Quantum Technologies in Singapore - preparing for the future

Presenting views from the Quantum SG research community

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www.quantumsg.org

Foreword

Singapore made an early move into quantum science in 2002 with the creation of a group in quantum information, which was scaled up to become the Centre for Quantum Technologies in 2007. More recent structured programmes are the A*STAR Quantum Technologies for Engineering Programme and the Quantum Engineering Programme launched by NRF. These funding strategies have attracted quantum talent to Singapore: we now have about 40 quantum-related research groups across our universities and research institutes (see https://quantumsg.org/).

With the seeds for rapid innovation in place, the challenges for the local community are how to scale up activities and how to remain competitive and relevant in the face of increasing international competition for talent and ideas. There is consensus in the community that overcoming these challenges requires a larger quantum workforce. We summarise further recommendations in the report.

This document has emerged from an open consultative process. The editorial team for this document canvassed their colleagues to give viewpoints. This document went through two rounds of consultation where the community was invited for comments and feedback. The editorial team would like to thank all the contributors who actively engaged with the process. The editors remain ultimately responsible for the text.

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Executive Summary

Singapore has the potential to be an international hub in quantum technologies thanks to its far-sighted investment in research. This document presents views from the research community. It makes specific, actionable recommendations to prepare for the future.

Maintaining a globally competitive research base will both support the development of a highly skilled workforce and create innovation. There are already early signs of research contributing to the local economy, through engagement with industry partners and the creation of spin-off companies. Considering the country's active startup culture and excellent industrial base, we think Singapore could find an international role as a test-bed for deploying quantum applications. We identify areas where Singapore has an advantage on the international stage based on the country's strengths as a hub for research, innovation and business.

It is a critical time to review Singapore's strategy in quantum technologies because of the launch of other national and international initiatives in the field. In the face of increased global funding for quantum technology research, the fledgling quantum ecosystem in Singapore is facing unprecedented competition. Therefore it is important to ensure that potential talent continues to find Singapore an attractive place to work on quantum technology projects to maintain the first mover advantage.

Section 1. Introduction

Quantum technologies are any methods or devices that use the phenomena of superposition and entanglement to outperform instruments based on conventional physics. Quantum devices may be expected to be faster, more precise or more efficient than their classical predecessors. In this document, we consider work in quantum technologies across four domains: (i) quantum computation and simulation, (ii) quantum communications, (iii) quantum sensing and metrology and (iv) upstream research.

Global investment in quantum technologies is growing fast. This trend is an implicit acknowledgment of the promise of quantum technology leading to economic benefits - and a confirmation of Singapore's foresight in beginning investments in quantum technology research some two decades ago. Figure 1 provides a snapshot of national and international investments.

