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# Future Directions in Quantum Information Science: A Joint Workshop Between the United States and Australia

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# Executive Summary

Steeped in a combination of physics, computer science, and electrical engineering, the field of quantum information science (QIS) applies the peculiar characteristics of quantum mechanics toward the processing, transmission, retrieval, and storage of information. The widespread excitement about QIS stems from the potentially monumental technological advantages offered by quantum information over classical—advantages that derive from unique properties entirely resistant to analogy within the classical paradigm. In just the past few years, numerous impressive breakthroughs in QIS research have been supported by a confluence of increased government and industry investment worldwide. Together with major national, international, and industrial initiatives, these advancements have raised the profile of QIS globally.

The governments of the United States and Australia have recently committed to collaboration on QIS research and development. On May 24–25, 2022, the Basic Research Office of the U.S. Department of Defense (DoD) and the Defence Science and Technology Group of Australia jointly sponsored the Future Directions Workshop (FDW) on Quantum Information Science. Both countries consider QIS a critical technology area for both national security and economic development reasons, and this meeting was viewed by the government sponsors as a first step towards fostering the desired collaboration. Although sponsored by the Defense components of each country's government, this workshop was focused on basic research opportunities, and its results as documented in this report should not be viewed as defense-specific.

In attendance at the workshop were U.S. and Australian scientists selected from a wide range of QIS disciplines, as well as a group of government observers from both countries. The workshop was organized as 2 days of breakout and plenary discussions that culminated in a set of proposed "grand challenges" that could foster collaboration between the two countries in this critical scientific area. The workshop was intended to inspire American-Australian partnerships that could further current research efforts, tighten collaborative ties, and stimulate scientific growth.

Taking place during the third year of the global COVID-19 pandemic, this workshop allowed a rare face-to-face meeting for scientists and government observers from the United States and Australia. That interaction stimulated rich discussion and numerous ideas which are the focus of this report. Participants identified opportunities for collaboration within quantum sensing, computing, and communication. The topics considered spanned length scales from the atomic to the continental, incorporating workforce and infrastructure components that could both contribute to the scientific progress of both nations and support economic development of new technologies.

This report first provides background on the context in which the workshop was held. It then documents the wide-ranging discussions that occurred throughout, providing an overview of the grand challenges and opportunities for collaboration that participants identified during the meeting.

## Opportunities for Progress in QIS

Inspired by recent advancements, workshop participants identified numerous opportunities for further research in quantum sensing, imaging, communication, and computing. These opportunities include the following:

- Identifying new materials and fabrication methods towards more efficient coupling in hybrid platforms and increased operating temperatures of high-performing solid-state quantum devices
- Use of computational methods for qubit engineering, wave-function engineering, and materials discovery
- Achieving optimal entanglement estimates, quantum-mechanics-free subsystems, and hypercube or novel entangled states for correlation measurements with quantum-limited precision, highly precise noise-free force measurements, or sensing of sub-$\hbar$ momenta
- Novel approaches to gravimetry and magnetometry, possibly incorporating multimodal or distributed concepts, for applications in position, navigation, timing, resource detection, and mining
- Improved signal deconvolution methods, real-time error correction, and understanding of decoherence mechanisms for quantum sensing
- Merging of QIS with biology for unique imaging and sensing opportunities
- Entanglement distribution across sensors and modular computing architectures, including build-out of necessary interfaces and interconnects
- Developing robust theoretical frameworks for understanding interfaces between quantum systems, including relevant decoherence mechanisms
- Discovery of novel algorithms for practical quantum computing use-cases, for parallelizing across separate clusters of entanglement, or that employ decoherence-free subspaces
- Tailoring quantum error correction (QEC) and error detection methods for particular devices and architectures and error correction within interconnects and transmission lines

- Developing quantum repeaters
- Defining consensus definitions, benchmarks, standards, and figures of merit for quantum processes (e.g., transduction), devices, and systems
- Developing generalized conceptual paradigms that enable translation of solutions and insights among QIS sub-fields

A common theme throughout workshop discussions was the need to collaborate across traditionally siloed groups of researchers—not only within QIS (e.g., theorists and experimentalists), but also with other fields of science and engineering (e.g., biology, signal processing).

Participants were highly cognizant of challenges in the QIS ecosystem that were viewed as barriers to accelerated progress. For example, participants desired QIS-dedicated, flexible fabrication facilities (*foundries*) that would enable greater reliability, rapidity, and affordability for obtaining high-quality materials and quantum system components desired for their research. Furthermore, talent development was viewed as a substantial barrier to progress in QIS, with numerous ideas put forward by participants on ways to build a larger, more quantum-proficient workforce. A key feature of this discussion was the need for greater involvement of industry with the training of students. Finally, participants expressed a desire for more industry-driven support for system engineering and integration. For example, participants sought an available supply (from vendors) of modular commercial off-the-shelf laser systems, detectors, cryogenic systems, or other components important to QIS research, as well as access to expertise for packaging, integration, low-power signal processing, and thermal management.

## Grand Challenges and Opportunities for U.S. – Australia Collaboration

During the workshop, participants identified three candidates for grand challenges that could be pursued via long-term collaboration between the United States and Australia. These grand challenges have the potential to inspire novel QIS technology development while being able to serve as useful organizing principles for galvanizing new basic research directions.

The first of these grand challenges was the creation of physical qubits capable of supporting $10^{-6}$ errors per operation in large-scale (many qubit) systems, a revolutionary improvement in qubit fidelity. To facilitate the design and fabrication of these qubits, participants proposed a collaborative institute between the United States and Australia. This institute would strive to balance the tradeoffs between fabrication sophistication, high throughput speeds, and the processing flexibility required to accommodate a wide range of materials and innovative qubit approaches. Not merely a fabrication initiative, this institute would also comprise theoretical and computational capabilities that further distinguish it from more narrowly focused commercial alternatives, and support direct collaboration between theorists and experimentalists.

The second grand challenge was focused on developing satellite-linked intercontinental quantum entanglement between the United States and Australia. More specifically, participants envisioned linking differing types of quantum memories in the two countries via a satellite-hosted quantum repeater. This challenge was motivated in part as a source of numerous smaller research directions, such as those involving transduction, robust quantum memories, and error correction approaches for distributed systems. Participants also felt that the final network would be a useful testbed for numerous basic research topics. This idea was also seen as a natural candidate for U.S.-Australia collaboration and, because of the connection to space technologies, one that would be particularly inspirational for attracting students to QIS.

The third idea was a large-scale, collaborative initiative to design, synthesize, and deploy molecules for quantum sensing in solution or in-vivo biological environments. The ability to create and address coherence in single molecules, coupled with targeted design of their chemical structure and properties could support new modalities for monitoring, imaging, or manipulating chemical, biological, and biochemical systems in real time. This concept also included an opportunity for collaboration between quantum simulation and quantum sensing disciplines in the design of molecular sensors. This project would combine the disciplines of QIS, biology, materials science, computational chemistry, medicine, and chemical synthesis.

In addition, participants discussed several specific ideas for the two countries to develop joint workforce or infrastructure development programs. One such program would be focused on building a shared network of quantum foundries and testbeds, while others would be exchange programs or dual-degree programs for post-doctoral scholars and students. Participants recognized that both these programs and the proposed grand challenge research collaborations would require the involvement of government and industry stakeholders to coordinate workable funding, schedule, immigration, and intellectual property arrangements.

# Preface

Since 2011, the Basic Research Office of the U.S. DoD has been sponsoring a series of meetings known as FDWs:

> The Future Directions Workshop (FDW) series…seeks to examine emerging research and engineering areas that are most likely to transform future technology capabilities. Rather than a standard conference format, these workshops are designed primarily around small-group breakout sessions and whole-group discussions for scientists and engineers from academia, national laboratories, and industry to express their perspectives and outlooks over areas of rapid progress in fundamental research and shed insight on three overarching questions:
>
> - How might the research impact science and technology capabilities of the future?
> - What is the possible trajectory of scientific achievement over the next 10–15 years?
> - What are the most fundamental challenges to progress? (Under Secretary of Defense for Research and Engineering [USD(R&E)] n.d.)

Previous workshops have covered diverse topics such as human-machine teaming (2019), synthetic biology for energy and power (2018), and computer vision (2015). The workshop documented in this report focused on QIS, and was an international event co-sponsored by the United States and Australia. The U.S. – Australia Future Directions Workshop on Quantum Information Science was held in person from May 24–25, 2022, in Sydney, Australia. In attendance at the workshop were U.S. and Australian scientists (listed in Appendix C) selected from a wide range of QIS disciplines, as well as a group of government observers (listed in Appendix D) from both countries. A photo of those who attended the workshop is provided in Figure 1. Each invited scientist at the workshop was also given the option to select a post-doctoral scholar to accompany them to the meeting; these post-docs participated fully in all workshop activities. Taking place during the third year of the global COVID-19 pandemic, this workshop was a rare opportunity for face-to-face meetings among scientists and government observers from the United States and Australia. These interactions stimulated rich discussion and numerous ideas, which are the focus of this report.

**Figure 1. Group photo of participants and observers at the Future Directions Workshop on Quantum Information Science held in Sydney, Australia, on May 24–25, 2022.**

Unlike prior FDWs, this international workshop was jointly sponsored by the Australian Defence Science and Technology Group (DSTG) and the Basic Research Office of the U.S. DoD. Although sponsored by the Defense components of each country's government, this workshop was focused on basic research opportunities, and the outcomes as documented in this report should not be viewed as defense-specific. In fact, QIS has been identified as a critical technology area of both security and economic importance by the governments of both countries, with the establishment in the United States of the National Quantum Initiative in 2018, and in Australia of the National Quantum Strategy and Quantum Commercialization Hub in 2021 (Australian Government CTPCO 2021; Australian Government Department of Industry, Science and Resources 2021; U.S. Congress 2018; USD(R&E) 2022).

QIS has been highlighted as an area for collaboration between the two nations. In late 2021, the United States and Australia released a Joint Statement on Cooperation in Quantum Science and Technology (U.S. Department of State 2021), in which the two countries identified an intent to cooperate to "explore new theoretical and practical applications of quantum technologies" as well as "promote joint research, development and exchange of quantum technologies." In addition, quantum technologies are among the advanced capabilities highlighted under the recently signed Australia – United Kingdom – United States (AUKUS) Partnership, and are being pursued under this trilateral agreement through the AUKUS Quantum Arrangement (AQuA), which "will accelerate investments to deliver generation-after-next quantum capabilities." (The White House 2022). Although plans for this workshop began well before these agreements were signed, the workshop nonetheless represented a timely first step towards furthering the goals set forth in these agreements. The shared U.S.-Australian sponsorship is indicative of the significant value that the governments of these nations place on collaboration to achieve scientific achievement and technological progress in this critical research area.

## Motivating Concept and Format

The motivating concept for this meeting was framed as follows: The interplay between instrumentation and scientific research is central to scientific and technological progress. In the quantum information sciences, this interplay is especially striking. Recent advancements in the creation and control of individual quantum states have led to staggering gains, not only in sensitivity but in expanding the empirical reach of quantum measurements. Even so, many challenges remain. The quantum-classical boundary and the role of decoherence in quantum systems, for example, lie at the heart of many important open scientific and technological questions. Such fundamental questions—along with advancements in the creation and control of quantum systems, mitigation of decoherence, error correction, and extension of entanglement—will bring about new frontiers of research inaccessible via classical means, at both macro- and microscopic scales.

This widening foundational comprehension represents a boon not only for scientific advancement but for the evolution and emergence of quantum technologies. Indeed, insights derived from the study of the aforementioned challenges stand to improve the development of quantum-enabled technologies, many of which could have significant economic consequences. The ensuing technological progress in areas such as quantum simulation, computing, imaging, and sensing offer attractive prospective capabilities within both the industrial and defense sectors, encompassing the realms of mining, satellite communication, pharmacology, microbiology, materials science, and more.

The considerable ambition of these efforts inspires close, long-term international collaborations. This FDW brought together scientists from the United States and Australia, combining foundational inquiries with the development of novel quantum science platforms. The workshop was intended to stimulate American-Australian partnerships that could further not only current research efforts but that would also tighten collaborative ties and stimulate scientific growth.

The workshop was organized in four sessions:

- Session 1: Driving Scientific Advances for Quantum Technology
- Session 2: Practical Applications of Quantum Sensing and Imaging
- Session 3: Quantum Communication and Computing
- Session 4: Grand Challenges and Opportunities

Session 1 aimed to ground the discussions in the current state of the science and highlight key fundamental scientific questions that remained open and in need of novel research ideas. Sessions 2 and 3 were designed to enable workshop participants to consider specific technical problems under the umbrella of QIS, and to imagine novel research pathways that could address those problems. Session 4 was intended to build upon the prior discussions and allow workshop participants to conceptualize grand challenges and ways in which collaboration between the United States and Australia could support and enhance research progress in the field of QIS. The workshop was organized to emphasize small breakout group discussions, with periodic plenary sessions in which the full set of participants could hear and discuss the ideas of other groups. Prior to the workshop, participants were also asked to consider a specific set of questions in order to prepare for the kinds of discussions to be held at the meeting. The full workshop agenda and list of questions participants were asked to consider can be found in Appendix E.

## Report Purpose and Structure

This report is intended to summarize key takeaways from the workshop and lay out a path for the United States and Australia to work together in the years to come. This report seeks to capture the rich ideas and thoughts shared at the workshop, synthesize key scientific directions for QIS, and highlight opportunities for U.S.-Australia collaboration. This report is not a transcript of the workshop meeting; nor are the opinions or views of individual workshop participants identified in this report.

The report is organized into three sections. In Section 1, we briefly describe the field of QIS and summarize the state of the science at the time of the workshop by highlighting several key advances made in the few years prior to the meeting. A more detailed discussion of these advances, many of which were raised by participants in the opening session of the workshop, can be found in Appendix B. In Section 2, we describe specific technical challenges and opportunities for the future of QIS that were discussed during the breakout groups and first three sessions of the meeting. These are organized into three sub-areas that reflect themes encountered in discussions throughout the meeting (sensing and imaging, communication and computing, and the QIS ecosystem, which includes infrastructure, workforce, and engineering and integration capabilities). In Section 3, we delve into specific areas for potential bilateral collaboration, first highlighting several key distinguishing features of the U.S. and Australian QIS ecosystems. We then discuss three specific grand challenge (moonshot) ideas identified and developed during the workshop. Finally, we cover opportunities for the two nations to collaborate on infrastructure and talent development to try to further their shared technical goals in this field. To illustrate how the report sections address the three overarching questions (or "pillars") listed above, Figure 2 associates each with the corresponding report section(s). Note, however, that participants did not necessarily restrict themselves to the 10–15-year time frame when discussing trajectories for scientific achievement.

This report is intended to be accessible to a wide audience of QIS researchers and government program managers that may be considering supporting the collaboration of the two nations in QIS. It is our hope that this report and the results of the workshop that it documents can inspire new scientific research directions and inform government collaboration in this area of critical importance to both nations.

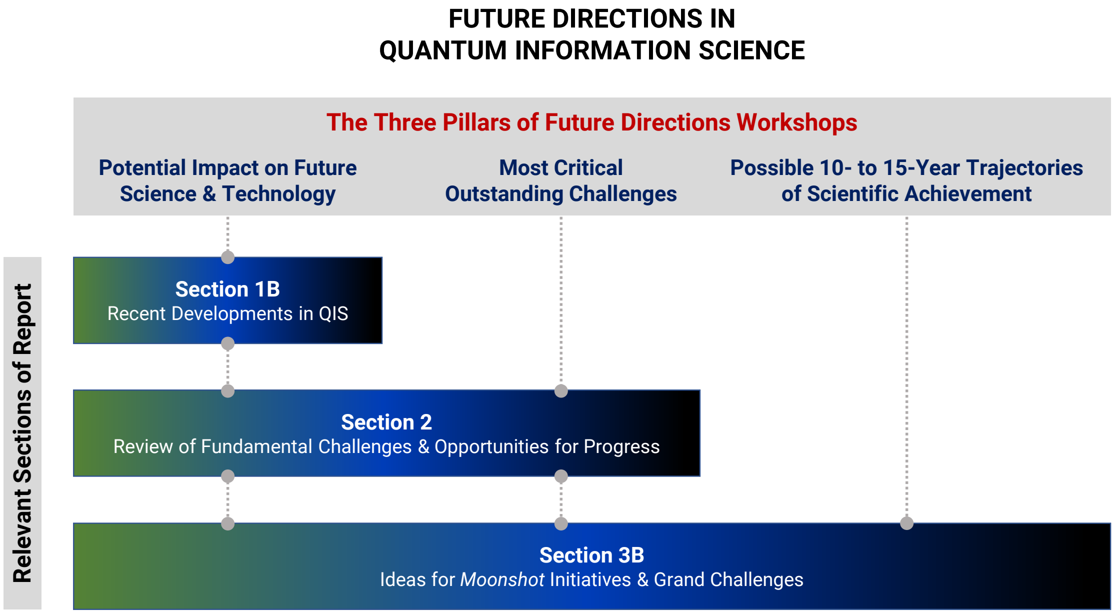

**Figure 2. Structure of this report relative to the Future Directions Workshop (FDW) framework. The horizontal bars depict relevant sections of the report; the dashed vertical lines indicate the corresponding FDW pillars that are addressed.**

# Contents

# 1. Introduction

## A. Quantum Information Science (QIS) – A Brief Introduction

Steeped in a combination of physics, computer science, and electrical engineering, the field of quantum information science (QIS) applies the peculiar characteristics of quantum mechanics toward the processing, transmission, extraction, and storage of information. The widespread excitement about QIS stems from the potentially monumental technological advantages offered by quantum information over classical—advantages that derive from unique properties entirely resistant to analogy within the classical paradigm.

Most discussions of QIS research focus on three primary areas of interest: quantum computation, communication, and sensing. By way of logical operations performed with quantum states, quantum computers (QCs) offer a means of solving certain problems that are impractical with classical techniques. Quantum communication, on the other hand, centers on the transmission and reception of quantum information, which could, in particular ensure ultra-secure communication channels and networks. Perhaps the closest of the three areas to practical applications is quantum metrology and sensing, which exploits phenomena such as quantum coherence and entanglement to perform precise measurements inaccessible to classical devices. The following sections of this report will further expound on these areas of research and where they might take QIS within the coming decades.

The power of quantum computation, communication, and sensing is founded upon four unique features of quantum information: superposition, the process of measurement, computational reversibility, and the existence of entangled states. Unlike classical systems, which can take on only definite states, the outcome of finding a quantum system in a given state is represented by a probability.[1] Prior to measurement, quantum systems occupy a linear superposition of all possible states. Likewise, while classical bits can each take on only one of two real logical states, quantum bits (called *qubits*) can each assume a linear superposition of these two states. The state of $n$ qubits thus inhabits a superposition of $2^n$ distinct classical states.[2] This superposition will persist until a measurement is performed,

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[1] This is also fundamentally different from the uncertainty in a classical chaotic system.

[2] This might suggest that quantum computers offer immense promise for parallel computation, but the truth is more complicated. Though a combination of $n$ qubits might possess a definite state prior to measurement, this state is unknowable prior to measurement. Still, for a small number of important, specialized problems, quantum computers can provide a considerable computational advantage over their classical counterparts.

upon which the initial superposition is reduced to a state that is compatible with the measurement.[3] This measurement-induced destruction of superposition is a key feature and advantage of quantum information systems, and a fundamental understanding of this behavior remains elusive.

