 7.

Syndicate name:	***Time variance authority***
Use-case	The proposed use-case is to leverage the strengths of both classical and quantum computation in a hybrid computation network that is able to: • Collect classical and quantum sensor data on a truly modern scale • Use data to model scenarios, and their impact to political, social, infrastructure systems • Use models to create plans for the allocation and distribution of scarce resources • inform action to pre-empt threats to Australia's national security The network is to have the following characteristics: • Distributed and robust to loss of nodes • Intelligently distributes classical and quantum computing power to tasks suiting those platforms • Reliable and trusted by users and citizens • Sovereign capability, with capacity for allied system integration baked-in
The-stack	• A hybrid system consisting of classical and quantum computation power required to model systems from very large amounts of data • A vast sensor network and data collection scheme is required for generating the data required for a large computing network • The network needs to be distributed with redundancy measures to ensure the network is robust to node loss • Quantum memory and fault tolerant quantum computers with reproducible measurements required for quantum components of network • Both classical and quantum computing components require metrics with which to validate performance in operation • Network needs a robust communications technology such as optical communications between nodes
Strategy	• Standardise communication protocols for components within the stack and between network nodes • Secure of supply chains both in relation to adversarial attack and robustness to environmental disasters • Develop high level languages, debuggers and DEVSECOPS practices in the quantum computing space • Train and support users and developers of quantum computing leveraged systems

	- Develop modelling methods for disaster scenarios and optimisation algorithms for disaster scenario recovery - Develop a QC workforce that spans the breadth of the effort required to build QC technology; from sourcing raw materials and manufacturing, to high level software development and cutting edge research - Conduct technology foresight and current technology reviews to measure the progress of the industry on a fine-grained level - Develop security protocols and engage the users and stakeholders to ensure the technology is trusted and verified
Enablers	- Standards body for communications protocols - Legal policies for vast nature of data collection, protection of privacy - Social awareness and trust in the storage, processing and purposes of the data collection - Political agreements for sharing of data between partner states - Funding and incentives for hardware breakthroughs and promising quantum technologies - Investment in Australian QC companies to enable expansion as Australian grown QC world-beaters - Sell the opportunities and national security benefits of QC technology to the people, ensuring that the technology is trusted and secure - Invest into the quantum workforce with PhD scholarships and apprenticeships - Independent trusted advisory to the government on QC issues - Stable energy supply and government funding commitment

A.5.4. Cyber and communications

Table 8. Future QC technology concept 8.

Syndicate name:	***Pacifically quantum***
Use-case	*Multi-scale quantum networks* Secure full-bandwidth communications: quantum link verification Earth observation: 100 km large aperture telescope from space Blind quantum computing: homeomorphic encryption to/from server
The-stack	***Control/software***: Error correction. Classical networking protocols running in parallel with quantum (plus some new quantum protocols) ***Hardware***: Fast low-loss optical switching, quantum memory, quantum interconnects, quantum repeaters, ground-to-space tracking.
Strategy	• In next 12 months: Establish 7-year Centre focussed on quantum networks • In next few years: Continue stream of startup companies in quantum tech (9 in last 2 years!) • Work with industrial and academic partners (e.g. Defence primes, Australian space-laser company, Space Trailblazers, etc.)
Enablers	1. Establish all aspects of a high-tech sector in Australia: TAFE, technicians, modern electronic engineers, coordinated support for other high-tech industries 2. Uniform national approach to moving IP from Universities to application. Establish photonic and electronic foundries with guaranteed industrial access, such as IMEC, etc.

Table 9. Future QC technology concept 9.

Syndicate name:	***Psi Corps***
Use-case	Quantum-assured communications between allied nations during response and recovery. Quantum optical networks secured by shielded end-points allow for continuous transfer of information with verification of authenticity through quantum verification algorithms and analysis of content (misinformation analysis). A universal quantum computer based on photonic qubits is core to this system.
The-stack	***Qubit:*** Can use existing qubits but it is possible to also develop and research brand new materials to generate qubits suitable for application. ***Hardware:*** Quantum memories, ultra-low-loss optical components and interfaces. Foundries are also needed. Quantum computing-optimised materials for qubit interactions. ***Software:*** Fast quantum control, measurement, as well as fast classical processing ***Algorithms:*** Machine learning for identifying misinformation. Quantum authentication ***Integration:*** Smaller quantum computers as repeaters. Networking with optical qubits. Early quantum computing systems used to simulate new materials to develop the required quantum computer for information verification.
Strategy	Highly skilled quantum workforce Good supply chain/good supply of materials incl. work on novel materials required for high quality materials (e.g. shielding). Quantum ISO standards Quantum-ready technological hubs (stores information that is to be transmitted over the network).
Enablers	Enduring government funding for basic research Trusted users willing to support the network between nations (trust must be established before the network is established). Hubs have room temperature superconductors to deflect cosmic rays

	Intermediate commercial (or other) users are required to ensure the successful development of the final system Good legal infrastructure that balances the security of the infrastructure with the openness that is required to actually build the system.

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