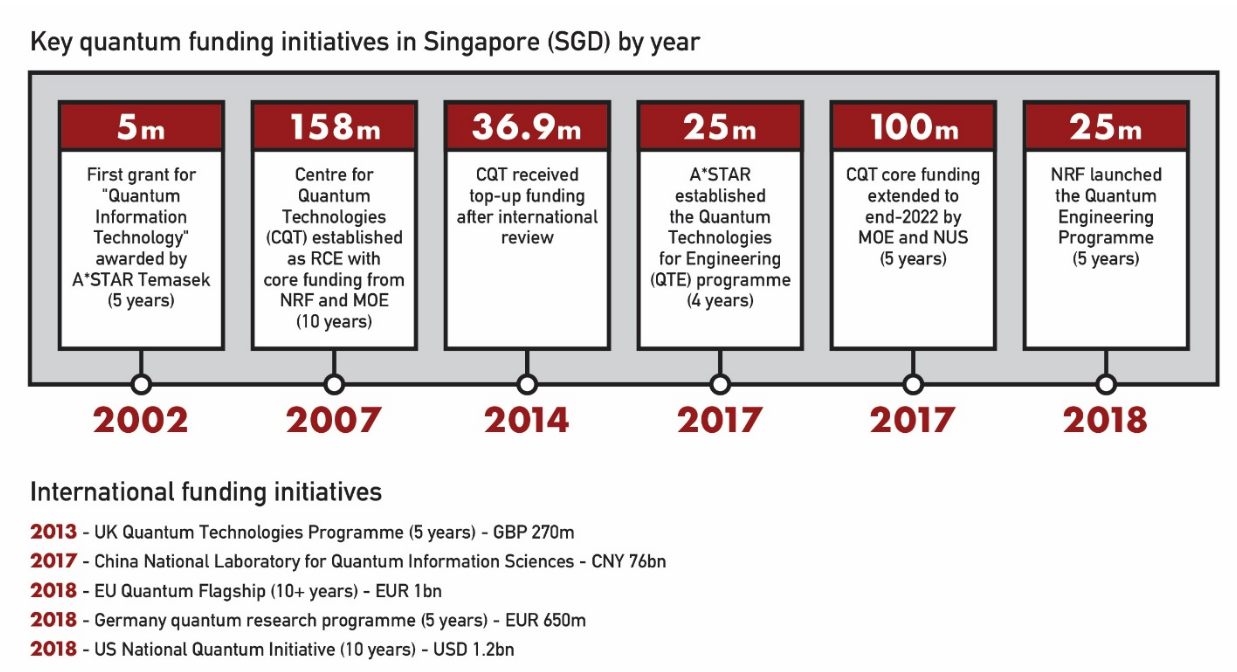

Figure 1: Research in quantum technologies is drawing major investment.

There is increased competition for global talent spurred by dedicated funding for quantum technologies in the EU, USA and China. Today, Singapore's quantum research environment counts about 40 research teams across Singapore's universities and research institutes, an impressive per capita number. How can Singapore's quantum research environment remain competitive?

To address the challenges, the quantum community has held a series of open dialogue sessions called the Quantum Vision meetings, bringing together all the interested research teams in Singapore to discuss research directions and to foster collaboration.

One result of the Vision meetings is the QuantumSG network (http://www.quantumsg.org). Another result is this document, intended to summarise the community view about where Singapore can be competitive when considering the range of possible investments in quantum technology. This document also provides a snapshot of the current state-of-the-art of quantum technologies within Singapore. We hope this may attract scientists and engineers outside the existing community to identify areas where they can contribute to the development of quantum technology.

We also hope this document can help to strengthen collaboration between industry and academia, supporting the private sector to identify fruitful areas for participation. Already, established and startup companies have emerged to provide enabling technologies and to explore potential applications. These include home-grown startups led by entrepreneurial scientists (https://www.quantumlah.org/page/key/spinoffs), spanning all three of the application domains discussed in this document.

Quantum technologies are at different levels of maturity. Some concepts such as quantum key distribution are already being translated to commercial applications, while a universal quantum computer may be decades away with quantum simulators somewhere in between. Coupling downstream research with entrepreneurial efforts, and utilising Singapore's rich digital connectivity and advanced industrial base make the country an attractive location for hosting test-beds of relevant quantum technology.

Historically, all quantum technology has started out as upstream research driven by curiosity about phenomena and speculation about applications. It is important that free inquiry in upstream activity should continue lest we overlook and miss out on emergent techniques that are vital to the future development of quantum technology. Consider the example of quantum computing. A decade ago, superconducting qubits were not widely seen to be competitive, but today they are one of the leading contenders for quantum computing technology. The engineering principles governing quantum technologies are only just being developed.

Success in both downstream and upstream research depends on the local research community, and the workforce that it trains, being globally competitive. In this document, we present a concise description of the strengths and achievements of the local community across the domains of quantum technology, discussing how future initiatives could build on the current status.

Section 2 describes the status of the local quantum community within each of the three application domains, and provides a description of what could be further achieved. In Section 3, we provide a list of recommendations of possible steps to sustain the quality of local research, ranging from greater support for upstream research, to recommendations about engaging startups for translation activity.

The community intends this to be a living document, where the details and recommendations may be updated periodically. It can be found on the QuantumSG site.

Section 2. Singapore's Quantum Landscape

Singapore has a community of a few hundred researchers and students working in quantum technologies, distributed between institutes of higher learning and activities as shown in Figure 2. In this section, we consider the impact and potential of this workforce in the three application domains and in upstream research.