The superposition principle and measurement process combine to further differentiate the theories of classical and quantum information. Aside from the NOT operation, the logical operations of most classical computing architectures are inherently irreversible.[4] The logical operations performed on the gates of a QC are all reversible, which means the transformation of initial states into final states requires only invertible processes. Reversible processes entail no loss of information and underlie all of quantum computing—with the sole exception of measurement.

The components of quantum systems, such as the qubits within a QC, often interact with each other and couple to their environment. Consequently, the state of a single qubit within an *n*-qubit system is not always described by its own unique, separable state. When this occurs, the qubit is *entangled* with one or more other qubits. Described by Schrödinger as *the* distinguishing characteristic of quantum mechanics, entanglement changes the relationship between what one can know about an entangled system and its components—a distinction that does not exist for interacting classical systems (Schrödinger 1935). In an entangled system, more accurate information is available about the entire system than about its individual components.[5]

Quantum computing, communication, and sensing at once exploit and contend with the unusual properties of quantum information, and the challenges vary widely by context. QCs demand exacting control of their components, which require maximal isolation from the decohering influence of the surrounding classical environment. Similarly, quantum networks must maintain sufficient isolation to prevent the intrusion of noise into their communication channels. Quantum sensors, on the other hand, require a precise, controlled

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[3] In short, a *measurement* constitutes any act of accessing or "reading out" information from a quantum system by way of a classical apparatus.

[4] There are exceptions. Toffoli gates, for example, can be used to create reversible classical computing architectures, but these are not widely deployed in practice.

[5] In the language of entropy, the story is the same. The total entropy for a classical bipartite system (i.e., a system consisting of two parts) must be larger than the entropy of either subsystem, but this is not necessarily true for the quantum analogue. Contrary to classical behavior, a quantum-entangled bipartite system can possess a smaller total entropy than that of either subsystem alone. John Preskill illustrates the ramifications of this relationship by considering two books—an ordinary book and another with quantum-entangled pages (Preskill 2018). Whereas an ordinary book reads in the conventional manner, with each page building sequentially on its predecessors, the pages of the entangled book would seem nonsensical. In the entangled book, the information is determined by correlations between pages, and a complete knowledge about the entangled book as a whole does not entail a complete knowledge about any of the pages contained.

means of coupling *to* the surrounding environment, exploiting quantum coherence and entanglement to measure electromagnetic fields, gravitational fields, temperature, and a variety of other physical phenomena.

The discussions at the Future Directions Workshop (FDW) addressed these primary areas of QIS research, along with their attendant goals and challenges. Chapters 2 and 3 cover those discussions and their implications for the trajectory of quantum science and technology.

## B. Recent Developments in QIS

### RECENT DEVELOPMENTS IN QUANTUM INFORMATION SCIENCE

**Appendix B** presents a more detailed account of recent QIS developments, with a focus on the following topics:

1. **Qubit platforms, control, and readout**
    a. Spin-based semiconductor systems
    b. Superconducting systems
    c. Rydberg-controlled interactions for cold-atom qubits
    d. Molecular systems
2. **Interfaces, transduction, and supporting technologies**
3. **Fabrication capabilities and manufacturing scalability**
    a. Large-scale fabrication of quantum-dot spin qubits
    b. Isotopic enrichment of silicon
    c. High-precision ion implantation
    d. 3D-integrated superconducting qubits
    e. Reducing transmon size with hexagonal boron nitride
4. **Improvements in error correction and suppression**
    a. New QEC code
    b. Noise-tailored QEC
    c. Experimental demonstrations

**Box 1. Recent Development in Quantum Information Science (QIS)**

During a round-robin at the beginning of Session 1 of the workshop, attendees were asked to identify up to two recent breakthroughs that they viewed as very important to QIS. In just the past few years, numerous impressive advances in QIS research have been supported by a confluence of increased government and industry investment worldwide. Here we describe the general categories of these breakthroughs that were highlighted by participants during this round robin. We focus our discussion on those topics that were explicitly raised by workshop participants, rather than attempting to summarize all important advances that occurred during the last 2 years. The enumeration of exciting recent advances helped set the stage for the later parts of the meeting, provided a common baseline, and stimulated discussion among participants with widely varying technical specialties. Box 1 lists the key topics that were identified during the round-robin. These topics are summarized briefly here, and described in more detail with reference to recent academic publications and review articles in Appendix B.

First, a variety of qubit platforms have seen significant recent progress, particularly spin-based semiconductor systems, superconducting systems, and Rydberg-controlled interactions for cold-atom qubits. Silicon-based spin qubits, for example, achieved fault-tolerance, offering a route to manufacturable large-scale quantum platforms. At the same time, commercial entities have continued to develop photonic and ionic platforms. There have also been developments studying quantum-coherent phenomena in several molecular systems, creating the potential for molecular qubits.

There have also been exciting demonstrations of novel approaches to creating quantum interfaces, including spin-phonon and photon-spin interfaces. For practical applications, QIS systems must not only process and store information but exchange information with other networked quantum systems. At present, no particular quantum system offers a complete suite of capabilities, making necessary quantum interfaces that can coherently link disparate quantum platforms. During discussions of networked quantum systems, participants cited the importance of effective quantum interfaces and transduction strategies, highlighting recent parallel demonstrations of quantum-acoustomechanical and optically addressable photon-spin interfaces.

Fabrication and manufacturing technology, which are essential to the realization of scalable platforms, has also continued to advance. Particularly highlighted by participants were improvements in large-scale quantum-dot spin qubit fabrication, methods of isotope enrichment in silicon, precise ion implantation, three-dimensional (3D)-integration methods for superconducting qubits, and strategies to reduce the size of transmons in hexagonal boron nitride.

Accompanying these developments have been advancements in error correction and suppression methods, including new quantum error correction (QEC) codes (QECCs), noise-tailored QEC approaches, and experimental demonstrations of QEC. For networked QIS platforms to exhibit quantum advantage, physical qubits require lower gate-error rates. Current gate-error rates present a heavy burden for error correction, necessitating both better qubits and concurrent improvements in these techniques.

## C. Growing visibility and complexity of QIS R&D

Recent QIS advances such as those highlighted above—combined with the field's current nascence but truly transformative potential—place the research community at shifting frontiers of understanding, capabilities, and expectations. The potential of QIS research and development (R&D) to yield transformative new technologies has spurred tremendous excitement in the past few years, launching national and international initiatives (Kung et al. 2021), garnering more than $1 billion in venture capital investments in quantum computing companies in 2021 alone (Temkin 2021), and seeding a steady cadence of international press coverage of research findings and publications. A recent report by McKinsey & Company notes that as of 2021, public investment in quantum computing had reached $30 billion and there were more than 200 start-ups focused on quantum computing globally, with the largest fraction of these located in the United States (Biondi et al. 2021). Some have begun to frame QIS and quantum technology development, especially for quantum computing, as a "race." At the same time, much of QIS sits within the domain of fundamental science, where substantial opportunity for discovery about the universe lies, and which is necessary to sustain progress toward future technologies.

Enthusiasm, R&D funding levels, and media coverage both reflect the state of the science and influence perceptions of the field—including among potential QIS students and researchers, the established R&D community, funders, and the public at large. Workshop participants noted that the current moment presents an important opportunity for the QIS community to act deliberately to chart a path forward. This includes contributing to clear and open communication about the state of the science with the public and other stakeholders, transparent reporting of results, open sharing of research data where possible, and proactive replication of experiments. Such careful attention to scientific review and validation will ensure that continued investment in this technology remains well-informed of risks and uncertainties while still attracting talent, striving towards meaningful progress in tackling the field's technical challenges, and accelerating the pace of breakthroughs.

# 2. Challenges and Opportunities for Progress

This section documents discussions held during the first three sessions of the workshop concerning key challenges in quantum sensing, imaging, communication, and computing, and possible opportunities for progress in these areas.

## A. Quantum Sensing and Imaging

In Session 1 of the workshop, participants reflected on opportunities for advancing quantum sensing, providing a smooth transition to Session 2, which addressed the practical applications of quantum sensing and imaging. Quantum sensing featured prominently throughout the workshop, owing largely to its wide range of applications and potential for certain near-term realizations. This section summarizes the central themes that emerged during these discussions.

The bane of QIS systems is decoherence—the loss of quantum information stemming from relaxation and dephasing. One common source of decoherence comes from interactions at the sensing interface. The idea that a quantum sensor is essentially a classical-quantum interface was mentioned a few times at the workshop. Interfaces often impede the preservation of optical entanglement and coherence; participants viewed the investigation of methods to mitigate such decoherence at sensing interfaces (e.g., interface engineering) as an important research direction.

The materials that comprise quantum sensors are also a fundamental source of decoherence. Materials development also functions as an intermediate node in the continuous loop between scientific inquiry and technological advancement. Thus, workshop participants frequently mentioned a number of device layers and components that would benefit from materials or geometries with lower losses. To sufficiently lessen the deleterious effects of decoherence on qubit performance, most solid-state quantum devices require millikelvin temperatures, entailing overhead-intensive cryogenic cooling and readout electronics that are not compatible with practical implementation of many prospective applications. Participants thus emphasized the need for new materials capable of increasing operating temperatures without impairing device performance or internal power consumption.

The participants expressed a similar eagerness for the advancement of fabrication and manufacturing techniques. Enhanced deposition and post-processing techniques, for example, could reduce decoherence in superconducting qubits by circumventing the formation of undesirable amorphous layers. Nanostructured patterning is central to a growing number of qubit designs, calling for better lithographic and etching techniques—vital for the achievement of smaller, more complex features (Siddiqi 2021).

As recent demonstrations of 3D-integrated transmons have shown, advanced patterning and bump-bonding methods can enable device geometries that alleviate interconnect crowding and improve thermal isolation (Rosenberg et al. 2020). While especially critical for quantum-computing applications, these capabilities stand to improve solid-state quantum-sensing devices as well. Due to the mismatched strengths and weaknesses of different quantum systems, a growing number of efforts has focused recently on hybrid platforms. Workshop participants agree, for example, that quantum-photonic approaches will prove critical not only as computing and sensing platforms but as interfaces between dissimilar qubit architectures or for readout and control.[6] The arena of silicon-based photonics, thanks in part to the maturity of silicon very large-scale integration (VLSI), is the most mature of photonic approaches, and the capacity for room-temperature functionality makes silicon photonics attractive within passive networks (Elshaari et al. 2020). Still, the performance of silicon-based photonic devices is limited by loss and speed of electro-optic modulation; photonic materials and approaches based on lithium niobate and aluminium nitride offer improvements in these respects (Elshaari et al. 2020). For some interfacing and coupling applications (e.g., the integration of quantum memories), reliable single-photon emission is necessary; in these cases, color centers in diamond and III-V quantum dots are attractive systems (Elshaari et al. 2020).

Despite this mounting interest, efficient coupling methods remain elusive in some cases. New materials and fabrication methods will likely occupy a central role in integrating hybrid platforms. Even seemingly straightforward upgrades, such as more purified bulk materials, would improve certain quantum-sensing platforms. Achieving superior isotopic enrichment, for example, is critical for improving the performance of donor-spin qubits, which function as superb strain and magnetic-field sensors.

Of course, selecting materials for optimal qubit performance demands more than materials engineering, equipment, and laboratory techniques. More powerful theoretical and computational approaches are also paramount in improving quantum-sensor design. Bemoaning an inadequate understanding of complex materials interactions, properties, and emergent phenomena, workshop participants touted new computational methods as indispensable for qubit engineering. Chief among these methods was computational materials design, which combines multiple approaches (e.g., high-throughput *ab initio* methods, multi-length-scale modeling, machine-learning) in predicting materials

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[6] As discussed in Appendix B.2, photonic interfaces offer a convenient, efficient means of coupling qubits to readout devices. For example, photonic devices enable the coupling of superconducting qubits to optical fiber for readout. Photonic strategies also afford optical access to T-center qubits, which stand to accommodate vast entangled networks of photon–spin qubits.

properties and guiding selection (Louie et al. 2021). Other oft-cited computation-enabled approaches for materials design included wave-function engineering, a tactic frequently used to describe quantum-dot heterostructures (Kagan et al. 2021).

Its relevance to guiding materials selection notwithstanding, wave-function engineering also tied into deliberations on assessing the usefulness of a given quantum state for sensing applications. Though the Heisenberg uncertainty principle limits the size of a given state's phase-space distinguishability (relative to its initial state) to $\hbar$, both Schrödinger-cat and compass states exhibit distinguishable features below $\hbar$. In discussions about the utility of such states for realistic sensing applications, hypercube states were suggested as a means of sensing sub-$\hbar$ momenta—germane to the development of ultrasensitive microelectromechanical systems (MEMS)-based gravimeters and the imaging of distant astronomical objects with small apertures (Howard 2019). Related exchanges centered on the measurement of nonclassical correlations and the information that they can provide about a system.

Of particular interest to workshop participants was achieving optimal entanglement estimates (requiring an estimator that saturates the Cramér-Rao bound), enabling correlation measurements with quantum-limited precision (Brida et al. 2010). A quantum sensor designed to measure noise-spectral density or hot-phonon correlations, for instance, would require the construction of a system with naturally occurring correlations (e.g., materials hosting correlated electrons) and a high degree of entanglement (Brida et al. 2010). In the same discussion, participants also considered the potential advantages of realizing a quantum-mechanics-free subsystem (QMFS) in a quantum sensor (de Lépinay et al. 2021). Indeed, such a sensor with access to four quadratures would have wide implications for quantum sensing, offering a strategy enabling noise-free force measurements of unprecedented precision (de Lépinay et al. 2021). Examples of potential applications include quantum magnetometry, gravimetry, and the sensing of weak mechanical forces (Tsang and Caves 2012).

Quantum gravimeters figured into many workshop discussions, with a frequent emphasis on their applicability to mining and groundwater detection. Gravimeters are also applicable to position, navigation, and timing (PNT) technology, which is the first technical topic identified for investigation under the Australia – United Kingdom – United States (AUKUS) Quantum Arrangement (AQuA, The White House 2022). However, mining and resource detection are also applications of this technology, and these applications were raised more persistently than PNT during workshop discussion. Though the best atomic clocks function as superb gravimeters, they are complex and unwieldy, motivating their miniaturization. Still, participants expressed excitement about the recent demonstration of a cold-atom gravity gradiometer capable of detecting shallow underground tunnels without large measurement times, due largely to its insensitivity to vibrational and micro-seismic noise (Stray et al. 2022). At more than a meter in length, the device is not particularly compact, but the demonstration was cited as an indication of quantum gravimetry's potential for application (Stray et al. 2022). Efforts to miniaturize atomic clocks more generally are also underway, for example, see the recent work of Kale et al. (2022).

For mining applications, multimodal approaches could prove especially profitable. Gravimetry used in tandem with magnetometry would not only offer a means of locating mineral deposits but provide information about their composition. To achieve practical quantum gravimeters, however, researchers must better understand the decoherence mechanisms at play in atomic vapors. Workshop participants also cited the need to develop better methods for deconvoluting measurement results and more advanced real-time error-correction techniques. As quantum gravimeters simultaneously improve in performance and decrease in size, standoff mass detection will become feasible—a capability of great interest not only within mining and hydrology but also shipping and agriculture. While many of the challenges in this area are more related to systems integration, signal processing, and engineering than basic science, there is nonetheless an opportunity for novel multidisciplinary collaboration that could spur additional interesting basic research questions.

Australia-focused conversations about quantum sensing, in fact, often turned to mining due to the country's vast mineral deposits. In addition to gravimeter-based applications, gas detection featured in several mining-related exchanges. The mining industry's recent interest in switching to hydrogen as a fuel source introduces concerns about the attendant explosion risks. Quantum sensors could offer sensitive, real-time measurements of the concentrations of ortho and para spin isomers of molecular hydrogen in the condensed phase, to monitor the risk of interconversion resulting in potentially dangerous vaporization. Perhaps more valuable yet than mining, though, is the detection of groundwater deposits. Participants cited demonstrations of atom-trap trace analysis in detecting trace amounts of noble-gas isotopes ($^{81}$Kr, $^{39}$Ar/Ar ratios) that are present in underground water deposits—a resource increasingly valued by countries wealthy and poor alike (Jiang et al. 2011).

The workshop expressed a strong collective interest in exploring how quantum sensors could further biological research. The most noteworthy of these avenues focused on engineering molecular sensors for biological systems. With a single-molecule sensor situated within a cell, for example, one could acquire the ability to characterize proteins and cellular structures, potentially *in vivo*. Biological timescales span many orders of magnitude, from milliseconds (protein-folding) to femtoseconds (bond vibrations), potentially requiring measurements of unrivaled speeds (Fisette et al. 2012). Many challenges will need to be overcome to enable such single-molecule sensing in biological systems, including methods of insertion, activation, and readout, as well as maintaining sensor coherence in a noise-filled environment.

Still, tractable near-term applications exist for quantum sensing in biological systems, such as magnetometers sensitive to biomagnetic signatures (e.g., in the heart or brain). One idea that emerged during discussions entailed the use of entangled qubits for depth-resolved magnetic sensing—possibly a molecular qubit coupled to a nitrogen-vacancy (NV) qubit, which could measure 3D magnetic fields (Chatzidrosos et al. 2017). The ability to perform ultrasensitive magnetic-field measurements in 3D would appeal to both academic and commercial biologists, a salient consideration in the promotion of quantum-enabled biosensors for industrial use. Indeed, workshop participants agreed that collaborations with biotech companies and the pharmaceutical industry will first require impressive proof-of-principle demonstrations, such as accurate tests for diseases and *in vivo* characterizations of drug candidates. Such demonstrations represent a longer-term goal that will require solutions to many of the problems noted above. Though many of the above-mentioned applications are still leagues away from commercially viable realizations, the monumental difficulties of merging QIS with biology nonetheless present inspiring opportunities for interdisciplinary collaboration.

## B. Quantum Communication and Computing

### 1. Quantum Algorithms, Applications, and Advantage

The paucity of known practical applications for quantum computing and communications was emphasized throughout workshop discussions. Several participants noted that much of the interest in QIS concerns its utility in answering fundamental questions and its potential for achieving quantum advantage for a practical task. In practice, QCs have not found applications outside of research and development because 1) few quantum algorithms are known that would offer substantial improvements over existing classical methods in completing a useful computation, and 2) building QCs that are stable, accurate, precise, and large enough to implement such algorithms is nontrivial. While several recent experiments suggest that QCs are capable of quantum supremacy (Arute et al. 2019; Zhong et al. 2020; Madsen et al. 2022), efforts to apply this power in useful ways is still in early stages. Participants noted the important opportunity to find new applications and methodologies that may emerge for QCs. Advances in quantum algorithms, including error correction algorithms, could reveal future practical use-cases for QCs.

Several participants were skeptical that quantum communications would engender practical applications with substantial advantages over classical techniques. Quantum key distribution can support secure encryption key exchange, but classical methods suffice in practice and are being improved. Participants noted that quantum networking—a concept extending beyond communications—could offer value in the context of supporting entanglement across distributed sensors (with potential applications for astronomical or other types of sensing and signal detection), coupling sensors to processors, and scaling up QCs (by coupling modular quantum information processing components).

## 2. Error in Quantum Computing and Communications Systems

Despite continued progress in QEC and error suppression, and improving precision and accuracy of control protocols, noise-induced system error remains a major technical barrier to developing stable or fault-tolerant quantum computing and communications systems. Both algorithmic and engineering improvements are needed.

Algorithms that could be distributed across separate quantum processors—or across stable or decoherence-free subspaces of a single quantum processor—might help to leverage quantum entanglement where it is most needed for a computation, leading to stable computation even before large, fault-tolerant processors are available. A key opportunity would be for theorists to collaborate with experimentalists in order to tailor quantum algorithms to specific device architectures and performance specifications. This co-design approach would aim to improve the likelihood of successfully performing complex quantum computations on near-term machines. For example, might Shor's algorithm prove parallelizable across multiple processors or decoherence-free subspaces in a previously unknown manner, and still yield substantial (even if less-than-exponential) speedup? Moreover, how could algorithms be designed around practically achievable chunks of quantum entanglement in real devices? As noted in Appendix B, recent work in system-tailored QEC has decreased overhead for improving performance of actual systems. In addition to reducing overall system error, could QEC overhead be further reduced by way of decoherence-free subspaces? Searching for new algorithms amenable to parallelization across separate clusters of entanglement could yield important breakthroughs toward practical implementation and theoretical understanding of the potential of quantum systems.

Major engineering challenges persist in error correcting quantum devices. Reliable implementation of QECCs to achieve fault tolerance is likely to require physical qubits with low gate error rates to start, with specific requirements dependent on the QEC in question. Reduction of overhead involved with QEC implementation (e.g., by increasing gate speeds and devising efficient QECCs) is another important but general approach. For device-specific approaches, improved methods for detecting error channels (e.g., for loss and dispersion) would enable more targeted improvements of the most problematic qubits; such methods could be developed through collaborations between theorists and architecture designers.

Alongside improvements in gate fidelities and precision of fabrication, packaging, and control techniques, methods are needed for reducing or correcting errors in device interconnects and transmission lines. High-fidelity interconnects (to distribute entanglement across quantum processors in support of modular build-out of QCs) could lead to more powerful systems than those achievable with exclusively on-chip coupling. Correction of error in interconnects remains an unsolved problem.

For quantum communications, some error and signal loss are inherent or introduced by imperfections in the transmission media (e.g., fiber optics or the atmosphere for through-space transmission). Transmission over arbitrarily long distances will require quantum repeaters, which enable entanglement swapping between network nodes, mitigating this loss problem. However, quantum repeaters have not yet been demonstrated. Their realization was viewed as an important mid- to far-term goal. Several workshop participants noted that a quantum repeater is essentially a special-purpose QC.

### 3. Interfaces, Transduction, and Hybrid Systems

Workshop participants discussed a variety of challenges and opportunities related to interfaces between a variety of quantum systems in multiple contexts. The ability to create interfaces between quantum systems—such as those needed for system readout, sensing, or manipulation—without degrading the underlying systems is important across QIS areas. Key categories include light-matter interfaces, optical-microwave interfaces, matter-matter interfaces, and quantum-classical interfaces. A general challenge associated with achieving these capabilities is the lack of a robust theoretical framework for understanding each of these interfaces, including relevant decoherence mechanisms, complicated by relatively limited engagement across experimental and theoretical work in these areas. Interfaces for coupling of disparate quantum systems are important for the development of modular QCs (at chip- or system-scales), quantum networking and distributed quantum computing or sensing (at lab- to city- to global-scales), quantum memory, and hybrid systems (involving coupling between different physical instantiations of quantum systems or coupling between quantum and classical systems).

One popular potential pathway for scaling up QCs is through a modular approach to system design. For example, rather than creating a one million qubit processor, one could create 1,000 thousand-qubit processors and couple them together through local-scale quantum networking. If cleanly coupled, entanglement could be distributed across the modules; lower-fidelity coupling across modules might be suitable for implementing distributed algorithms, as discussed in the preceding section. Development of interfaces or interconnects that enable modular build-out of quantum information processing capacity present a major opportunity for advances in QC.

Hybrid quantum systems are in general at early stages of development. For example, researchers have not yet achieved a scheme for coupling a trapped ion qubit-based system with a superconducting qubit-based system (among the most technologically mature quantum processors at present)—though recent work demonstrating phonon-mediated transduction of microwave-to-optical photons indicate progress toward this objective (Brubaker et al. 2022). Other areas where progress toward hybrid quantum systems has been made include atomic to optical transduction, single-photon detection, and entanglement-swapping between processors across a microwave link.

There was some debate among workshop participants on the value of focusing on hybrid (disparate, coupled, heterogeneous) quantum systems. Some suggested that, because different types of qubit technologies have distinct performance profiles across the range of desired attributes of quantum systems, different physical instantiations may be indicated for different elements of an integrated quantum device. For example, atom-based qubits, which can exhibit long coherence times (as long as on the order of an hour [P. Wang et al. 2021]), could be more suitable for building quantum memories than those with shorter coherence times. Similarly, hybrid quantum systems could support transduction of quantum signals from one energy regime (such as microwave frequencies used to readout superconducting qubit circuits) to another (such as infrared frequencies that travel efficiently through fiber-optic cable) (Lauk et al. 2020). One participant asserted that large QCs will necessarily be hybrid systems.

Others suggested that hybrid systems, while an interesting topic for fundamental scientific inquiry, are not compellingly motivated by QC development needs. Some suggested that photon-photon interfaces are challenging, but could potentially be mediated by phonons; others felt that photon-photon interfaces were not the most compelling research topic.

Development of materials that support coupling between heterogeneous systems is a substantial challenge. One participant described entanglement swapping across different qubit implementations as a "holy grail" for QIS R&D. Participants saw opportunities to make progress in the area of quantum transduction through cross-disciplinary collaboration (e.g., spanning theoretical and experimental science and engineering in superconducting circuits, optomechanics, atomic physics, quantum photonics), development of consistent definitions by which to specify requirements for transduction and interfaces, and establishment of standard approaches for moving quantum coherence between architectures.

## 4. Advancing Paradigms that Transcend the Boundaries of Quantum Computing or Quantum Communications

Opportunities to frame engineering challenges associated with one type of quantum technology in the practical context of another were a recurring workshop theme. Recognizing the commonalities between the delineated sub-categories of quantum information technology informs a more general framework for inquiry across QIS fields, and can help to avoid pigeon-holes that inhibit collaboration and progress. The commonalities between quantum computing and quantum communications can be described as follows: A QC involves many degrees of freedom distributed over a relatively short distance, while quantum communications involve relatively few degrees of freedom distributed over a larger distance. Distributed quantum computing involves many degrees of freedom distributed over large distances.

While quantum communication is often thought of as transmitting quantum information between two locations, it can also be conceptualized as a computational channel that implements the identity operation across two hardware elements. Quantum repeaters can be thought of as pared-down or special-purpose QCs. A modular QC, which would require interconnects for distributing entanglement across hardware components, can be viewed as a specialized quantum network.

Developing such generalized conceptual paradigms presents an important opportunity to translate solutions and insights between QIS sub-fields. For example, one could conceptualize a quantum network as undergoing a specific type of error process subsumed under the general problem of QEC. This approach could help to make progress in global (rather than local, chip-focused) error correction for modular or distributed QCs.

## 5. Benchmarks and Figures of Merit

Participants noted the importance of characterizing systems and components, especially to support heterogeneous quantum system development. Figures of merit for this research could include engineering-focused metrics for system components and problem-specific metrics for systems, analogous to approaches used in classical computing. For quantum repeaters, metrics could include process fidelity, the number of entangled pairs that can be generated across a given distance within a particular time interval, or the amount of time that a repeater can hold information.

Participants engaged in some in-depth discussion on approaches for comparing performance of quantum computing architectures. In conventional computer benchmarking, computers are run through a standard series of problems representative of particular types of computing problem. For example, the LINPACK benchmark is used to measure high performance computers' ability to solve dense systems of linear equations (Top 500 n.d.). The computer's ability to execute each problem is measured according to several metrics (for example, how long did the solution take? How much power was used?), and the performance of the computer can then be readily compared to other computers that have solved the same standard set of problems. To decide which computer is best for a given application, one only needs to compare the performance on the most representative problem. A similar approach should be possible for evaluating and comparing quantum computers, but it would require standardized definitions of the representative problems and the key metrics on which the systems would be rated. In fact, the Institute for Electrical and Electronic Engineers (IEEE) has a working group to develop a standard for quantum computing benchmarking (IEEE Standards Association n.d.). For evaluation of components that comprise such computers, engineering figures of merit will still be required. The International Standards Organization (ISO) and CEN-CENELEC (the

European Committee for Electrotechnical Standardization) also have quantum-specific efforts underway, though not specific to benchmarking (ISO n.d.; CEN-CENELEC n.d.).

The benchmarking problem applies not only to comparison among quantum computers, but also to comparison between quantum and classical computers. Because algorithm optimization can strongly affect runtimes and other outcomes, and because algorithms implemented in a classical computing architecture will differ from those implemented in a quantum computing architecture, such comparisons will need to be very carefully structured.

## C. The QIS Ecosystem

In addition to the technical discussions on research opportunities and scientific questions that occurred throughout the workshop, themes surrounding infrastructure, workforce, and large-scale system engineering and integration challenges emerged persistently in breakout and plenary sessions. This section attempts to summarize the key challenges that were identified, discuss relevant context, and, where possible, point to potential solutions.

### 1. Infrastructure Challenges

A widely shared view of participants throughout the workshop was the desire for dedicated foundries for quantum materials and devices. The challenge, as described by workshop participants, is that researchers in academia have limited access to the highest quality materials and devices because of the difficulty of accessing reliable, state-of-the-art fabrication infrastructure and the technical expertise required to operate such tools. Several individuals noted that most industry-managed quantum device processing facilities would be unwilling to set up temporary or small-scale processing runs to produce bespoke devices for researchers. The result is that researchers must either acquire and maintain their own niche equipment, a costly endeavor, or go through extensive searches to identify and string together tools available from research collaborators or small companies that could help produce what they require.

The desired foundries were envisioned as centers that could provide devices or materials to researchers, while not necessarily being research facilities themselves. The staff running the foundry were imagined as professional materials and process engineers that could ensure process control, uniformity, and reproducibility, while still being willing to work with researchers to adapt production lines for short periods of time to meet particular needs. Therefore, the equipment involved would need to be flexible enough to enable such tailoring, while still being reliable enough to produce consistent results. An additional key wish for these facilities was for the processing equipment to be kept clean and free of contaminants. At minimum, separate tools for metal and non-metal processing were highly desired. However, dedicated equipment for processing several other specific materials was also mentioned repeatedly. These materials included diamond, silicon carbide, lithium niobate, gallium arsenide, and isotopically purified silicon, carbon, and other precursor elements. Desired capabilities included bulk material synthesis, high quality thin film synthesis, and post-growth development of the quantum system layer, which could involve a variety of toolsets such as etching chambers and lithography systems. Moreover, appropriate characterization tools (including those capable of atomic-scale characterization) would be needed to verify successful device production.

Participants exhibited substantial concern about how to decide which materials should be included in each foundry. It was widely agreed that building such a foundry or network of foundries would need to begin with a comprehensive roadmapping exercise to determine what to build and who should build it. Such an endeavor would involve careful enumeration and description of existing capabilities in both the United States and Australia to identify gaps and prevent unnecessary duplication.

More generally, participants recognized that obtaining such fabrication capabilities would be a very challenging business proposition, although assisted by such roadmapping efforts. Several participants felt that these foundries could not be created without government support, although some suggested that adapting select complementary metal-oxide semiconductor (CMOS) fabrication facilities to become quantum-dedicated might be a more cost-effective route.

A few facilities with at least some characteristics in common with this concept exist today that could potentially serve as models for what the workshop participants imagined. For example, the Australian National Fabrication Facility network was mentioned as a potential model for the quantum foundry envisioned by participants (Australian National Fabrication Facility (ANFF) n.d.). This network "acquires cutting-edge micro and nanofabrication equipment, ensures its upkeep, and makes it accessible to anyone that wishes to use it." The network also includes expert engineers that can provide training or complete work under fee-for-service agreements. The network is not quantum-specific, but quantum-specific facilities could fit well under its umbrella.

Other facilities mentioned by participants included the Laboratory for Physical Sciences (LPS) Qubit Collaboratory (LQC), located at University of Maryland, College Park, and the University of California Santa Barbara (UCSB) National Science Foundation (NSF) Quantum Foundry. The LQC was announced in November 2020 and is intended to enable collaborative research among academic, government, industry, and non-profit organizations in the quantum information processing technology space (LQC n.d.). The UCSB NSF Quantum Foundry is a facility that "develops materials and interfaces hosting the coherent quantum states needed to power the coming age of quantum-based electronics." (UCSB 2022)

Beyond the above examples discussed explicitly by participants, the United States is home to several additional facilities that could serve as useful models or that might already provide some capabilities that meet the participants' stated needs. These include the Manufacturing USA Institutes (e.g., AIM Photonics, which offers "access to a supporting infrastructure of services across the entire silicon photonics development cycle: design, simulation, fabrication, packaging, validation, and a path to volume manufacturing" (AIM Photonics 2022)) and the Department of Energy's (DOE) National QIS Research Centers, which aim to "create and steward the ecosystem needed to foster and facilitate advancement of QIS." (DOE 2022).

Other types of infrastructure were also desired by participants, such as dark fiber networks for testing quantum communication and networking technologies up to city-scale, similar to the one connecting the Chicago Quantum Exchange headquarters, the University of Chicago, and Argonne National Laboratory (Fore 2022). Test beds and test structures for various types of sensors were also of interest.

### 2. Workforce Challenges

It was noted throughout the meeting that the most valuable and scarce resource for QIS is trained, skilled people. The demand for workforce development in the quantum information science and technology (QIST) field has driven multiple publications and workshops in recent years (Asfaw et al. 2022; Aiello et al. 2021; Fox et al. 2020; Hughes et al. 2022). In the United States, a National Strategic Plan for QIST workforce development was released shortly before the FDW (Subcommittee on Quantum Information Science 2022). Participants at the workshop described a current environment in which graduate students, post-doctoral (post-docs) scholars, and professors were being hired at high rates by industry, making it difficult to hire within academia. This strong hiring pressure from industry for QIS PhDs and post-docs is symptomatic of imbalance between the demand for QIS talent and the supply available from academic programs, as well as the inability of PhD programs to quickly adjust to the rapid rise in industry demand.

Participants felt that this problem was especially noteworthy in the areas of theory and QEC.[7] Participants felt that academia badly needed to retain more theorists, and described a particular desire for more people that could work at the confluence of theory for QIS, statistical mechanics, and quantum chemistry. A few examples of topics that participants wanted to see addressed by theorists included: tools from quantum information theory applied to many-body problems, new ideas for what to do with large parallel

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[7] Hughes (2022) found based on a survey of 57 companies in the quantum industry that quantum-specific skills were considered 'important' to the following job roles: photonics/optics engineer/scientist, quantum algorithm developer, computational chemist, theoretical physicist, experimental physicist, application/solutions architect, and error correction scientist. Note that companies indicated that they expected to be hiring in these roles in the next 5 years.

quantum computing systems or networked quantum sensors, and exploration of approaches to tuning error correction to particular classes of quantum systems (rather than focusing on generalized error correction strategies).

At the same time, participants felt that the quantum industry in general needed to be more interconnected with other industries. For example, there was interest in creating collaborations between quantum laboratories and biology laboratories, interfacing between theoreticians and experimentalists (for example, through co-design of quantum processing chips and other quantum devices), and bringing expertise from signal processing into the world of QIS.

The participants at the meeting wanted to scale their educational training capacity to meet industry demand, but they also suggested that industry should participate in the education of QIS professionals. Proposals for addressing these workforce development challenges included 1-year master's programs in which industry would get involved with student education, short (3–6 month) exchanges of students into industry when industry had a need for a very specific skill, and joint mentoring of students between industry and academia. Emphasis was placed on the need for such dual-mentored students to be permitted to publish based on their work. One existing program that could be a model for this type of industry participation in student training is the Quantum Information Science and Engineering Network (QISE-NET). The QISE-NET program provides up to 3 years of funding ($10,000 per year) to graduate students that are paired with one industry or national laboratory mentor and one university principal investigator (PI) (QISE-NET 2020). The student works with these mentors to develop specific research goals while gaining networking opportunities and access to the industry mentor's site. Currently a small program in the United States supported by the NSF, this concept could be scaled up and replicated by other agencies.

An additional key idea for meeting the workforce needs was establishing degree programs in 'quantum engineering.' A quantum engineer,[8] as described by workshop participants, is an individual that can extend quantum systems to new applications and potentially integrate them with other technologies while not necessarily being an expert in the underlying physics of QIST. The quantum engineer would understand the fundamental principles of quantum science, but would not necessarily be specialized in a particular type of quantum system (e.g., trapped ions, Rydberg atoms), and would instead have other skills that would enable industrialized applications of these technologies. This idea has been put forward before, for example, by the United States' National Quantum Coordination Office

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[8] A recently published article by Asfaw et al. (2022), "Building a Quantum Engineering Undergraduate Program," defines *quantum engineering* as "the application of engineering methods and principles to quantum information systems and problems." This publication was the result of the NSF Workshop on Quantum Engineering Education, which took place in February 2021.

(The White House NQCO 2020a). In the view of workshop participants, such a person could be trained at the bachelor's or master's level, potentially also mitigating the workforce scaling problem. However, there was disagreement about how to construct curricula for such degree programs, a topic that was thoroughly explored in a recent NSF workshop in the United States (Asfaw et al. 2022). Some participants felt that a collaborative effort between the United States and Australian government to define a curriculum for quantum engineering would be worthwhile, but others felt that close government involvement in the design of educational programs was inadvisable. It was widely accepted that industry demand needed to drive decisions about stimulating academic training—not the other way around. For example, one participant suggested that applications with industrial value as identified by industry would naturally drive the market for talent, helping to stimulate increased supply of students.

Industry surveys to date support the conclusion that many jobs in the QIST industry do not require a PhD. At the same time, such surveys do not necessarily support the idea that industry needs a quantum engineering master's or bachelor's degree (Hughes et al. 2022, Fox et al. 2020). Interviews of representatives from companies in the quantum industry found that often candidates from traditional engineering disciplines such as electrical engineering or computer science that have taken a 1- or 2-semester course introducing them to QIS are desired (Fox et al. 2020). Another study found that quantum-specific skills were not viewed as 'important'[9] to many bachelor's or master's level roles in the QIST industry, although such skills were often important to PhD-level roles (Hughes et al. 2022). Indeed, the consensus of the NSF Workshop on Quantum Engineering Education was that the QIST industry was not yet ready for a quantum engineering bachelor's degree, and that minor programs, quantum 'tracks' within traditional engineering bachelor's programs, or a single introductory course to the field would go a long way toward meeting industry needs (Asfaw et al. 2022). These concepts match the 'add-on' approach to designing an interdisciplinary curriculum as described in Aiello et al. (2021).