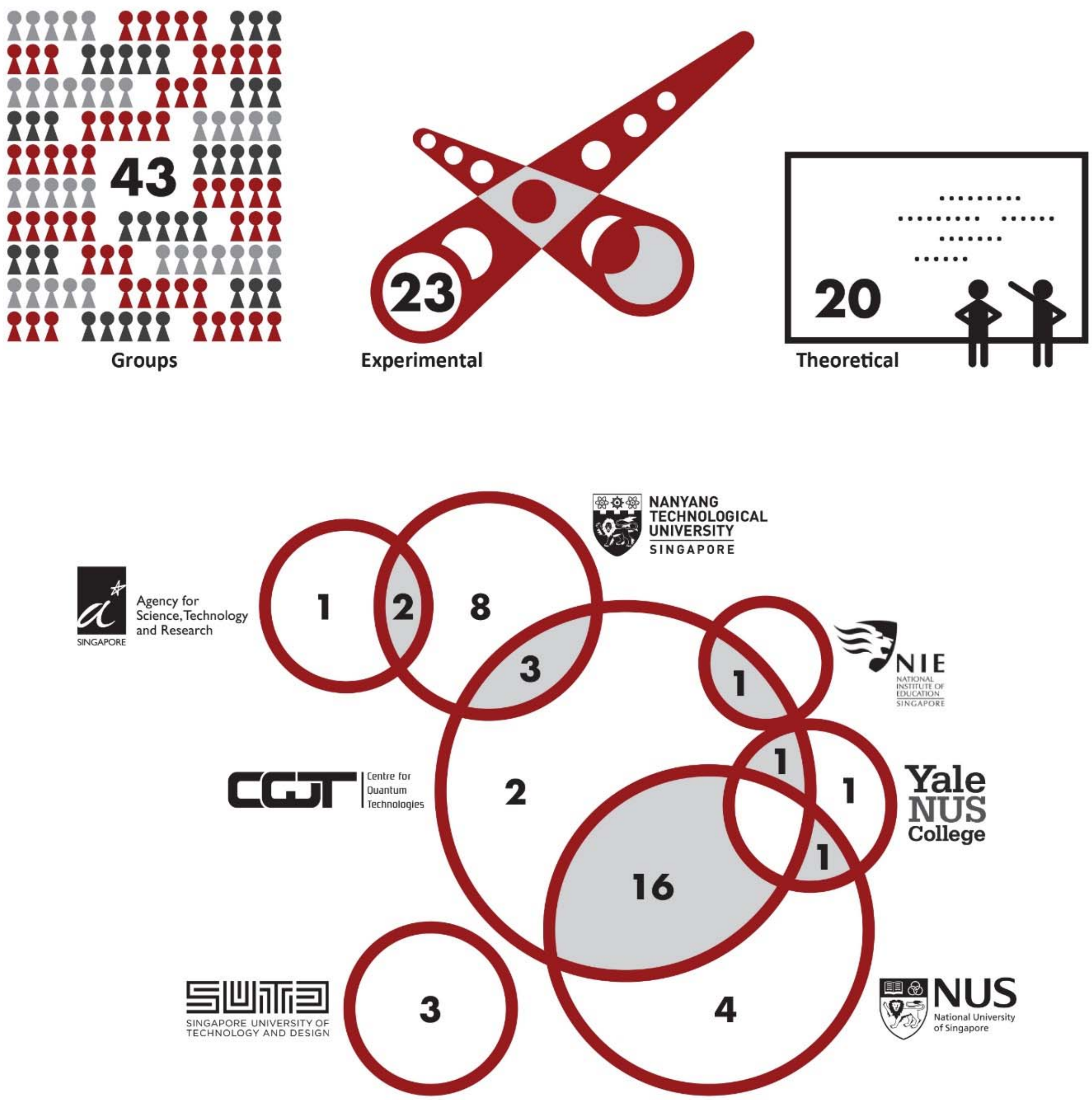

Figure 2: The composition of quantum research groups in Singapore that are part of the Quantum SG network (https://quantumsg.org/)

Section 2.1. Quantum Computation and Simulation

Quantum computing can potentially revolutionise computing as we know it. Reprogrammable quantum devices are expected to be able to solve demanding computational problems beyond the reach of classical machines. Such problems include hard optimisation tasks, complex database searches, problems in machine learning and big data, factoring large numbers, as well as pattern recognition tasks. Quantum computers can tackle these problems by putting into use exotic but real phenomena of the quantum realm, such as entanglement and superposition. These phenomena allow for entirely new ways of processing information.

Quantum simulators are a different kind of device: special purpose quantum computers that model real world systems, not always reprogrammable. Simulators usually operate on an analog approach where artificially built and well controlled quantum systems simulate the behaviour of real but challenging to model complex systems. Quantum simulators aim at tackling specific hard problems from materials science, high energy physics, and chemistry that are beyond the abilities of today’s supercomputing resources both in terms of time and memory.

The challenging technical requirements for constructing fully operational quantum computers have kept hardware development confined mainly to academic laboratories for the last two decades. More recently, private institutions including startups and large information technology companies like Google, IBM and Alibaba have entered the race to construct quantum computers. Some major challenges are to scale up to large numbers of qubits and to make the devices fault tolerant.