The above studies were mostly centered on the QIST industry in North America and Europe, and did not appear to analyze the workforce needs of the QIST industry in Australia. We note that non-PhD degrees in QIST are already available from some universities in Australia, including a master's degree in Quantum Technology offered at the University of Queensland and a bachelor's degree in Quantum Engineering offered at the University of New South Wales.

It is important to note, however, that there is currently no singular, comprehensive data source on the QIST workforce and industry demands for that workforce

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[9] In this study, a skill was considered 'important' if at least 50% of respondents for that role said it was needed for that role (Hughes et al. 2022).

(Subcommittee on Quantum Information Science 2022), although some data collection has been conducted by the United States' Quantum Economic Development Consortium (QED-C) (Hughes et al. 2022). In fact, collecting such information and data is the first critical action listed in the U.S. QIST Workforce Development National Strategic Plan. Collecting data on industry demands for the quantum workforce would be consistent with the view of workshop participants that industry should help inform academic curriculum development, and could be facilitated jointly or in parallel by the U.S. and Australian governments. Such data collection would likely also benefit from multilateral, rather than only bilateral, engagement.

Specific ideas for how the United States and Australia can work together on workforce development will be discussed further in Section 3.C.

### 3. Challenges to Large-Scale System Engineering and Integration

Workshop participants also persistently expressed their desire for modular and commercial off-the-shelf components for building quantum information systems. While off-the-shelf software tools, such as randomized benchmarking codes, are possible to obtain, off-the-shelf hardware is much harder to find. Participants viewed these components as enabling technology to allow academics better access to larger scale quantum systems that are currently too costly and time-consuming to build in academic laboratories, or that require expertise well outside of quantum physics to be built well (e.g., materials processing, electrical engineering). Participants agreed that access to such modular components, if manufactured well, could enable faster scientific turnaround by reducing the burden on researchers to develop the components in-house. Researchers also noted that such modular components could support space-based quantum systems research. Examples of desired components included:

- Lasers with standardized inputs and outputs that are robust, stable, cheap, and widely available, and are not necessarily at telecom wavelengths
- Agile microwave synthesizers
- Modulators, switches, amplifiers, and other optical components
- Detectors beyond lasers, such as superconducting nanowire single photon detectors (SNSPDs) or other high quantum efficiency detectors with reduced cryogenic overhead
- Cooling systems and cryoelectronics
- Wafers

Some of these desires, such as the wafers and optical components, tie in with the foundry idea discussed in Section 2.C.1. However, many of these ideas were envisioned as components that could be provided by commercial vendors. Participants felt that such companies could help miniaturize these components in addition to creating the interfaces needed to integrate them with other parts of the quantum system. Ensuring high quality links between modules was viewed as a key technical challenge that would determine the usefulness and quality of any such modular system design.

Alongside specific modular component development, participants viewed community knowledge on packaging, integration, thermal management, and low-power signal processing for quantum systems as important expertise that would be helpful to import into their labs from industry. These areas were viewed as the sort of technical know-how that might be provided by the quantum engineers discussed in Section 2.C.2. Participants noted that advanced packaging capability is an opportunity for collaborative advantage that the United States and Australia might wish to capitalize upon.

This discussion of systems engineering and integration inevitably led participants to consider the problem of standardization. Standardization of measurements and interfaces and consensus over definitions of key metrics for quantum systems were all raised as important challenges facing the quantum community and potential collaboration opportunities between the United States and Australia. One argument in favor of standards development work is the potential of standards to facilitate export control consideration, which can sometimes delay technology transition to market. It is worth noting, however, that there are some who feel strongly that many QIS technologies are not yet mature enough for standards development to make sense.

Participation by U.S. and Australian scientists in standards development working groups can help ensure that both countries remain at the forefront of these nascent industries. However, there is little incentive for early career researchers to engage with standardization efforts, as these are usually not highly visible and do not build a strong publication record. Nonetheless, quantum scientists would benefit from increased awareness of work ongoing in standardization for quantum technologies, as well as for the enabling industries of electronics and photonics. In the United States, the National Institute of Standards and Technology (NIST) has supported the QED-C, which is “a consortium of stakeholders that aims to enable and grow the U.S. quantum industry” that actively engages with standards development, among other activities (QED-C n.d.). Similar support in Australia may also be worth pursuing.

# 3. Opportunities for U.S.-Australia Collaboration

## A. QIS Strengths and Capabilities in the United States and Australia

The past 40 years have witnessed enormous growth in QIS research within the United States and Australia, fueled by numerous commercial ventures, academic efforts, and governmental initiatives. The economic and scientific forces that propelled this growth have not only given rise to a broad variety of QIS proficiencies within these two countries but shaped their respective needs for quantum technologies. This section identifies the strengths of the United States and Australia within QIS, placing an emphasis on those cited during workshop discussions. Given the large number of QIS-focused institutions, companies, and initiatives, care was taken to avoid "more is better" biases when making attributions of capability.

As of 2020, Australia had a population of just under 26 million, making the breadth of its QIS competencies nothing short of remarkable. With support from the Australian Research Council (ARC), top Australian universities have established centers and research hubs to catalyze progress within QIS, such as the Centre of Excellence (COE) for Quantum Computation and Communication Technology (CQC2T) hosted at the University of New South Wales and the Centre of Excellence for Engineered Quantum Systems (EQuS) hosted at the University of Queensland. In fact, the ARC has used such COEs to galvanize collaborations between institutions and support the development of research infrastructure for quantum sciences since 2003, when two earlier COEs (the Australian Centre for Quantum Atomic Optics (ACQAO) and the Center for Quantum Computing Technology (CQCT)) were founded. Australian universities have also benefited from partnerships with industry, including collaboration between Microsoft and the University of Sydney and between IBM and the University of Melbourne.

These coordinated quantum-focused efforts, both within and among universities, have given rise to a host of QIS proficiencies in Australia. Workshop participants from both countries spoke often of Australia's strengths in theoretical quantum computation, especially in the development of QECCs, with its pioneering contributions toward larger fields of study, such as condensed matter. Australia's strength in QC theory, however, extends into a number of other areas, complementing world-class experimental proficiencies in quantum control, quantum photonics, and efficient, high-fidelity quantum memories.

The close relationships maintained by universities with spin-off companies engenders yet more growth. Workshop discussions referred often to the successes of such start-ups as Q-CTRL (University of Sydney) and Silicon Quantum Computing (University of New South Wales), which have each raised tens of millions of U.S. dollars as of late 2021 (Biercuk 2021; Haigh 2022). Numerous others, including Quantum Brilliance, Nomad Atomics, Vai Photonics, and QuintessenceLabs (all spin-offs of Australian National University), bolster Australia's QIS infrastructure by providing a well-rounded suite of quantum software and hardware (InnovationAus 2022; BusinessWire 2021).

During deliberations on the practical applications of QIS research, workshop participants often mentioned Australia's burgeoning emphasis on orbital spaceflight. In particular, discussions cited a keen interest within Australia on establishing satellite-based quantum networks. Australia's location on Earth is attractive for satellite launch and communication (e.g., closeness to equator for near-ideal launch trajectories, ample room for many ground stations, regions of high visibility and low backgrounds), and several space-related initiatives are underway, including the Australian Defence Satellite Communication System (also called the *JP9102*), the Australian Space Manufacturing Network (ASMN) (Harrison 2021; Chapman 2022), and the Innovative Launch, Automation, Novel Materials, Communications and Hypersonics (ILAuNCH) Hub (University of Southern Queensland 2022). Coinciding with these initiatives are QIS research efforts that could enable space-based quantum-communication. One such effort at the Cooperative Research Centre for Smart Satellite Technologies and Analytics (Australian National University) centers on the use of solids doped with rare-earth ions for quantum memories—vital components for space-based quantum communication (SmartSat Cooperative Research Centre n.d.; Rančić et al. 2018). Another prominent investigation within the InSpace Laser Communications Program (also at Australian National University) is developing quantum-communication techniques with adaptive optics (Mandow 2019).

Australia's massive global presence in the mining industry sets up another compelling motivation for developing quantum technologies. The fourth-largest country in mining production by weight, Australia's mining sector maintains a strong awareness of sensing technologies that could aid detection of mineral deposits (Reichl and Schatz 2022). Workshop discussions suggested quantum magnetometers and gravimeters as potentially lucrative for mining, in addition to quantum-enabled devices for gas detection—citing Orica's place as the global leader in the production of explosives and blasting technologies for mining.

With the United States' large population and broad national support for scientific research, U.S. expertise encompasses most topics and subdisciplines currently within QIS. The United States invests heavily in the private and public sectors, leading the world in public and private funding for QIS research; and QIS-focused companies, start-ups, academic groups, and governmental organizations (Mohr et al. 2022).[10] A number of the commercial efforts underway aim to fabricate large-scale qubit platforms spanning a wide range of approaches. Among the companies leading these endeavors are Google, IBM, and Intel—supported by multibillion-dollar budgets and vast experience in related chip-fabrication activities. Startups such as PsiQuantum and Rigetti have received hundreds of millions of dollars in equity funding (Statista 2022). The U.S.'s dominance in high-performance computing (HPC), for example, will help catalyze the advancement of quantum platforms. As of June 2022, 8 of the top 20 HPC systems in the world are located in the United States, and 13 of the top 20 HPCs worldwide derived from U.S. manufacturers or vendors (Top 500 2022).

Due in part to the aforementioned benefits of a large population and broad investment in scientific research, the United States is home to hundreds of colleges and universities. Of the largest universities, a significant portion have prioritized QIS research and formed quantum-centered institutes. Examples include the Harvard Quantum Initiative, the Massachusetts Institute of Technology (MIT) Center for Quantum Engineering, the Berkeley Quantum Information & Computation Center, the Chicago Quantum Exchange, and the Yale Quantum Institute, among others. During the past 2 years, federal support has led to additional QIS consortia, spanning academia, industry, and government laboratories. To facilitate broad collaborations and address key challenges across QIS subdisciplines, the DOE formed five National QIS Research Centers in 2020, each led by a different DOE National Laboratory. Moreover, in response to multiple governmental initiatives calling for the advancement of QIS, the NSF has founded 5 university-led institutes that integrate more than a dozen academic institutions with 22 commercial enterprises and 8 National Laboratories (NSF 2020). These recent government-founded conglomerations accompany a range of mature federal QIS assets, such as the three quantum institutes encompassed by NIST—JILA (at the University of Colorado Boulder), the Joint Quantum Institute, and the Joint Center for Quantum Information and Computer Science (both at the University of Maryland, College Park).

Several workshop participants conveyed surprise that the United States has not pursued any space-based demonstrations of quantum communication, calling the approach more attractive than systems relying on optical fiber and repeaters. The United States is the global leader in satellite launches, satellite manufacture, launch-vehicle production, and total launches per year—driven today by an active commercial space sector led by outfits such as SpaceX, Virgin Orbit, Astra, Blue Origin, Orbital Sciences, and Virgin Galactic (Harrison 2022; Krebs 2022; Satellite Industry Association 2022; *The Economist* 2018).

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[10] Note that China and Japan are excluded from this assessment, as funding data about QIS research in these countries are likely incomplete or inaccurate.

The U.S.'s long-standing and growing investment in space technologies could both motivate and enable future satellite-mediated demonstrations of quantum communication.

## B. Moonshots and Grand Challenges

During the final session of the workshop, participants were tasked with trying to develop grand challenge or "moonshot" ideas that could galvanize and organize new basic research directions including many of the ideas that had been put forward throughout the meeting. These grand challenges would need clear goals that would inspire excitement and interest among researchers and committed government support. They would also need to be on a scale that would require collaboration and participation among numerous research groups while having the potential to spin off many smaller directions of inquiry. Ideally, they would also take advantage of the respective strengths of the United States and Australia. During Session 4 of the workshop, which was an entirely plenary session (i.e., no breakout groups), participants were first asked to nominate the best moonshot ideas that they had heard throughout the meeting. The group then voted on which ideas they wished to elaborate upon, and proceeded to discuss technical challenges, key scientific questions, and possible outcomes. This section describes, in alphabetical order, the three moonshot ideas that the participants selected.

### 1. Achieving Large-Scale Quantum Platforms with Better Qubits

Following the emphasis on quantum computing and communication in Session 3, breakout groups were asked to propose a networked hybrid quantum system, with consideration given to the hardware and interfaces required. One group decided that a prioritization of hybrid systems and interfaces is premature, however, given the many outstanding fundamental problems impeding the integration of disparate systems. After first examining the on-demand interactions desirable for hybrid systems, the group eventually focused on the need for physical qubits capable of significantly lower gate error rates—a critical precondition for networked computing platforms that exhibit quantum advantage. Participants observed that systems have plateaued at gate error rates of $10^{-2}$ to $10^{-3}$, a heavy burden for error correction. Dramatic reductions in error rates would reduce this burden, along with other overheads as well, such as logical clock speeds and qubit-count requirements.

The discussion ultimately converged upon this question: How might quantum science create physical qubits capable of supporting $10^{-6}$ errors per operation in large-scale systems? The concept of quantum integration and scaling while pursuing extreme high-fidelity qubits became the motivating concept behind the first moonshot discussed. The group argued that addressing this challenge was uniquely suited to Australian-U.S. collaborations, while also being central to the attainment of several practical quantum technologies. Consequently, to facilitate the realization of this objective, a QIS-centered institute merging American and Australian capabilities was proposed. This institute would strive to balance the tradeoffs between fabrication sophistication, high throughput speeds, and the processing flexibility required to accommodate a wide range of materials and innovative qubit approaches. The idea for this moonshot is summarized in Box 2.

### MOONSHOT #1: ACHIEVING LARGE-SCALE QUANTUM PLATFORMS WITH BETTER QUBITS

**Description –** The creation of physical qubits capable of supporting $10^{-6}$ errors per operation in large-scale systems.

**Proposed solution –** To revolutionize the design and fabrication of qubit platforms by founding a QIS-centered institute that combines American and Australian strengths.

**Central questions –** How would such an institute balance competing requirements for processing flexibility, fabrication sophistication, and high throughput speeds?

**Ten-year trajectory –** Concurrent establishment of the following:

**(1)** An advanced fabrication facility capable of supporting a wide range of materials and qubit approaches

**(2)** Computational and theoretical resources for advancement of materials, qubit architecture, and error-suppression strategies.

**Box 2. Moonshot #1: Achieving Large-Scale Quantum Platforms with Better Qubits**

As with most worthwhile moonshots, this one stands to stimulate a variety of other important findings as well. A goal of low-error, large-scale quantum computation will most likely be met through a combination of improved physical qubits and improved error correction schemes. Thus, this collaboration could include research into QEC approaches as well as catalyze the discovery of new strongly correlated materials. Not merely a fabrication initiative, this institute would also comprise theoretical and computational capabilities that further distinguish it from more narrowly focused commercial alternatives. A strong emphasis on QEC would encourage theorists and experimentalists alike to revisit outmoded assumptions and devise new QEC approaches with specific platforms in mind at the outset. To identify and assess error sources at the levels of precision required for rates approaching $10^{-6}$, the proposed institute would also invest in (or help develop) new fabrication and characterization tools. Novel QECCs and qubit designs will each influence the advancement of the other, requiring a cutting-edge means of understanding relaxation and dephasing mechanisms in new qubit architectures.

## 2. Intercontinental Quantum Links

### MOONSHOT #2: INTERCONTINENTAL QUANTUM LINKS

**Description –** Demonstrate and study distributed quantum entanglement

**Proposed solution –** Build a satellite-linked quantum network between the United States and Australia

**Central questions –** How can we develop robust quantum memories, quantum repeaters, and quantum interfaces that can work together to produce satellite-linked intercontinental entanglement? What advantages does distributed entanglement enable, what algorithms are needed, and how may they be tested?

**Ten-year trajectory –** Achieve the following steps. Some steps may be concurrent.

**(1)** Feasibility studies and roadmapping
**(2)** Identify a set of most promising quantum memory platforms to locate in each country and on the satellite
**(3)** Design and develop robust interfaces for transferring information between these disparate quantum systems
**(4)** Propose protocols for entanglement swapping, single photon detection, and error correction
**(5)** Create a quantum repeater that can survive satellite launch
**(6)** Establish entanglement swapping between each continent and the space-based system
**(7)** Establish entanglement swapping between the two countries
**(8)** Use the network as a testbed for studying entanglement, advanced imaging, error correction algorithms, quantum gravity, and other topics.

**Box 3. Moonshot #2: Intercontinental Quantum Links**

The second grand challenge or 'moonshot' discussed at the workshop was the idea of demonstrating and studying distributed quantum entanglement between the United States and Australia via a satellite-linked quantum network. This idea was viewed as an inspiring scientific and technical challenge that could motivate numerous students and researchers and produce many significant scientific and technological advances. Participants viewed this as an opportunity to experiment with distributed entanglement while solving problems translatable to a wide range of quantum technologies. In other words, this would be a platform built by scientists and engineers for the purpose of conducting and inspiring groundbreaking scientific research—not a commercial or application-focused endeavor. Box 3 summarizes this moonshot concept.

The participants believed that the challenge could be structured similar to the LIGO project—that is, as a basic research project in which collaborators from the United States and Australia could work together to advance the field of QIS while also continuing to publish individual research and create offshoot technologies. Some even suggested that with the decreasing cost of space launch, this idea could be a component of a new space launch facility dedicated to scientific research that could galvanize collaborative efforts across scientific disciplines beyond QIS (Roberts 2022; Jones 2018).

The most concise summary of this idea as framed by the participants was to link a quantum memory in the United States to a different type of quantum memory in Australia via a satellite containing a quantum repeater. The scientific goal would be to distribute entanglement between the continental United States and Australia, a distance of more than 7,000 miles. Although costly and rife with technical challenges, using space-based linking has two key advantages: first, it minimizes signal transmission losses related to propagation of photons through atmosphere or fiber optics, and second, it minimizes the need for scalable implementation of the technically challenging quantum repeater (Lu et al. 2022).

The need to solve a wide variety of technical challenges was viewed as a positive attribute of this moonshot idea because it would drive prolific innovation and scientific development in areas applicable outside of the intercontinental quantum network mission. Some of the technical challenges highlighted by participants included creating robust interfaces between at least three different types of quantum state, creating a stable type of quantum memory that could survive the launch into space, ensuring exquisite timing control for enabling entanglement swapping, improving single photon detection over long distances, and establishing functional quantum error correction across distributed systems. Once the intercontinental quantum network was established, it could then serve as a one-of-a-kind experimental test bed. Possible topics of study mentioned included extremely long (multi-hour) coherence times, the process of entanglement, advanced imaging techniques for astronomy, distributed error correction algorithms, and quantum gravity.

This idea was also seen as natural candidate for U.S.-Australia collaboration. Participants noted that Australia has unique near-equatorial space-launch capabilities, as exemplified by the Arnhem Space Center, which was recently used by the National Aeronautics and Space Administration (NASA) to launch a sounding rocket to study distant stars (Turnbull 2022). In addition, Australia is working on developing a network of optical ground stations that should be compatible with future communications methods, including quantum communications (Bennet et al. 2020). Thirdly, Australia also hosts significant expertise in QEC and rare-earth memories, for example, leading the way on Erbium-based memories with long coherence times (Rančić et al. 2018). Strengths of the

United States that were mentioned include a leading space access industry, expertise in a variety of materials platforms that represent candidates for ground- or space-based memories, and strong presence in photonics and microelectronics hardware technology that would likely be essential to this collaboration.

Suggested topics for collaboration included:

- Identification and development of candidate quantum memories for each component of the quantum network
- Development of transducers between candidate quantum states, including spin-optical, microwave-optical, superconducting-microwave, and spin-photon-spin transducers
- Parallel algorithm development between the United States and Australia for control and error correction on the distributed quantum network
- Homomorphically encrypted or ‘blind’ quantum computing
- Standards and protocols needed for the successful operation of this kind of network
- Connected imaging satellites for very large baseline telescopes

It was clear that feasibility studies and roadmapping exercises would be needed to determine the most promising quantum resources and components for inclusion in the full system. However, exploration of a wide variety of possibilities would characterize the beginning of this collaboration, which was anticipated to have an important stimulating effect on research across the QIS community. Many of the above topics, such as algorithm development, transducer development, and development of individual classes of quantum memory, have clear application to a wide variety of terrestrial quantum technologies. In addition, this moonshot would require mastery of a variety of classical supporting technologies, such as locking and pointing stabilization for the satellite.

This idea is also one that closely links with many other themes discussed at the workshop. For example, the foundries described in Section 2.C.1 could facilitate experimental studies needed to identify and develop hardware components for the space- or ground-based systems. Similarly, the modularization of supporting technologies described in Section 2.C.3 would help both the fundamental research of this collaboration and the ultimate production of components for the space-based system. Finally, this moonshot would be a way to inspire students and build the quantum workforce, a key need outlined in Section 2.C.2.

We note that some of the technical goals involved with establishing this system have already been demonstrated on China’s Micius satellite–in particular, the goal of distributing entanglement between space and distant ground stations and the goal of an intercontinental quantum network (without entanglement distribution) (Lu et al. 2022; Liao et al. 2018; Yin et al. 2017). This project would aim to push the boundaries of distributed quantum entanglement beyond what that program has achieved. Some similar goals to the ones listed above have been described as targets for future research programs in China (Lu et al. 2022).

We also note that this is hardly the first time that intercontinental entanglement distribution has been proposed, even within the United States. For example, a workshop co-sponsored by NIST and NASA in 2020 outlined a very detailed staged approach to establishing satellite-linked entanglement swapping between the United States and Europe (NASA and NIST 2020).[11] That approach, which has not been implemented as of the writing of this report, was called 'qEDISON' and was designed around technologies that were available at the time of that workshop. Thus, the proposed approach did not include a requirement for a quantum memory, quantum repeater, or space-worthy cryogenic system. At the time, the authors viewed 2030 and 2035, respectively, as reasonable timeframes for the development of spaceflight-ready quantum memory or fault-tolerant quantum repeater technology. However, many key components identified then are shared with the needs of the current proposal, such as quantum sources, single photon receivers, space- and ground-based optical terminals, and system-level analysis tools.

We also note that U.S. policy on this topic has recently advocated for a deliberative approach that will limit the risk of investing too much, too soon in a quantum space program. Space-to-ground connections and intercontinental space-based entanglement were both initially called out as near-term areas for exploration in the National Quantum Coordination Office's 2020 document "A Strategic Vision for America's Quantum Networks." (The White House NQCO 2020b) However, the National Science and Technology Council's Subcommittee on QIS later published "A Coordinated Approach to Quantum Networking Research," which states that "care should be taken so resource allocations for large-scale demonstrations do not negatively impact fundamental QISE studies with smaller test beds" (Subcommittee on Quantum Information Science 2021). Although that report still agreed with the potential for a project such as this to stimulate scientific research, it advocated for feasibility studies and more research to understand the potential unlocked by such a test bed prior to investing large-scale resources. At the same time, that report recognized the importance of international collaboration and multi-agency investment in quantum networking R&D, which would be cornerstones of this proposed moonshot.

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[11] This also was not the first such proposal. The same report mentions a 2019 workshop between the United States. and European Union that also discussed a trans-Atlantic quantum link using a satellite to bridge the distance.

## 3. Quantum Engineering and Imaging of Molecules

### MOONSHOT #3: QUANTUM ENGINEERING AND IMAGING OF MOLECULES

**Description –** Control quantum coherence at the molecular scale to create new modalities for monitoring, imaging, or manipulating chemical, biological, and biochemical systems in real time.

**Proposed solution –** Large-scale, collaborative initiative to design, synthesize, and deploy molecules for quantum sensing in solution or in-vivo biological environments.

**Central questions –** How can we design, produce, and apply single molecules with engineered coherence for biological, biochemical, and chemical sensing?

**Ten-year trajectory –** Achieve the following steps. Some steps may be concurrent.

**(1)** Synthesize molecules with site-selectivity for isotopes and engineered coherence
**(2)** Develop and test methods for mitigating noise and maintaining coherence in solution and in-vivo
**(3)** Use ab initio simulations to design quantum sensing molecules for particular tasks
**(4)** Image protein structure folding or other metabolic processes in real time
**(5)** Collaborate with biotechnology industry to develop commercial application proofs of concept

**Box 4. Quantum Engineering and Imaging of Molecules**

The third moonshot idea discussed was for a large-scale, collaborative initiative to design, synthesize, and deploy molecules for quantum sensing in solution or in-vivo biological environments. Inspired in part by some interesting recent demonstrations of molecular quantum sensor synthesis (e.g., optically addressable molecular spins in organometallic molecules (Bayliss et al. 2020), attachment of a diamond quantum sensor to a protein (Xie et al. 2022)), participants were compelled by the potential of controlling quantum coherence at the molecular scale in new modalities for monitoring, imaging, or manipulation of chemical, biochemical, or biological systems in real time. This work could yield new scientific tools and methods with the potential to help address medical, security, and environmental challenges. It was suggested that, if the same level of effort and funding going toward development of quantum computing was provided for work in quantum sensing and imaging, the impacts could be transformative. The workshop participants expressed eagerness to collaborate with researchers from the biological sciences. Indeed, both the United States and Australia have strong science and engineering ecosystems around biotechnology that could join the QIS ecosystem to contribute to this multidisciplinary moonshot, which is summarized in Box 4.

Leveraging molecular systems for QIS has the advantage that molecules can be precisely and replicably synthesized (Wasielewski et al. 2020). The ability to create and address coherence in single molecules, coupled with targeted design of their chemical structure and properties could support quantum sensing in targeted locations of different environments. Namely, a molecular sensor designed to bind to specific biochemical sites could be used to make in-vivo measurements and reveal structure-function relationships. This could include or combine thermometry within cell features, single-molecule nuclear magnetic resonance (NMR) for identifying or characterizing local chemical structures, or optomechanical sensors to detect movement or conformation changes. Moonshot goals for these tools include:

- Real-time, *in situ* imaging of protein structures and folding or other metabolic processes, rather than relying on ensemble-averaged or protein crystal structures outside of a biological context,
- Non-invasive detection of disease markers in living tissue, and
- In-vivo observation of drug candidates' uptake pathways and biological activity.

This moonshot would center around targeted design, simulation, synthesis, and testing of molecules to be used as quantum sensors. Access to classical supercomputers would support simulation of the chemical and quantum coherent properties and behavior of molecules. Promising candidates could then be synthesized and their performance tested in a lab. As quantum computing and simulation technologies mature, they would enable improved simulation of candidate molecules. This thus represents an opportunity for collaboration between theorists specializing in quantum simulation and experimentalists specializing in the synthesis, testing, and optimization of quantum sensors. The envisioned "molecular foundry" would need to support short feedback times between synthesis and testing, and also enable developments in materials science. After an iterative engineering feedback loop, candidate molecular systems could be tested *in vitro* and then *in vivo*.

Major technical challenges to overcome include avoiding or correcting errors due to noise in solution and biological systems to achieve truly quantum measurements leveraging quantum phenomena in molecules and at biological temperatures. Other challenges include the interface between the biological system and the control and readout of the sensor *in situ*. Leveraging infrared radiation, which can penetrate skin, could yield a partial solution.

Optically detected magnetic resonance could be another tool, for boosting signal-to-noise. With single-molecule NMR, noise and decoherence would be introduced by the immediate nuclear environment of the molecule and be affected by the isotopic purity of its constituent atoms. Coherence times for these systems could be improved by synthesizing molecules from isotopically pure materials, so that the active nuclei are not exposed to nuclear isotopes within the same molecule that could disrupt the coherence. Isotope-specific synthesis—for example, using precursors with purified $^{12}C$ and selected $^{13}C$ at the intended location in the molecule, could optimize location of the spin-active nucleus relative to the target while removing potential noise sources.

Research facilities to support these efforts would combine biology, synthetic chemistry, and quantum science laboratories. This moonshot would require collaborations across a range of fields, including quantum information science, quantum and synthetic chemistry, biology and biochemistry, and medicine and pharmacology, as well as researchers with multidisciplinary training.

## C. Infrastructure and Talent Development

Opportunities for joint infrastructure development were widely discussed at the meeting, as covered in Section 2.C. In this section, we add details of this goal that were not fully described in the other sections. It was generally agreed at the workshop that a few key steps should be taken for the United States and Australia to establish needed infrastructure for QIS research. First, a joint effort to identify and describe existing facilities and capabilities in the two countries was needed. Existing facilities, such as synchrotron user facilities at National Laboratories in the United States, could form natural focal points for collaboration between the two nations. After charting existing infrastructure, a joint roadmapping effort to determine gaps in foundries and testbeds would be necessary. Finally, the two countries would need to agree on which country would build what, and how to fund the effort. Shared access agreements and intellectual property (IP) frameworks were also highlighted as key discussions under this umbrella. Academic participants noted that access to government points of contact that could help navigate IP and export control landscapes for shared institutes and international collaborations would be invaluable. Participants also noted, however, that parallel infrastructure might be worthwhile in some cases and that facilities did not necessarily need to be 'one-offs' located in one country or the other, but not both. Finally, finding ways to smooth the ability of the two countries to share critical minerals relevant to QIS research was also discussed.

Participants also considered specific ideas on how the United States and Australia could collaborate on workforce development. Ideas included a joint dual PhD degree between the United States and Australia, similar to France's "cotutelle" concept, short exchanges (~6 months) of students or post-docs between the two countries, and a 4- or 5-year post-doc program jointly funded by the two countries. It was agreed that any joint fellowship program, whether for students or post-docs, needed to be general enough that it would garner broad awareness and interest among potential applicants. In other words, it could not be tied to a small number of specific QIS topics, but instead needed to support proposals in the broad area of QIS. One possible model for this last idea was Canada's Natural Sciences and Engineering Research Council (NSERC) Post-doctoral Fellowships program, in which a Canadian post-doc may receive funding regardless of whether they will be at a Canadian academic institution, Canadian provincial research institution, or a research institution abroad (NSERC 2022).

A few other challenges were also noted for each of these ideas. For cotutelle, the disparate timelines of the U.S. and Australian PhD were viewed as an important barrier. The Australian PhD is typically 3–4 years, while the U.S. PhD can extend longer, but is more typically 5–6 years. Some mechanisms to allow for longer Australian PhDs or shorter American PhDs were needed to enable the cotutelle idea. Participants also noted the barrier that visa requirements in Australia prevent foreign students from changing research advisors. In the case of the 6-month exchange idea, several participants indicated that this length of time was not likely to be appealing to the potential short-term mentoring PI, because it would be barely enough time to train a student on a new tool or method. Undergraduate researchers were viewed as a preferred resource for short-term assistance. In the case of the long-term post-doc fellowship, the Australian participants noted that limited-term government funding schemes in Australia could make 4- or 5-year fellowships for post-docs challenging to fund because institutions could not offer appointments longer than the available funding.

In general, there was a lot of enthusiasm and many ideas for possible approaches to improving workforce development for QIS as well as increasing access to QIS fabrication and testing infrastructure. However, it was also clear that these challenges could not be solved by academics alone, and would require the involvement of government and industry stakeholders to coordinate workable funding, schedule, immigration, and IP arrangements.

## D. A Path Forward

The FDW resulted in numerous discussions between American and Australian scientists and government program managers, and many participants came away from the meeting expressing a wish to see further engagement on the technical topics that were covered. For the grand challenges, there was wide agreement that follow-on technical workshops to build out in-depth detail as to how to accomplish each goal would be beneficial. Moreover, participants were eager to see collaboration between the two countries on new, joint research programs and roadmapping efforts. Although the workshop design resulted in a focus on bilateral opportunities, many of the technical topics and ideas developed during the meeting (and even some of the grand challenge ideas) could also be of interest for multilateral initiatives—a possibility made more interesting by the recently signed AUKUS agreement. It was clear that many opportunities exist for research in QIS, from fundamental theoretical studies of algorithms or decoherence mechanisms to large scale system-level demonstrations requiring solutions to numerous engineering and fabrication pitfalls. Such research will impact a myriad of scientific fields and engineering disciplines and will inspire scientists for decades to come.

# Appendix A.
# List of Abbreviations

| | |
|---|---|
| ACQAO | Australian Centre for Quantum Atomic Optics |
| AQuA | AUKUS Quantum Arrangement |
| ARC | Australian Research Council |
| ASMN | Australian Space Manufacturing Network |
| AUKUS | Australia – United Kingdom – United States |
| CMOS | complementary metal-oxide semiconductor |
| COE | Centre of Excellence |
| CQC2T | Centre of Excellence for Quantum Computation and Communication Technology |
| DoD | Department of Defense |
| DOE | Department of Energy |
| DSTG | Defence Science and Technology Group |
| EQUS | Centre of Excellence for Engineered Quantum Systems |
| FDW | Future Directions Workshop |
| HPC | high-performance computing |
| IEEE | Institute for Electrical and Electronic Engineers |
| ILAuNCH | Innovative Launch, Automation, Novel Materials, Communications and Hypersonics |
| IP | intellectual property |
| ISO | International Standards Organization |
| LDPC | low-density parity check |
| MEMS | microelectromechanical systems |
| MIT | Massachusetts Institute of Technology |
| NASA | National Aeronautics and Space Administration |
| NIST | National Institute of Standards and Technology |
| NMR | nuclear magnetic resonance |
| NQCO | National Quantum Coordination Office |
| NSERC | Natural Sciences and Engineering Research Council |
| NSF | National Science Foundation |
| NV | nitrogen-vacancy |
| PI | principal investigators |
| PNT | position, navigation, and timing |
| QC | quantum computer / quantum computing |
| QD | quantum dot |
| QEC | quantum error correction |
| QECC | QEC code |
| QED | quantum electrodynamics |
| QED-C | Quantum Economic Development Consortium |

| | |
|---|---|
| QFC | quantum-frequency conversion |
| QIS | quantum information science |
| QISE | quantum information science and engineering |
| QISE-NET | Quantum Information Science and Engineering Network |
| QIST | quantum information science and technology |
| QMFS | quantum-mechanics-free subsystem |
| QVECTOR | quantum variational error corrector |
| R&D | research and development |
| SiC | silicon carbide |
| SiV | silicon-vacancy |
| SNSPD | superconducting nanowire single photon detector |
| SnV | tin-vacancy |
| VLSI | very large-scale integration |
| $VV^0$ | neutral divacancy |

# Appendix B.
# Recent Developments in QIS

This Appendix expands on the list of recent breakthroughs (summarized in Section 1.B) that workshop participants highlighted during the round-robin of Session 1 of the workshop, placing them in the context of recently published research articles and review papers from the academic literature.

## 1. Advances in Qubit Platforms, Control, and Readout

This section briefly describes a selection of noteworthy qubit-related advancements that took place during the year preceding the workshop and the preparation of this report.

### Spin-Based Semiconductor Systems

Semiconductor qubits typically manipulate either spins or charges, exploiting either degree of freedom to store information in the quantum state of a confined electron, hole, or nucleus.[12] Spin-based systems, in particular, have seen remarkable progress recently. Despite notable achievements in research on charge qubits, this section will focus solely on spin-based systems.[13]

Spin-based semiconducting qubits encompass a range of implementations, though recent efforts have largely focused on three primary systems. Spanning mere nanometers, the smallest of these qubits are color centers, in which the spin (or orbital) states of one to several crystalline impurities are optically manipulated, addressed, or read. The most promising and widely studied host for these color centers is diamond. In addition to offering scalable manufacturing, the properties of diamond effectively isolate spin states

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[12] A single spin-$1/2$ particle (e.g., an electron) is a two-state system and the quintessential qubit. Unlike charge qubits, which suffer from charge noise in the presence of ambient electric fields, spins couple weakly to ambient electric fields. Spin qubits have spin-coherence times ($T_2$) exceeding the charge-dephasing times of their charge-based counterparts by many orders of magnitude. The disparity in typical relaxation times ($T_1$) is similarly extreme between spin- and charge-based qubits. Still, qubit isolation is a mixed blessing, presenting a tradeoff between addressability and coherence time. While charge qubits have shorter coherence times than spin qubits, they are more conducive to manipulation.

[13] One recent demonstration of a novel charge-qubit platform was reported by Zhou et al. (2022), whose work was mentioned on several occasions by workshop participants. In their work, Zhou et al. developed a single-electron charge qubit by trapping isolated single electrons on a pristine solid neon surface *in vacuo*. To enable control and readout with microwave photons, the authors incorporate the electron trap within a hybrid circuit quantum electrodynamics (QED) platform (Zhou et al. 2022).

from decohering influences. The left panel of Figure 3 is an image of color centers in diamond, captured by ultraviolet photoluminescence. Only slightly larger in footprint are qubits based on *shallow dopants*, consisting of implanted donor atoms (often in silicon) that allow for the encoding of information into electron- or nuclear-spin states. Though *gate-defined quantum dots* are considerably larger, their development draws upon the immense industrial maturity of VLSI techniques and materials. In the right panel of Figure 3, a scanning-electron micrograph captures an array of gate-defined quantum dots (de Leon et al. 2021).

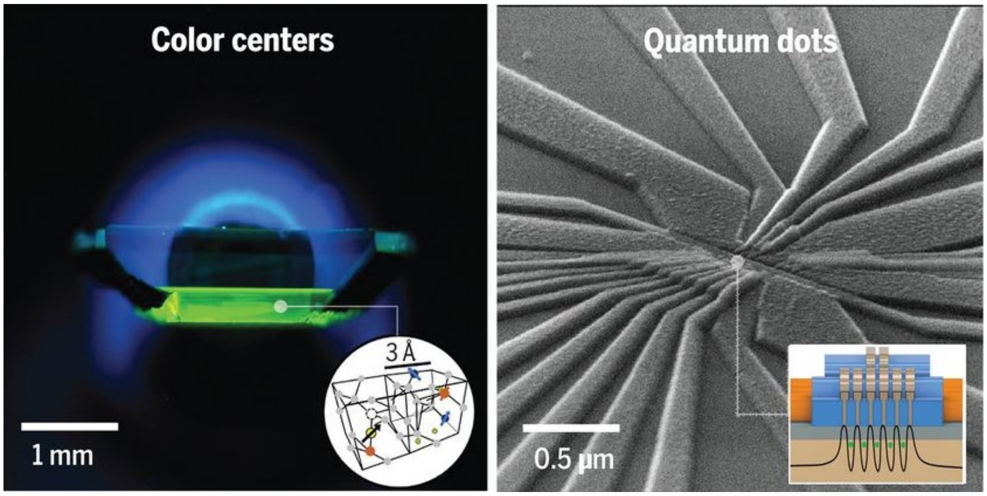

**Figure 3. Two semiconductor-based qubit platforms. Left: Ultraviolet emission from color centers in diamond; the inset illustrates the defect structure. Original image courtesy of N.P. De Leon. Right: Semiconductor-based gate-defined quantum dots; the inset illustrates the confining electrostatic potential. Original image courtesy of S. Neyens and M.A. Eriksson. Figure adapted from de Leon et al. (2021) with permission.**

In most qubit architectures, a tradeoff exists between the speed of addressability and coherence times.[14] Qubits based on color centers or shallow dopants, for example, are weakly coupled to their respective environments, affording ultralong coherence times (Mądzik et al. 2022). But environmental isolation has a downside—such qubits can be difficult to address, control, and read out (Huang et al. 2021). Attaining smaller critical dimensions and qubit densities, too, presents numerous challenges, such as introducing noise during qubit manipulation and readout (Huang et al. 2021). Moreover, smaller qubit dimensions tend to generate larger device-device fabrication variabilities, further limiting system performance.