Today, efficient small scale quantum processors exist as noisy intermediate scale quantum (NISQ) computers. NISQ devices have the potential to outperform classical computers on certain software tasks even without error correction. Quantum processors with more than 50 controllable qubits are now available worldwide, approaching the scale where classical simulation is prohibitively hard. The regime where quantum devices can outperform classical machines is known as the quantum supremacy or quantum advantage regime. These developments are helping to move quantum computation and quantum simulation towards solving real-world problems.

Some of the earliest applications of quantum simulation and computation with NISQ devices will be in quantum chemistry and materials science, with other ideas for work in finance, data science, drug design, and machine learning. Quantum simulators based on cold atoms in optical lattices worldwide have already been used for example to simulate complex quantum many-body phenomena such as quantum magnetism.

Corporations including Airbus and Volkswagen are exploring the use of quantum computing to solve problems in their sectors. Tackling real-world problems in the near future will require the development of novel hybrid quantum-classical algorithms adapted to NISQ computers. Solutions may involve both digital and analog approaches combined with classical and quantum machine learning methods.

In Singapore, there is already a base in both quantum software and hardware, as discussed in the following two sections.

a) Quantum Algorithms and Software

In Singapore, our work on quantum algorithms, simulations and software has ranged from tackling fundamental questions in complexity theory to developing optimisation tools and quantum compilers.

We have done fundamental work on the use of hidden symmetries and other algebraic structures in data sets for novel quantum algorithms with significant speed ups. For more near term applications, we have investigated quantum machine learning for optimisation problems and randomised algorithms. This is complemented by ongoing research in variational approaches for analog quantum simulation and computing in driven quantum systems, aiming at tackling problems in materials, chemistry and data science.

We have done some of our work in collaboration with leading experimental groups outside of Singapore. One example in quantum simulation is a collaboration of local theorists with the Google quantum hardware group to study quantum phases of matter. Researchers in Singapore are also working with the quantum computing technology of IBM and Rigetti.

Some of our achievements in quantum computing and simulation have been visible worldwide. We see an opportunity to further support and expand research in quantum software, especially given the uptick in industry engagement. Numerous public and private institutions are seeking employees trained in developing quantum software at different levels, including hiring into local startups.

We propose that Singapore could capitalise on its current position as a quantum software pioneer, integrating with the local deep-tech sector to become a key player in the world arena of quantum software development in the next decade.

b) Hardware

The leading candidates for scalable quantum computing worldwide currently are trapped ions and superconducting chips. We have demonstrated small-scale, gate-based operations in both types of systems. In 2019, we established in Singapore a quantum foundry to support the design and fabrication of such devices.

Experimentalists are also putting in effort to scale and interconnect different quantum systems. The goal is to optimally combine qubits with distinct properties for precise control and low errors. Alternative qubits under development in Singapore include solid state systems such as nitrogen vacancy (NV) centres and silicon defects.

As the systems scale, it will become feasible to implement software developed in Singapore including quantum error correction protocols. This adds impetus for funding hardware development. We consider this particularly important given that access to quantum hardware developed in other countries may be restricted by proprietary issues or legislative controls.

Meanwhile, the push for quantum simulation is happening in a wide variety of experimental systems. This is because different quantum systems offer different tunable "knobs", which can be adapted to mimic an assortment of problems in material physics and chemistry. This plays to one of the strengths of Singapore's research landscape which contains a broad range of experimental systems that may be applied to simulation, comparable to top regions in quantum research around the world.

Systems we have locally include: ultracold atoms in optical traps to probe quantum many-body physics; trapped ions whose high controllability make them ideal candidates for emulating small quantum systems; polar molecules and highly excited (Rydberg) atoms whose rich interactions provide a new route to understanding superconductivity, superfluidity, and the physics of dopants in materials; and atomic-superconducting hybrid systems that can combine the advantages of both technologies. High impact results to date include the simulation of non Abelian gauge fields with ultracold atoms for robust spin control and implementing the world's smallest quantum refrigerator with trapped ions.

All the above systems require exquisite control. As the hardware becomes more sophisticated, we anticipate new opportunities for synergistic collaborations between local experiment and theory groups to push the limits on quantum simulation.

Section 2.2. Quantum Communications

The idea that quantum information can improve communication techniques is relatively mature. In this domain, we study how information is transmitted via quantum signals (e.g., single photons, weak coherent states, etc) and how information processing can be assisted by unique quantum resources like entanglement. Importantly, one can design protocols using quantum communication that are faster and more secure than those achievable with conventional methods. Prominent applications include cryptography, time synchronisation, and distributed computing.