Despite these considerable complications, the past year has witnessed remarkable progress in the advancement of semiconductor spin qubits. In one such effort, Bartling et

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[14] A great many articles discuss this tradeoff within the QIS literature. See Huang (2021) and Kono (2020), for example.

al. (2022) used a single nitrogen-vacancy (NV) center to address identical interacting $^{13}$C pairs in diamond, a system selected for several built-in protective mechanisms against decoherence. Demonstrating excellent control over these nuclear-spin pairs, Bartling et al. (2022) achieved an unprecedented inhomogeneous spin-dephasing time ($T_2^*$) of nearly 2 minutes at 4 K. The very sensitivity of NV centers exploited by Bartling et al. (2022), however, presents drawbacks when located proximal to other surfaces. Other species of substitutional defects, such as the group-IV color centers, show promise as potential alternatives for use within photonic nanostructures (Debroux et al. 2021). The inversion symmetry offered by silicon-vacancy (SiV) centers in diamond and silicon carbide (SiC), for example, diminishes spectral diffusion and thus accommodates higher rates of entanglement generation (Debroux et al. 2021). Tin-vacancy (SnV) centers in diamond offer advantages similar to those of SiV centers but with longer spin lifetimes and more resilient optical cycling (Debroux et al. 2021). In demonstrating a spin-coherence time of $T_2$ = 0.3 ms and a spin-dephasing time of $T_2^*$ = 1.3 μs at 1.7 K, Debroux et al.'s (2021) work places SnV centers in diamond as a promising candidate within a growing suite of spin-photonic systems. SiC-based defect-spin qubits, too, have shown record-breaking progress during the past year. In addition to its wide availability and support of both CMOS and nanophotonic integration, SiC hosts neutral divacancy (VV0) spins that offer many of the same qubit capabilities as color centers in diamond (Christle et al. 2015). Using commercial n-type SiC wafers, Anderson et al. (2022) demonstrated spin-to-charge conversion (SCC) for VV0 in SiC for the first time, measuring each VV0 charge state by performing all-optical single-shot readout. In turn, each of these charge measurements provided a high-fidelity means of determining each corresponding initial VV0 spin state (Anderson et al. 2022). The work boasts the longest single-electron coherence time ($T_2 >$ 5 s) exhibited in any naturally occurring semiconductor, with spin-relaxation $T_1$ times of ~100 s, representing a 100-fold improvement over previous experiments (Anderson et al. 2022).

Within the past year, silicon-based quantum devices, too, have experienced substantial development. In conjunction with its dominant presence in the microelectronics industry, silicon also supports excellent isotopic purification—critical for spin-qubit platforms. Several research groups have recently achieved important breakthroughs with silicon-based spin qubits, reporting gate fidelities that approach or even surpass the quantum error-correction threshold.

Among the systems shown to surpass the fault-tolerance threshold are quantum-dot arrays in isotopically enriched silicon. In separate demonstrations reported by Noiri et al. (2022) and Xue et al. (2022), one- and two-qubit gates show average fidelities exceeding 99%. Both approaches apply a magnetic-field gradient to enable fast spin control with electric-dipole spin resonance (Noiri et al. 2022; Xue et al. 2022). The high gate fidelities observed stem largely from fast gate speeds—approximately 0.1 μs in each case (Noiri et al. 2022; Xue et al. 2022). With an altogether different silicon-based approach—a pair of 31P nuclei implanted in silicon—Mądzik et al. (2022) also executed universal quantum-logic operations in fault-tolerant one- and two-qubit gates. One key advancement by Mądzik et al. (2022) was their realization of controlled interactions between two nuclear spins with an intermediate electron qubit hyperfine-coupled to both nuclei.

Among the approaches developed for controlling nuclear spins, two primary methods have emerged—via microwave pulses applied to a hyperfine-coupled electron (the approach employed by Mądzik et al. (2022)) and via coherent radio-frequency driving (Maity et al. 2022). Maity et al. (2022) exhibit control, however, using a third approach. Using mechanical vibrations produced by surface-acoustic devices, Maity et al. (2022) govern a lone 13C spin by way of a hyperfine-coupled SiV center in diamond. Applicable to any nuclear spin without diminishing coherence, the approach is scalable. Indeed, the fabrication of on-chip surface-acoustic waveguides and transducers is straightforward, and the power required during control is substantially lower relative to more mature approaches (Maity et al. 2022).

A number of excellent review articles cover the current state of spin-based semiconductor systems (Chatterjee 2021; Wolfowicz 2021; Burkard 2021).

### Superconducting Systems

The largest quantum architectures typically employ transmon qubits (charge qubits based on capacitor-shunted Josephson junctions), such as those captured in Figure 4 (de Leon et al. 2021). Conducive to scalable manufacturing and device integration, transmons offer excellent noise-protection and long coherence times. Companies such as IBM and Google have focused on superconducting qubit systems for these reasons. Despite the success of the transmon, however, several other qubit types are emerging, or re-emerging, as potential building blocks for superconducting quantum systems.

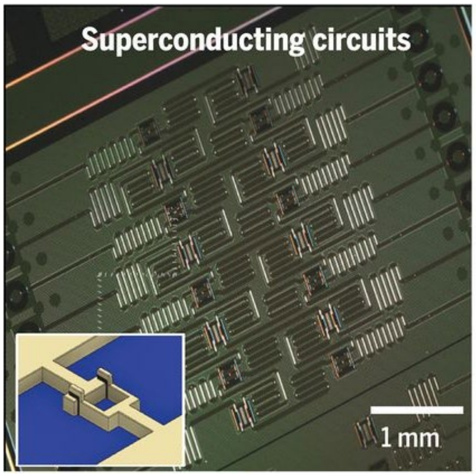

**Figure 4. Superconducting-based qubit platform. Superconducting qubits fabricated by IBM; the inset illustrates a Josephson junction. Figure adapted from de Leon et al. (2021) with permission, IBM image, CC BY-ND 2.0.**

Among the most promising of these alternatives is the fluxonium qubit (a Josephson junction shunted by a large inductor), first demonstrated in 2009 as a means of avoiding charge offsets and low-frequency charge fluctuations (Manucharyan et al. 2009). Relative to transmons, fluxonium qubits offer more desirable energy anharmonicity, along with high-speed frequency response and long relaxation and coherence times, all of which contribute to error-correction improvements. Using a scheme based on fluxonium qubits, Bao et al. (2022) have demonstrated low-loss one- and two-qubit gates with respective fidelities of 99.97% and 99.72%—on par with comparable transmon-based systems. In theoretical study, Nguyen et al. (2022) further promote fluxonium-based architectures by proposing a processor that exploits high anharmonicity and multiple coupling paths to enable qubit entanglement. This scheme provides a route toward diminishing frequency-crowding, crosstalk, and energy-state leakage (Nguyen et al. 2022).

The interest in fluxonium notwithstanding, transmon- and flux-qubit systems have also witnessed recent improvements—especially within the realm of qubit integration. One such advancement centers on the demonstration of tunable, coherence-preserving interactions between multiple qubits. In a study led by K. Zhang et al. (2022), a central transmon qudit (an N-level transmon) is coupled symmetrically to an unprecedented four transmon qubits. Similarly, Menke et al. (2022) display tunable interactions in three flux qubits coupled via a common coupler circuit. This progress in controlling multi-qubit interactions will allow for the simulation of many-body interaction Hamiltonians, along with a variety of quantum-computation applications (Menke et al. 2022).

As mentioned previously, many-qubit quantum architectures are based on the transmon due to its long coherence time, low vulnerability to noise, and scalability. Still, a sufficient means of frequency-tuning individual transmons is lacking, and frequency-sensitive defects and fabrication variabilities tend to degrade system performance. Separate efforts by E. Zhang et al. (2022) and Kim et al. (2022) have employed laser-annealing to tune the frequencies of selected transmons (all without reducing coherence times), enabling a potential means of scaling transmon-based systems to beyond 103 qubits.

Thorough reviews of superconducting-qubit platforms and recent advances are provided by Gyenis et al. (2021), Siddiqi (2021), and Dmitriev, Yu., and Astafiev (2021).

### Rydberg-Controlled Interactions for Cold-Atom Qubits

Cold-atom approaches to QIS are based on either trapped neutral atoms or trapped ions. Recent work on neutral atoms, in particular, has yielded remarkable progress toward the advancement of scalable qubit architectures. Though the most mature large-scale quantum platforms employ superconducting- or trapped-ion qubits, exceeding a few dozen qubits presents a formidable challenge for these systems. Moreover, whereas the static, unchangeable layouts of solid-state architectures constrain qubits to local interactions, neutral-atom platforms accommodate dynamic, nonlocal interactions between qubits and thus more degrees of freedom (Bluvstein et al. 2022).

A common technique for situating atoms in an array of desired spacing uses strongly focused laser beams, which can manipulate individual atoms with submicron precision. Clock states within the ground-state hyperfine structure enable long qubit coherence times, largely due to their magnetic insensitivity. On the other hand, ground-state atoms interact weakly at typical atomic spacings (~1 μm), making the formation of entangled states a challenge. One solution to this problem involves atoms excited to states of high principal quantum number, known as Rydberg atoms. Efforts led by Graham et al. (2022) and Bluvstein et al. (2022) demonstrate novel techniques that use Rydberg atoms, which interact strongly, to generate entanglement between the selected ground-state atoms in the array. This Rydberg-mediated entanglement enabled long-lived qubit coherence and fast gate speeds—prerequisites for engineering the programmable circuits used in each effort to run an assortment of quantum algorithms (Graham 2022; Bluvstein 2022).

Given that many demonstrations use different potentials for Rydberg states and the ground-state atoms, the Rydberg-based approach can limit interaction times and lead to the loss of trapped atoms (Wilson et al. 2022). Wilson et al. (2022) remedy this shortcoming by devising a way to trap both the Rydberg and ground-state atoms with the same optical tweezer. In their experiment, they succeeded in extending the lifetime of Rydberg states, thus prolonging the interaction times between Rydberg atoms and ground-state atoms—vital for QIS applications such as quantum computing and simulation (Wilson et al. 2022).

Excellent reviews of Rydberg-enabled cold-atom platforms are provided by Morgado and Whitlock (2021), Kaufman and Ni (2021), and Browaeys and Lahaye (2020).

### Molecular Systems

Workshop participants also commented on recent developments in generating and detecting quantum-coherent phenomena in molecular systems. For example, electron spins in paramagnetic transition metal complexes are proving promising for encoding qubits (Lavroff et al. 2021). Moreover, optically trapped ultracold $^{87}$Rb$^{133}$Cs qubits exhibit a low sensitivity to magnetic dephasing, displaying coherence times of > 5.6 seconds (Gregory et al. 2021). Recently, evidence has been reported of quantum-coherent electronic energy transfer between a platinum phthalocyanine complex and a zinc phthalocyanine complex donor-acceptor pair on a sodium chloride surface (Kong et al. 2022). Very low-temperature single molecules also present promise as potential single-photon optical transducers (Toninelli et al. 2021).

Recent reviews of molecule-based QIS systems include those by Wasielewski et al. (2020), Toninelli et al. (2021), and Yu et al. (2021). In another recent study, investigators cooled a sodium-potassium molecular gas to 21 nK, nearly a third of the corresponding Fermi temperature (Schindewolf et al. 2022).

## 2. Interfaces, Transduction, and Supporting Technologies

For practical applications, QIS systems must not only process and store information but exchange information with other networked quantum systems. At present, achieving all of these goals requires quantum interfaces that can coherently link disparate quantum platforms. This section discusses these linking technologies, with a focus on optically enabled quantum interfaces.

Due to the control and environmental isolation afforded by photons in sending quantum information, photonic approaches offer great promise for entanglement distribution in large-scale quantum networks. Because many quantum platforms emit photons at energies exceeding those of the telecom band, quantum-frequency conversion (QFC) is needed to minimize losses and thus increase distances between nodes. Though several efforts have used QFC to distribute entanglement between quantum nodes, these nodes were not independent.

In a recent effort using trapped-atom qubits, van Leent et al. (2022) demonstrated a novel approach to achieving entanglement between two independent memory nodes linked by up to 33 km of optical fiber. Each composed of trapped $^{87}$Rb atoms, the two nodes exhibited coherence times of $T_2 > 300$ μs with respectable fidelities (83% for a 6-km link, 62% for the 33-km link) (van Leent et al. 2022). In another recent effort, Đorđević et al. (2022) employed a nanostructured photonic-crystal cavity (PCC) linked to an optical fiber to couple neutral atoms and photons. In that work, optical tweezers were used to place two $^{87}$Rb atoms near the PCC, coupling them to a cavity mode and lowering photonic loss (Đorđević et al. 2022).

Several demonstrations of entangled spin-photon systems have been reported, but they suffer from a range of challenges, including spin-qubit emissions outside the telecom bands. To avoid this difficulty, Shandilya et al. (2021) created an optomechanical quantum interface between telecom photons and NV spin qubits in a diamond microdisk cavity. The cavity serves as the interface, coupling to the hosted NV qubits via tuned spin-phonon interactions and to a nearby fiber via photon-phonon interactions (Shandilya et al. 2021). Achieving a $T_2^*$ of nearly 1 μs, this method can accommodate not only color centers but the control of quantum dots (Shandilya et al. 2021).

A common theme that runs through some of the above-described work is the tradeoff between long qubit coherence times and the difficulty of addressing such qubits. Long coherence times often derive from weak environmental coupling, but this same decoupling can inhibit effective control and readout. Optically addressable photon-spin centers in silicon, however, could ameliorate this tradeoff. Higginbottom et al. (2022) reported the first optical observation in silicon of independent photon-spin interfaces. Known as T-centers, these photon-spin qubits provide a singular means of integrating the long-lasting coherence of electron and nuclear spins with photonic networks (Higginbottom et al. 2022). At once scalable and efficient, silicon T-centers present a potential route to the achievement of practical quantum networks.

Superconductor-based QIS platforms too have benefited from advancements in interfacing strategies. Despite the many high-budget commercial efforts underway to scale up superconducting quantum architectures, the coherence times of superconducting qubits are highly constrained by decoherence, due largely to their strong electromagnetic coupling with their surroundings. Novel quantum-acoustomechanical interfaces offer a potential solution to the decoherence problem. Owing to their weak environmental coupling, acoustic devices can support coherence times of nearly 2 hours—a factor of 106 longer than the record coherence time exhibited by a superconducting qubit (C. Wang et al. 2022). Workshop participants expressed excitement about two novel demonstrations of superconducting-acoustomechanical interfaces in particular—namely the parallel efforts of von Lüpke et al. (2022) and Wollack et al. (2022). Both demonstrations use a transmon to control a nanomechanical qubit within the strong dispersive regime, though the mechanical approach differs in each case (Lüpke et al. 2022; Wollack et al. 2022). Whereas von Lüpke et al. (2022) employ a nanomechanical qubit based on a bulk acoustic wave resonator, Wollack et al. (2022) implement two phononic-crystal resonators. In each case, the transmon-resonator system is piezoelectrically coupled within a flip-chip-bonded structure (von Lüpke et al. 2022; Wollack et al. 2022). Despite relatively short coherence times (~1-10 μs), these two innovative approaches illustrate the utility of acoustomechanical techniques in improving qubit performance and control.

As all current superconducting systems require cryogenic temperatures during operation, linking them via non-cryogenic technologies is desirable, if not necessary, for many practical quantum applications. The most common means of controlling single superconducting qubits is via microwave coupling, for which novel theoretical schemes and engineering innovations continue to emerge.[15] The quantum information contained within microwave signals suffers degradation at non-cryogenic temperatures, however, making potentially more robust optical alternatives attractive. Indeed, long-distance optical links are resilient at room temperature, affording a more practical means of attaining high-speed, remote networks of superconducting qubits. Still, optical fields tend to perturb the operation of superconducting qubits, which poses a major obstacle in achieving entangled links between superconductor-based processors (Delaney et al. 2022). To address this issue, Delaney et al. (2022) use an electro-optomechanical transducer with low backaction to access a transmon qubit integrated within a 3D circuit quantum electrodynamics system. Their approach stands to facilitate fast, efficient superconductor-optical networks capable of remote entanglement over large distances, potentially on the kilometer-scale (Delaney et al. 2022).

Recent review articles of quantum-optical interfaces and transduction techniques include Elshaari et al. (2021) and Pelucchi et al. (2022).

## 3. Fabrication Capabilities and Manufacturing Scalability

A central challenge in realizing more scalable quantum platforms concerns improving device fabrication—a key to attaining smaller feature sizes, larger device densities, lower losses, and more effective device integration. Consequently, fabrication techniques continue to see rapid evolution amongst academic and commercial researchers alike. This section briefly discusses recent fabrication and manufacturing innovations for quantum platforms. Though cold-atom and ion-trap architectures rely on the same advances, the bulk materials and surfaces comprising solid-state systems give rise to a broader array of noise sources. The emphasis in this section, therefore, rests on fabrication approaches for solid-state systems, which have benefited recently from a number of transformational developments.

Excellent review articles on qubit materials and fabrication include de Leon et al. (2021), Siddiqi (2021), Wolfowicz et al. (2021), Chatterjee et al. (2021), and Rodgers et al. (2021).

### Large-Scale Fabrication of Quantum-Dot Spin Qubits

Quantum dot (QD) spin qubits are the most transistor-like of all qubit types, thus making them attractive candidates for scalable CMOS-based process techniques. In a combined effort led by Intel Corporation and QuTech, Zwerver et al. (2022) fabricated

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[15] For examples, see Yan et al. (2021), Goss et al. (2022), and Di Paolo et al. (2022).

QD-based qubits with all-optical patterning on a process line akin to those employed for the fabrication of industrial-scale integrated circuits. A prototypical device and some key features are shown in Figure 5 (Zwerver et al. 2022). A 193-nm immersion lithography process is used to pattern QD arrays spanning a range of lengths, along with test structures for materials and process characterization. Two Si fins form the active region of each device—one fin for the sensing dot and one for the qubits. On 300-mm wafers, Zwerver et al. fabricated more than $10^3$ QD arrays with an impressive device yield (98% across 20 wafers) and competitive spin-coherence and spin-relaxation times exceeding 3 ms and 1 s (at 1 T), respectively. Moreover, the typical single-qubit gate fidelity approaches fault tolerance (Zwerver et al. 2022).

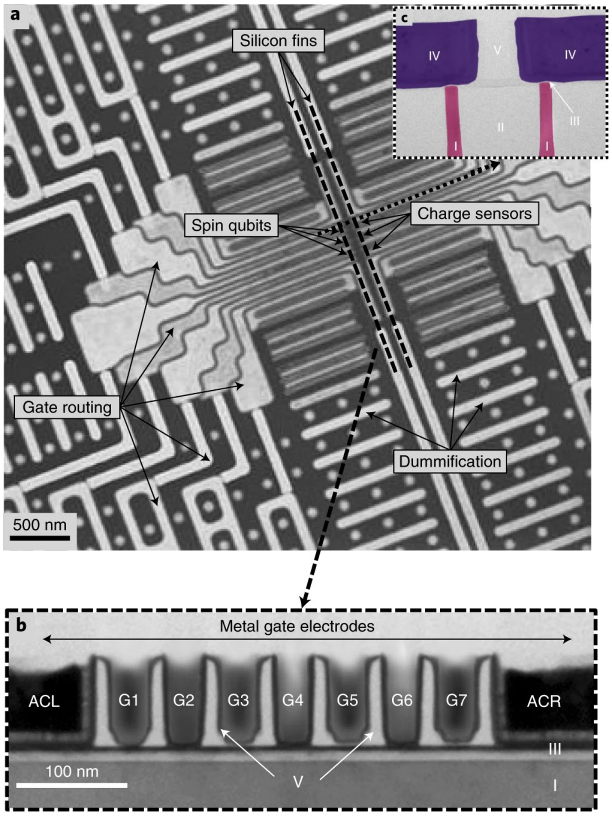

**Figure 5. Quantum dot (QD) qubits fabricated in an industrial facility. A characteristic structure is shown in (a), in which two parallel fins define the active region. (b) The cross-section along a silicon fin, showing the seven metallic gates defining the QD array and the accumulation gate on each end. (c) Cross-section perpendicular to the fins. Figure adapted from Zwerver et al. (2022), CC BY 4.0, http://creativecommons.org/licenses/by/4.0/.**

## Isotopic Enrichment of Silicon

In addition to its entrenchment within CMOS-device manufacturing, silicon possesses properties well-suited for spin qubits. Most notably, silicon possesses long spin lifetimes (due to weak spin-orbit coupling) and offers stable isotopes with zero nuclear spin, *I*. Chief among these isotopes is $^{28}$Si—the most naturally abundant at 92%—whose lack of nuclear spin contaminates qubits with little noise. The next most common silicon isotope is $^{29}$Si (at 5% natural abundance), which possesses a nuclear spin of $I = 1/2$ and thus restricts spin-coherence times for both electrons and donor nuclei. Lowering the $^{29}$Si concentration via isotopic enrichment, therefore, is necessary to optimize the host matrix for Si-based spin qubits (Holmes et al. 2022). Holmes et al. (2022) report a novel ion-sputtering-based approach to enhancing isotopic enrichment that reduces $^{29}$Si to 250 ppm—a three-fold reduction over typical commercial standards. The method preserves single-crystallinity in the resultant enriched $^{28}$Si layer (Holmes et al. 2022).

### High-Precision Ion Implantation

As discussed in Section 1.A, silicon qubits based on single donor spins are attractive as scalable quantum platforms. Competitive dopant-based architectures, however, demand precise high-yield implantation techniques for the shallow placement of single ions in silicon. To attain such near-surface precision, low implantation kinetic energies are required, and developing repeatable processes for deterministic single-ion implantation in donor-based devices has proven a challenge. To address this difficulty, Jakob et al. (2022) implemented a novel room-temperature approach that uses on-chip electrodes to detect electron-hole pairs resulting from single $^{31}$P$^{+}$ implants in Si. Based on these implantation signals, Jakob et al. (2022) can reliably determine the $^{31}$P$^{+}$ trajectories and detect deviations from desired locations, achieving an excellent single-ion detection (with ~99.9% confidence) and a controllable 98% Si-doping yield in 6-nm gate oxide.

### 3D-Integrated Superconducting Qubits

Despite the aforementioned recent progress in scaling up semiconductor-based quantum systems, the most mature solid-state platforms are constructed with superconducting circuits. Large commercial efforts by IBM, Google, Intel, Amazon, Oxford Quantum Circuits, and others are based on 2D superconducting circuits, with IBM's recently released Eagle chip possessing 127 qubits—the current record for any quantum platform.[16] Still, scaling up high-performance superconducting platforms presents formidable challenges. Chief among these obstacles is routing control wiring to all qubits, irrespective of scale and without decreasing performance. Due to the compatibility of superconducting circuits with silicon-based fabrication processes, large-scale superconducting platforms often address qubits at the chip edge.

In 2D layouts, however, a reliance on edge connections leads to interconnect overcrowding, limiting qubit density and various measures of device performance. 3D heterogeneous integration is one solution to mitigating interconnect crowding, as several

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[16] Note that this is a noisy intermediate-scale quantum (NISQ) platform.

demonstrations have shown in recent years using a range of approaches (Rosenberg et al. 2017; Rosenberg et al. 2020). Building on a technique that incorporates superconducting circuits within inductively shunted cavities, Spring et al. (2022) implemented 3D control wiring to integrate four uncoupled transmon qubits on one side of a substrate with four readout resonators on the opposing side. To accomplish this, the effort incorporated a via-like pillar that runs through the substrate to inductively shunt the circuit enclosure (Spring et al. 2022). The qubits exhibited competitive performance, with typical relaxation, dephasing, and coherence times, along with high single-qubit gate fidelities (> 99.98%) and highly suppressed crosstalk (Spring et al. 2022). This scalable approach will enable the fabrication of much larger qubit lattices with excellent coherence and significantly reduced crosstalk (Spring et al. 2022).

### Reducing Transmon Size with Hexagonal Boron Nitride

Though transmon qubits offer low sensitivity to charge noise, their size is an impediment to the construction of large-scale transmon-based platforms. Moreover, most superconducting devices experience dielectric loss within the tunneling barrier of Josephson junctions and in various oxide layers present throughout the device. To address this loss, qubits are engineered with large side-by-side capacitor electrodes and no dielectric. Recently, strategies employing 2D materials can reduce capacitor size—and thus the transmon footprint—without diminishing device performance. J. I.-S. Wang et al. (2022) implement a design using hexagonal boron nitride (hBN), a chemically inert 2D material with excellent insulating properties. In addition to determining key (but previously uncharacterized) properties of hBN, J. I.-S. Wang et al. (2022) and Antony et al. (2021) both implement low-loss hBN-based parallel-plate shunt capacitors within high-coherence transmon qubits. This approach enables up to a 1,000-fold footprint reduction in transmon size relative to an analogous conventional transmon with similar device performance (J. I.-S. Wang et al. 2022; Antony et al. 2021).

## 4. Improvements in Error Correction and Suppression

As mentioned in the preceding sections, qubits must be encoded into quantum states of actual physical systems that are highly susceptible to error-causing noise. This noise poses tremendous challenges for implementing quantum information processing and communications. Even in a carefully controlled environment, physical qubits are subject to several types of errors that compound over time. Imprecise operations (gating) of qubits can introduce coherent phase errors. Unwanted coupling of qubits to their surrounding environment can lead to decoherence. Damaged physical qubits result in qubit loss errors. So-called leakage errors result from the fact that physical systems are never truly two-level, and there is a non-zero probability that more than two levels contribute to the superposition state.

QEC is much more complicated than error correction in classical computing: qubits are subject to the no-cloning theorem and cannot be directly copied, and measurement collapses the state of the qubit, destroying the information that it encodes. The discovery of Shor's 9-qubit repetition code in 1995 (Shor 1995) showed that QEC was nonetheless theoretically possible. A variety of approaches to QEC have been developed over the years, requiring multiple physical qubits to encode a single, more stable, "logical" qubit and often requiring one or more auxiliary physical qubits, called "ancilla" or "syndrome" qubits, entangled with the logical qubit that can be measured without destroying the information that the system contains.

The threshold theorem states that, if error rates for physical qubit operations are below a certain threshold, increasing the depth (number of iterations or concatenations) of the QEC will increase system fidelity such that fault-tolerant quantum computing can be achieved (Almudever et al. 2017). Over the past few decades, researchers have worked to reduce the overhead (in terms of number of qubits and operations) and physical qubit readout fidelities required to successfully implement QEC in practice. One particular QECC—the "surface code"—has generally been viewed as a leading candidate, with a threshold on the order of a 1% physical error rate.

Workshop participants named several developments from the past few years—some as recent as the months leading up to the workshop—that indicate important progress toward practical fault tolerance. For example, several new approaches to QEC have been developed that may offer new improvements, including dynamic "Floquet" codes (such as the honeycomb code) and low-density parity check (LDPC) codes. Researchers are also working to develop and implement QECs that target the specific types of errors most likely to arise in specific experimental systems and thus optimize the value achieved for a given overhead cost. Improvements in system fabrication, fidelity, and control have also led to several important experimental demonstrations of QEC in superconducting, semiconducting, and trapped ion systems, respectively.

### New QEC Codes (QECCs)

In 2021, researchers introduced the "honeycomb code," so-called due to the hexagonal qubit lattice on which it is designed to operate (Hastings and Haah 2021). This code is unique in that it is theoretically capable of achieving fault tolerance but does not generate logical qubits from defined subsystems of qubits. Rather, it operates dynamically through an ordered sequence of two-qubit measurements such that, at any specific point in time, four qubits encode a logical qubit—but the identities of these qubits vary throughout the sequence. Theoretical modeling for a circuit model with native two-body measurements suggests that the threshold error rate for the honeycomb code could be as high as 2.0% in practice. When protected by the honeycomb code, a 600-qubit system with physical gate error rates of 0.1% could potentially be capable of conducting trillions of reliable logical operations (the "teraquop" regime) (Gidney et al. 2021). For example, two Floquet variants were theoretically shown for majorana zero mode-based architectures to raise the error threshold by an order of magnitude and to reduce overheads for below-threshold systems—without the need for ancilla qubits (Paetznick et al. 2022). This dynamic approach to logical protection of quantum information represents a new class of QECCs referred to as "Floquet codes," and presents a promising direction for further research.

Another emerging class of QECCs is the set of quantum LDPC codes, inspired by classical LDPCs. In 2013, it was theoretically shown that quantum LDPC codes were possible and could potentially enable fault tolerance at constant overhead (Gottesman 2013) per logical operation, even as the number of logical operations needed for a given computation increases. So far, one specific quantum LDPC code appears to be capable of enabling this under certain conditions, and a variety of other candidates have been developed. While surface codes appear to perform better for shorter calculations, they require an increasing number of physical qubits per logical qubit as the operations scale, increasing the overhead in terms of syndrome measurements required for logical protection. In the longer term, the scaling behavior of quantum LDPCs could provide an advantage (Breauckmann and Eberhardt 2021).

### Noise-Tailored QEC

In addition to developing new classes of error correction codes with the potential for increased efficiency, researchers have also pursued QECs that target the most significant types of noise in actual quantum devices, with promising results. One, the quantum variational error corrector or QVECTOR algorithm, builds on approaches for quantum machine learning to variationally optimize encoding schemes for a device based on data from device sampling. This approach yields more efficient encodings by catering to correlations among Pauli errors within the system (Johnson et al. 2017). Another example targeting the common fluctuator dephasing model of noise, common in NV-diamond, quantum dot, and superconducting qubit implementations, appears to offer a quantifiably exponentially efficient approach over general codes for near- and mid-term systems (Layden et al. 2020). Similarly, another group developed an efficient decoder for the surface code that yields a physical error threshold of 5% in a biased noise model where dephasing errors are two orders of magnitude more likely than bit-flip errors. Such codes show promise for use with near-term devices by focusing error-correction resources where they will have the most impact, rather than correcting for the full range of hypothetical noise (Tuckett et al. 2020).

### Experimental Demonstrations

In addition to theoretical advances, there have been several recent experimental demonstrations of error suppression or correction in actual quantum devices. For example, in 2021, 1D repetition code implemented on the 53-qubit Google Sycamore processor (a 2D array of superconducting qubits) established suppression of bit-flip and phase errors that improved exponentially with the number of physical qubits and proved stable for 50 error correction cycles (Google Quantum AI 2021). A 10-qubit trapped ion system encoding a logical qubit with a color code demonstrated reduced state preparation and measurement error and stability with syndrome measurements and dynamic Pauli frame adjustments or physical gate operations (Ryan-Anderson et al. 2021). Fault tolerant operations were also demonstrated in a logical qubit encoded in NV-diamond spin-based qubits with real-time stabilizer measurements and decoding (Abobeigh et al. 2022). Should physical qubit errors decrease in these systems, these protocols could enable large-scale fault-tolerant quantum computations. As one participant noted, we are at the threshold of the threshold.

# Appendix C.
# Workshop Participants

**David Awschalom, University of Chicago (American Co-Chair)** – David Awschalom is the Liew Family Professor and Vice Dean of the Pritzker School for Molecular Engineering at the University of Chicago, a Senior Scientist at Argonne National Laboratory, and Director of the Chicago Quantum Exchange. He is also the inaugural director of Q-NEXT, one of the U.S. Department of Energy Quantum Information Science Research Centers.

Before arriving in Chicago, he was the Director of the California NanoSystems Institute and Professor of Physics, Electrical and Computer Engineering at the University of California, Santa Barbara. He served as a Research Staff and Manager at the IBM Watson Research Center.

Professor Awschalom works in spintronics and quantum information engineering, exploring, and controlling the quantum states of electrons, nuclei, and photons in semiconductors and molecules. His research includes implementations of quantum information processing with potential applications in computing, communication, and sensing. He received the American Physical Society Oliver Buckley Prize and Julius Edgar Lilienfeld Prize, the European Physical Society Europhysics Prize, the Materials Research Society David Turnbull Award and Outstanding Investigator Prize, the American Association for the Advancement of Science Newcomb Cleveland Prize, the International Magnetism Prize from the International Union of Pure and Applied Physics, and an IBM Outstanding Innovation Award. He is a member of the American Academy of Arts and Sciences, the National Academy of Science, the National Academy of Engineering, and the European Academy of Sciences. Professor Awschalom received his BSc in Physics from the University of Illinois at Urbana-Champaign, and his PhD in Experimental Physics from Cornell University.

**Dr. Berk Diler Kovos** attended with Professor Awschalom.

**Andrew White, University of Queensland (Australian Co-Chair)** – Andrew G. White is a Professor of Physics and an Australian Laureate Fellow at the University of Queensland. Currently Director of the Australian Research Council Centre for Engineered Quantum Systems (EQUS), since 2000 he has been a founding member of an additional three Australian Research Council Centres of Excellence and one Special Research Centre, conducting research in quantum optics, quantum information science, and fundamental quantum science. His current research interests centre around exploring and exploiting the full range of quantum behaviours with an eye to engineering new technologies and scientific applications.

**Dr. Till Weinhold** attended with Professor White.

**Stephen Bartlett, University of Sydney, Australia** – Professor Stephen Bartlett is a theoretical quantum physicist and Professor in the School of Physics at the University of Sydney, Australia. He leads a team pursuing both fundamental and applied research in quantum information theory, including the theory of quantum computing and quantum error correction. He is a Chief Investigator in the Australian Research Council Centre of Excellence in Engineered Quantum Systems (EQUS), and an investigator on quantum programs supported by the U.S. Army Research Office and Defense Advanced Research Projects Agency (DARPA). He is a Fellow of the American Physical Society (APS) and the inaugural Lead Editor of the APS journal *PRX Quantum*.

**Dr. Thomas Smith** attended with Professor Bartlett.

**Warwick Bowen, University of Queensland** – Professor Warwick Bowen is the Director of the University of Queensland Precision Sensing Initiative, the Program Manager and Science Executive of the Australian Research Council's (ARC) Centre of Excellence for Engineered Quantum Systems, and Affiliate Professor at the Australian Institute for Bioengineering and Nanotechnology within the School of Maths and Physics, University of Queensland. His research focuses on the implications of quantum science on precision measurement, and applications of quantum measurement in areas ranging from quantum condensed matter physics to the biosciences. He is a Fellow of the Australian Institute of Physics, and a Theme Leader of the Australian Centre for Engineered Quantum Systems. His lab has made significant efforts in using quantum light and quantum-limited technologies to improve biological microscopy. They also have active research efforts on integrated photonics, quantum control of macroscopic mechanical devices, and superfluid helium physics. Professor Bowen's research is supported by the ARC, the U.S. Air Force Office of Scientific Research, Lockheed Martin, the U.S. Army Research Office, and the Australian Defence Science and Technology Group.

**Dr. Glen Harris** attended with Professor Bowen.

**Susan Coppersmith, University of New South Wales** – Susan Coppersmith, a theoretical condensed matter physicist, received her PhD from Cornell University, performed postdoctoral work at Brookhaven National Laboratories and AT&T Bell Laboratories, and was a visiting lecturer at Princeton University. She was a Distinguished Member of the Technical Staff at AT&T Bell Laboratories, a Professor at the University of Chicago, and a Professor and Department Chair at the University of Wisconsin–Madison. She is currently serving as Head of the School of Physics at the University of New South Wales (UNSW Sydney) in Sydney, Australia.

Dr. Coppersmith's research has focused on a variety of complex condensed matter systems driven far from thermal equilibrium. Over the past two decades a major research focus has been on the development of quantum computers using silicon quantum dots.

Dr. Coppersmith has served as Chair of the Condensed Matter and Materials Research Committee of the National Research Council of the United States, Chair of the Division of Condensed Matter Physics and of the Topical Group for Statistical and Nonlinear Physics of the American Physical Society, Chair of the Section on Physics of the American Association for the Advancement of Science, and as Chair of the Board of Trustees of the Gordon Research Conferences.

Dr. Coppersmith has been elected to be a Fellow of the Australian Academy of Science, the American Association for the Advancement of Science, the American Academy of Arts and Sciences, and the United States National Academy of Sciences.

**Ania Jayich, University of California, Santa Barbara** – Ania Bleszynski Jayich is a Professor of Physics and the Director of the Quantum Foundry at the University of California, Santa Barbara, where she holds the Bruker Endowed Chair for Science and Engineering. She received her PhD in Physics from Harvard in 2006. Her research interests include quantum assisted sensing and imaging on the nanoscale, diamond optomechanics, and hybrid quantum systems for sensing and quantum information. She is the recipient of the Presidential Early Career Award for Scientists and Engineers, the Air Force Office of Scientific Research Young Investigator Award, a National Science Foundation CAREER award, and the Geoffrey Frew Fellowship.

**Jungsang Kim, Duke University** – Jungsang Kim, Ph.D. is a Professor of Electrical and Computer Engineering, Physics and Computer Science at Duke University, where he has led many collaborative research and development projects at the frontier of foundational quantum computing technologies since 2004. Kim is also a Co-Founder and Chief Technology Officer of IonQ, founded in 2015 to commercialize quantum computers.

Prior to joining Duke University, Kim was a Technical Manager and a Member of Technical Staff at Bell Laboratories, Lucent Technologies between 1999 and 2004. There, he led a team to develop the world's largest optical cross-connect switch for optical communications, as well as digital antenna technology for improving in-building coverage of cellular phones and data services in the wireless communication network.