We have been working on quantum communication technologies in Singapore since the first dedicated quantum laboratory was established in 2002 at NUS. Our early efforts built expertise in free-space quantum key distribution (QKD), demonstrating that quantum signals can be distributed in Singapore's urban environment by day and night. Extending this work, Singapore became in 2016 the first nation to demonstrate a quantum light source in space, with the ultimate goal of building global QKD networks via satellite constellations. We have also demonstrated fast quantum random number generators (QRNG), a critical device in many cryptographic applications.

Steps to commercialise QKD in Singapore are underway with the involvement of network operator Singtel in a Corporate Laboratory at NUS and the founding of spin-off companies. There is also significant engagement with local authorities, notably with the Infocomm Media Development Authority (IMDA).

Building on this quantum communications ecosystem, Singapore is in a strong position to compete globally because:

- The country is highly connected and has one of the most advanced optical fibre networks in the world. Tests in the NUS-Singtel Cyber Security R&D Lab have shown that Singapore's fibre network can host sensitive quantum signals. This means fibre-based technology could be deployed quickly.
- Singapore has experts in device and materials engineering who can be engaged to address challenges in quantum communications hardware to build better and more cost-effective systems
- Singapore is an open country with deep ties to many advanced nations. This allows us to collaborate with other countries to co-develop critical support technologies where needed. The S$18 million satellite quantum key distribution testbed project established by Singapore and the UK is one such example.

In the near-term (5-7 years), we expect that civil and government entities will begin to deploy QKD systems. On the R&D side, we envisage continued work to build improved QKD and QRNG systems. We could aim to develop quantum chips for mobile devices, for example. This effort can be strengthened with additional investment in device engineering. For example, at this time single photon detectors are a bottleneck in many quantum communication systems and can be sourced only from a limited vendor selection.

We can explore software solutions for cryptography as well as hardware approaches, particularly new quantum-safe proposals for public-key cryptography. This requires knowledge of both classical cryptography and quantum algorithms, since you must check that new schemes are not vulnerable to quantum attack. At the same time, we should tap on the know-how created to shape global standards for quantum information security.

Looking further ahead, Singapore is in a strong position to build a quantum internet. A quantum internet could secure critical information infrastructures and speed up data analytics. Building a quantum internet would be a highly visible achievement that would increase Singapore's reputation as a safe and reliable city for living and business. This would require not only quantum networks but also quantum memories, computers, hubs, clocks, databases, and satellites. The co-location of quantum communications and quantum computing communities in our small city would be a great benefit in working towards this goal.

Section 2.3. Quantum Sensing and Metrology

Quantum sensing and metrology is the most mature application domain of quantum technology. Precision quantum sensors are used in a variety of fields spanning metrology, biology and earth science. Applications can include reference-free navigation, detection of unexploded ordnance (UXO) and time keeping. Atomic clocks are already a core technology of today's society, key to the global navigation satellite system.

The advantage of quantum devices comes because classical measurement devices are prone to drifts. A quantum sensor can make an absolute measurement related to a fundamental constant, which is drift-free. This is important for signal integration to improve accuracy and for continuous long-term monitoring, for example for tracing gravity in geologically active places.

In Singapore, we have built competence over the past decade in magnetometry, atom interferometry, optical atomic clocks and imaging.

Locally developed atomic magnetometers have demonstrated femto-Tesla measurement capability in biological systems. We have also developed magnetometers using nitrogen-vacancy centres in diamond, which enable the mapping of magnetic fields with nanometer resolution. These capabilities have application in bio magnetism, material sciences and characterisation, defense and earth exploration.

Atom interferometry technology is advancing in Singapore with the development of a portable gravimeter that should offer state-of-the-art capabilities, with applications in mapping underground composition, remote sensing of movement of big masses, volcanology and geology. There are also local efforts to miniaturise such technology using atoms guided in hollow-core fibres, and a separate startup aiming at commercial application. Atom interferometry systems could act as ultra-precise gyroscopes and accelerometers, paving the way towards reference-free navigation, which is today an open challenge.

Current world time standards are established by caesium atomic clocks. In research labs worldwide, however, the performance of optical atomic clocks now surpasses that of caesium devices, prompting discussion of the redefinition of the second. This raises a strategic need to build core competency in this technology. Singapore has an optical atomic clock programme based on the element lutetium which local researchers have proven to have superior clock properties compared to all other candidate atoms. A parallel project to use industry standard CMOS-fabrication to develop a chip-scale device has recently started. This contributes both to building expertise and technology development. Chip-scale ion traps could find other applications, too, for example in ion-trap quantum computing.