Kim received his Bachelor's degree in Physics from Seoul National University in Seoul, Korea, in 1992, and his PhD in Physics from Stanford University in 1999. He is a Fellow of the American Physical Society and Optica (formerly Optical Society of America) and a Senior Member of the Institute of Electrical and Electronics Engineers. Kim is an inaugural member of the United States National Quantum Initiative Advisory Committee, serving since 2020.

**Andre Luiten, University of Adelaide** – Professor Andre Luiten is Director of the Institute for Photonics and Advanced Sensing (IPAS) and Chair of Experimental Physics at the University of Adelaide. He is a Fellow of the Australian Institute of Physics and the Australian Academy of Technology and Engineering (ATSE), and a Graduate of the Australian Institute of Company Directors. He obtained his PhD in Physics from the University of Western Australia in 1997, for which he was awarded the Bragg Gold Medal. He subsequently held three prestigious Fellowships from the Australian Research Council. For his efforts, Andre was the joint inaugural winner of the Western Australia Premier's Prize for Early Career Achievement in Science. In 2013, Andre came to Southern Australia to take up the Chair of Experimental Physics at the University of Adelaide and a Premier's Research Fellowship. He has published 6 book chapters and authored 129 journal papers (with over 5,400 citations) and raised over $36 million for research. His work aims at developing state-of-the-art instruments across many diverse fields of physics. The excellence of that work, and interest in translation, is recognised by the award of the Barry Inglis Medal from the National Measurement Institute, the Australian Institute of Physics' Alan Walsh Medal for Service to Industry, and the 2018 Eureka Prize for Outstanding Science in Safeguarding Australia. Andre is Co-Founder and Managing Director of QuantX Labs Pty Ltd, a start-up named as Avalon 2019 Defence Subject Matter Expert (SME) of the Year.

**Dr. Andreas Boes** attended with Professor Luiten.

**Andrea Morello, University of New South Wales** – Andrea Morello is the Scientia Professor of Quantum Engineering at the University of New South Wales (UNSW Sydney), and a Fellow of the American Physical Society. He received his PhD from the University of Leiden in 2004, followed by postdoctoral work at the University of British Columbia. His group at UNSW Sydney has pioneered the use of donor spins for quantum information processing, demonstrating the first electron and nuclear spin qubits in silicon. For these contributions he received numerous awards, including the 2017 Landauer and Bennett Award for Quantum Computing. His research interests further extend to quantum chaos, quantum foundations, and quantum sensing. He is a passionate science communicator and a teacher: his YouTube videos gathered over 10 million views, and he led the creation of the world's first Bachelor's degree of Quantum Engineering at UNSW Sydney.

**William Oliver, Massachusetts Institute of Technology** – William D. Oliver is the jointly appointed Professor of Electrical Engineering and Computer Science, Professor of Physics, and Lincoln Laboratory Fellow at the Massachusetts Institute of Technology. He serves as the Director of the Center for Quantum Engineering and as Associate Director of the Research Laboratory of Electronics. Will's research interests include the materials growth, fabrication, design, and measurement of superconducting qubits, as well as the development of cryogenic packaging and control electronics.

Will is a Fellow of the American Physical Society, Senior Member of the IEEE, serves on the National Quantum Initiative Advisory Committee and the U.S. Committee for Superconducting Electronics, and is an IEEE Applied Superconductivity Conference (ASC) Board Member. He received his PhD in Electrical Engineering from Stanford University in 2003.

**David Reilly, University of Sydney and Microsoft** – Professor David J. Reilly joined Microsoft in 2017 where he is Partner and Research Manager of Microsoft Quantum – Sydney and a Professor in the School of Physics at the University of Sydney. The focus of much of Reilly's work is at the quantum-classical interface and the scale-up of quantum technology. As a leader in Microsoft's quantum effort, he bridges the gap between fundamental quantum physics and the engineering approaches needed to scale quantum devices into quantum machines. Prior to joining the University of Sydney, Reilly was a postdoctoral Fellow at Harvard University and has held a Fellowship from Hewlett-Packard. Born in Sydney, Australia, he holds a PhD from the University of New South Wales (UNSW Sydney) and a Bachelor's degree in Applied Science (Hons 1) from the University of Technology, Sydney (UTS).

**Dr. Kun Zuo** attended with Dr. Reilly.

**Irfan Siddiqi, University of California, Berkeley** – Irfan Siddiqi is a Professor of Physics and Electrical Engineering & Computer Science at the University of California, Berkeley. He also holds a faculty scientist position at Lawrence Berkeley National Laboratory (LBNL). Siddiqi is currently the director of the Quantum Nanoelectronics Laboratory at UC Berkeley, the Advanced Quantum Testbed at LBNL, and the Quantum Systems Accelerator—a national center for quantum computation funded by the U.S. Department of Energy. The Advanced Quantum Testbed offers access to superconducting quantum processors, allowing scientists and energizers nationwide to run protocols in quantum simulation, computation, and verification/validation in close partnership with testbed staff.

Siddiqi is known for contributions to the fields of superconducting quantum circuits, including dispersive single-shot readout of superconducting quantum bits, quantum feedback, observation of single quantum trajectories, and near-quantum-limited microwave frequency amplification. In addition to other honors, for his work in superconducting devices, he was awarded the American Physical Society George E. Valley, Jr. Prize in 2006 and the 2021 John F. Keithley Award for Advances in Measurement Science. Siddiqi is a fellow of the American Physical Society and a recipient of the UC Berkeley Distinguished Teaching Award in 2016, the institution's highest honor for teaching and commitment to pedagogy.

**Michelle Simmons, University of New South Wales** – Michelle Simmons is the founder of Silicon Quantum Computing and Director of the Australian Research Council Centre of Excellence for Quantum Computation and Communication Technology in Sydney. She is internationally renowned for creating the field of atomic electronics, pioneering new technologies to build computing devices in silicon at the atomic scale. She has been recognized by the American Computer Museum as a pioneer in quantum computing, awarded the U.S. Feynman Prize in Nanotechnology, and was named the 2017 L'ORÉAL-UNESCO Asia-Pacific Laureate in the Physical Sciences. She is a Fellow of the American Academy of Arts and Science, the American Association of the Advancement of Science, the American Physical Society, the UK Institute of Physics, the Australian Academy of Technology and Engineering, and the Australian Academy of Science. In 2018, Professor Simmons was admitted as a Fellow to the Royal Society of London and named Australian of the Year, one of the nation's pre-eminent awards. She was the inaugural Editor-in-Chief of Nature Quantum Information, and in 2021 was the Chair of the American Physical Society Division of Quantum Information.

**Dr. Samuel Gorman** attended with Michelle Simmons.

**Glenn Solomon, University of Adelaide** – Glenn Solomon is the Hicks Chair in Quantum Materials at the University of Adelaide, where he is a Professor in Physics and member of the Institute of Photonics and Advanced Sensing (IPAS). He is an adjunct fellow of the Joint Quantum Institute, a collaboration between the University of Maryland and the National Institute of Standards and Technology in the United States, where he worked for over a decade. He received his PhD from Stanford University. He was a founder and the President of CBL Technologies, a GaN crystal growth company, and Sunvolt Nanosystems, a solar cell company. He is a Fulbright Scholar, and a fellow of the American

Physical Society (APS) and the Optical Society (OSA). His current interests are in semiconductor quantum optics, nanophotonics, and topological physics, as well as applications in quantum technologies and integrated quantum photonics.

**Tom Stace, University of Queensland** – Professor Tom Stace completed his PhD at the Cavendish Lab at the University of Cambridge (UK) on quantum computing, followed by postdoctoral research at the Department of Applied Mathematics and Theoretical Physics, also at Cambridge, and Queens' College, Cambridge. Since 2006, he has held various Australian Research Council (ARC) research fellowships, most recently a Future Fellowship (2015–2019).

His research topics include device physics for quantum computing solid-state and atomic systems, quantum error correction, and quantum measurement and precision sensing.

Professor Stace is a former Deputy Director of the ARC Centre of Excellence in Engineered Quantum Systems and established the University of Queensland’s Masters in Quantum Technology program, the first such program in the Southern Hemisphere.

**Dr. Chris Escott** attended from the group of Professor Andrew Dzurak (University of New South Wales).

**Dr. Aaron Tranter** attended from the group of Professor Ping Koy Lan (Australian National University).

# Appendix D.
# Observers and Rapporteurs

## Observers

**Geoffrey Andersen**, Air Force Office of Scientific Research, United States

**Natalia Arenas**, United States Department of State, Canberra Embassy

**Chris Baker**, Defence Science and Technology Group, Australia

**Jennifer Becker**, Basic Research Office, United States Department of Defense

**Jean-Luc Cambier**, Basic Research Office, United States Department of Defense

**James Cerven**, United States Department of State, Sydney Office

**Melissa Edwards**, Basic Research Office, United States Department of Defense

**Cathy Foley**, Chief Scientist, Australia

**Scott Foster**, Defence Science and Technology Group, Australia

**Sara Gamble**, Army Research Office, United States

**Ken Grant**, Defence Science and Technology Group, Australia

**T. R. Govindan**, Army Research Office, United States

**Michael Mandelberg**, Laboratory for Physical Sciences, United States

**Nick McConnell**, Defence Science and Technology Group, Australia

**Bindu Nair**, Basic Research Office, United States Department of Defense

**David Pulford**, Defence Science and Technology Group, Australia

**Suneel Randhawa**, Defence Science and Technology Group, Australia

**Zoran Zterjovski**, Defence Science and Technology Group, Australia

**Duncan Tailby**, Defence Science and Technology Group, Australia

**X. Cliff Wang**, Army Research Office, United States

**Jennifer Wolk**, Office of Naval Research, United States

## Rapporteurs

**Dr. Matthew Brinkley**, Science and Technology Division, Systems and Analyses Center, Institute for Defense Analyses

**Dr. Emily Grumbling**, Science and Technology Policy Institute, Institute for Defense Analyses

**Dr. Jessica Swallow**, Science and Technology Division, Systems and Analyses Center, Institute for Defense Analyses

# Appendix E.
# Workshop Design and Agenda

Prior to the FDW, all participants were asked to consider the following set of questions:

- What do you view as the most important advancements in the last year for quantum information sciences and why?
- What do you think are the top two most significant challenges facing quantum information sciences and what would be the impact of solving those challenges? What would it take to do this?
- Where does QIS research need to go? What are the most exciting future directions for research in this field?
- What are the most promising opportunities for QIS to progress through collaboration between the United States and Australia or between disparate research fields?

These questions were intended to help participants prepare for the meeting. They both supported the initial round robin during the plenary portion of Session 1 and gave the participants a chance to get into the appropriate mindset to address the goals of the FDW.

The FDW was organized across 2 days with four sessions. The first three sessions included extended breakout group time, while the final session focused on plenary discussion and included time ("Opportunities for U.S. – Australia Collaboration," Day 2) for government observers to provide insights and thoughts back to the academic participants. Each session was designed to build on the results of prior sessions, with the final session designed to tie together all of the discussions held over the prior 1.5 days. Breaks were also included in the schedule to give participants opportunities for informal sidebars and discussions with government observers, who were otherwise asked to limit their comments during the main sessions. Participants were also provided worksheets during breakouts to help keep track of the goals of each activity.

The co-chairs assigned each breakout group in advance, with the exact composition of breakout groups being different for each session. For the first two sessions, there were three breakout groups composed of a mixture of post-doctoral (post-docs) participants and PIs, while for the third session there were four breakout groups, with one composed entirely of post-docs and the others composed entirely of PIs. In addition, each breakout group had a leader, selected by the co-chairs in advance, who was responsible for keeping the group on task and reporting out in the plenary sessions. No participant was asked to lead more than one breakout session. Finally, each breakout group also contained an organizer from the Institute for Defense Analyses (IDA) who assisted with keeping the group on task and recording discussions. The exception to this was the post-doctoral breakout during Session 3 for which the Basic Research Office provided a rapporteur.

Plenary sessions were facilitated by both the co-chairs and IDA organizers, with IDA staff also recording notes on the discussions. Figure 6 shows an image of one plenary session.

Both invited and post-doctoral participants were asked to participate fully in the workshop. A major reason for including the post-doctoral participants in the meeting was the goal of establishing long-term, new collaborations between the United States and Australia. Being at the beginning of their academic careers, post-doctoral scholars are well-positioned to support these brand-new collaborations. Post-doctoral scholars also provided important insights to discussions of workforce challenges and the choices facing recent graduates of physics programs as they consider how to continue their careers and whether to remain in academia or seek a position in industry.

The planned FDW agendas for Day 1 and Day 2 follow. Note that the schedule of the morning session on Day 2 was adjusted slightly on the fly in order to allow more time for the breakout groups to discuss. Specifically, the opening plenary portion of Session 3 was cut short in favor of starting the breakouts right away, and the morning tea was moved 15 minutes earlier, leaving the extra time before lunch to prime participants for the afternoon session.

Overarching Future Directions Workshop Questions

1. How might the research impact science and technology capabilities of the future?
2. What is the possible trajectory of scientific achievement over the next 10–15 years?
3. What are the most fundamental challenges to progress?
4. How could U.S. – Australia collaboration enable progress?

**Figure 6. Image of the plenary room during Session 4 of the Future Directions Workshop.**

## DAY 1

| Time Slot | Topic |
|---|---|
| 8:00–8:30 | **Registration** |
| 8:30–8:45 | **Welcome and introductions** |
| 8:45-9:00 | **Opening address by Chief Scientist** |
| 9:00–9:30 | **I. Driving Scientific Advances for Quantum Technology**<br>*Discuss recent advances in the field of quantum information science and their theoretical underpinnings.*<br>Short introductions with round robin where participants name two advances they feel are important.<br>Focus questions:<br>1. Where are the opportunities for critical breakthroughs that could accelerate scientific/technological progress or transform the field entirely?<br>2. What challenges must be overcome, and what is the missing infrastructure that might accelerate technological progress?<br>3. What advances outside of the conventional quantum ecosystem may be critical to advancing (or expanding) the field (materials, fabrication, fibers, packaging, etc.)?<br>4. How might we launch US-Australia collaborations to drive these efforts in the near and far term? |
| 9:30–10:45 | **Breakout instructions (three groups):**<br>(1) Select a critical challenge your group would like to see overcome or breakthrough your group hopes to see achieved<br>(2) Describe the type of infrastructure your group would need (that does not exist today) to address the challenge, and how that infrastructure would enable that work, and<br>(3) Identify where US-Australian collaboration might drive this work in the near and far term. |
| 10:45–11:00 | **Morning tea/coffee and transition to main conference room.**<br>**Leads prepare briefing summary.** |
| 11:00–11:45 | **Briefing from Breakout Session 1** |
| 11:45–13:15 | **Lunch** |
| 13:15–14:45 | **II. Practical Applications of Quantum Sensing and Imaging**<br>In breakout sessions, consider ways in which advancements in the understanding of the foundational questions discussed in the prior session might lead to:<br>1. Improved sensing or imaging within broad areas of science and technology<br>2. Entirely novel types of sensors or imaging techniques<br>3. Potential applications across the sciences<br>**Breakout instructions (three groups)**:<br>(1) Identify a specific way in which access to new signals, or significant improvement in coherence, could enable new types of imaging or sensing. What focus would you pursue?<br>(2) Describe a new collaboration, potentially with technical disciplines traditionally outside of QIS, that individuals in the group might pursue related to such imaging/sensing technology.<br>(3) Describe what you would explore in the collaboration.<br>Consider how the infrastructure and challenges discussed in the prior session might support/challenge your example. |
| 14:45–15:00 | **Afternoon tea/coffee and transition to main conference room.**<br>**Leads prepare briefing summary.** |
| 15:00–15:45 | **Briefing from Breakout Session 2** |
| 15:45–16:15 | **Summary of Day** |

| DAY 2 | |
|---|---|
| **Time Slot** | **Topic** |
| 8:30–8:45 | **Welcome and introductions** |
| 8:45-9:00 | **Opening remarks** |
| 9:00–9:30 | **III. Quantum Communication and Computing**<br>Building on the prior sessions, including both potential advanced sensing methods and improved understanding of theoretical questions, now focus on:<br>1. What applications are likely to see quantum advantage?<br>2. How might a quantum internet create opportunities for new science or technologies?<br>3. What advancements are needed in the field of error correction?<br>4. What classical hardware is needed for control or readout of future quantum tech?<br>5. Interfaces among different types of quantum systems, and<br>6. Possibilities unlocked by networking of disparate/hybrid quantum systems. |
| 9:30-10:45 | **Breakout instructions & morning break (four groups):**<br>(1) Propose a type of networked disparate / hybrid quantum system that may be of interest. What would access to this system enable that is not possible today?<br>(2) Consider what it would take to make such a system reality – what interfaces need to be developed, what hardware needs to be available? What are the requirements for those interfaces/hardware components?<br>(3) What will be needed to enable error correction for this system? |
| 10:45-11:00 | **Morning tea/coffee and transition to main conference room.**<br>**Leads prepare briefing summary.** |
| 11:00-11:45 | **Briefing from Breakout Session 3** |
| 11:45-13:15 | **Lunch** |
| 13:15-14:45 | **IV. Grand Challenges and Opportunities**<br>1. Based on discussion of previous sessions, what possibilities could be enabled by better understanding the limitations of measurement, the transition between quantum and classical limits, or the mitigation of decoherence?<br>2. Which questions or specific research directions stand to engender new technologies or a deeper understanding of foundational quantum challenges?<br>3. Which quantum-enabled technologies would inspire the scientific and engineering communities? What capabilities would these developments enable?<br>4. Discussion during this session should seek to address the FDW questions:<br>i. How might the research impact science and technology capabilities of the future?<br>ii. What is the possible trajectory of scientific achievement over the next 10–15 years?<br>iii. What are the most fundamental challenges to progress? |
| 14:45-15:00 | **Afternoon tea/coffee** |
| 15:00-15:45 | **Opportunities for US – Australia Collaboration** |
| 15:45-16:30 | **Closing remarks** |
| 16:30-17:30 | **Government Only Discussion Time** |

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14. ABSTRACT

During May 2022, the Basic Research Office of the U.S. Department of Defense and the Defence Science and Technology Group of Australia jointly sponsored the Future Directions Workshop on Quantum Information Science (QIS). In attendance at the workshop were U.S. and Australian scientists selected from a wide range of QIS disciplines, as well as a group of government observers from both countries. The workshop was organized as 2 days of breakout and plenary discussions that culminated in a set of proposed "grand challenges" that could foster collaboration between the two countries in this critical scientific area. Participants identified opportunities for collaboration within quantum sensing, computing, and communication. The topics considered spanned length scales from the atomic to the continental, incorporating workforce and infrastructure components that could both contribute to the scientific progress of both nations and support economic development of new technologies. This report documents the wide-ranging discussions that occurred throughout the meeting and provides an overview of the grand challenges and opportunities for collaboration that the participants identified, as well as discussion of the context in which the meeting was held, including recent advancements in QIS research and development.

15. SUBJECT TERMS

Australia; Future Directions Workshop; Quantum Computing; Quantum Information; quantum information science (QIS); Quantum Sensing

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