Applications in spectroscopy and imaging harness the quantum nature of light. Teams in Singapore are pioneering the development of an optical technique in the visible range that enables spectroscopy in the infrared range. It makes use of quantum correlations between photons: information about the infrared photon used for sensing is inferred from an entangled visible-range photon. This could offer a cheaper method of infrared spectroscopy for material analysis, sensing and microscopy. Another innovation that has drawn global attention was inspired by quantum information theory. A local research team invented novel optical devices that can extract more information from incoherent light, thereby enhancing the sensitivity and resolution of fluorescence microscopy, spectroscopy, and even optical telescopes.

Improvements in metrological technology have been a driving force of new applications and industries since the Scientific Revolution. Properly cultivated, development of quantum metrology can grow new capabilities in local industry.

The demanding technical requirements of quantum sensing and metrology instruments will drive research in supporting fields, too. The development of portable atomic systems and chip-scale devices, for example, provide new challenges in materials science and advanced micro-fabrication.

In Singapore, we have the capability to focus our quantum research efforts in sensing and metrology into a dedicated program. We can have global impact and drive the technology towards near-term applications.

Section 2.4. Upstream Research

Many of the applications described above are the results of upstream research. The basis of these technologies did not come out of a targeted search for solutions to a known problem, nor did they arise from the desire to solve a technical problem in a more efficient way. For example, the first suggestion of quantum simulators came from physicist Richard Feynman in the 1980s, who noted that nature is difficult to model because of quantum effects. More concretely, the field of practical quantum communication was initiated by speculation in the 1970s about making quantum money that would be impossible to forge.

Upstream research is necessary to mine for new ideas that will eventually benefit society at large, but in most cases it does not show short-term economic benefits. It is true that exploring unknown directions creates a risk of sometimes running into a dead-end. However, without taking this chance we will never find new paths. Moreover, we will fail to develop the skill of identifying new paths when they appear.

The challenge in nurturing a strong upstream research environment is which areas to pick, and how to support them. We consider first the style of support. Traditionally, research in quantum information science has been carried out in relatively small groups, and when results become promising, collaboration on a broader level emerges. Good upstream or fundamental research in quantum information science does not necessarily require huge investments in lighthouse projects. A more tiered approach of support might be tried, with funding limits depending on the risk of the research direction. There should be room to try a wild idea with a small effort, and then only develop it further if it shows promise.

Choosing areas is tricky. So far, Singapore has developed an internationally recognised ecosystem in fundamental research in areas of quantum information science, and experimental atomic, molecular and optical physics. This provides a solid foundation for exploring new ideas and directions in quantum technology.

Considering quantum information processing specifically, it is an open question which physical system among the many candidates is most suitable for device implementation. Superconducting and ion qubits look promising now, but we are unlikely to know even in the next five years if they are the final answer. We can approach this by keeping an open eye on other qubit candidates - as discussed in section 2.1.a - that complement these technologies or can be used in interconnected systems, and by working on novel approaches like topological material based quantum computation protocols. We note that areas like superconductors that were not strongly supported in the past now see large attention by international players. It is important to recognise that expertise in these advanced technologies requires preparation of an intellectual ecosystem over an extended time. We see opportunities for researchers in quantum technologies to build interdisciplinary collaborations, reaching out to communities focused on topics such as spintronics and low-dimensional materials.

There are collateral benefits of upstream research, too. This kind of research provides training for a graduate workforce skilled in technological problem solving. Any advanced industry, such as cutting-edge optical and semiconductor manufacturing, requires people who can solve problems that have not been tackled before.

In tackling unknowns, upstream research pushes the boundaries of instrumentation beyond what is achievable with the evolutionary approach practiced in product engineering. Many quantum technology providers of lasers, clocks, sensors, and data acquisition devices emerged from the pursuit of fundamental questions in quantum science. Big opportunities remain in the development of such “support technology”.

To shape support for upstream research in Singapore, we would like to see stronger engagement between government stakeholders and cross-institution bodies.

Section 3. Recommendations

Past investments have established Singapore as a significant location for research and development for quantum science and technology. To build on the current status and to prepare Singapore as a global hub for testing and deploying relevant quantum applications, we should take steps to enhance the local research ecosystem. This section lists a series of recommendations proposed by the community so that Singapore can remain an attractive research hub in this rapidly evolving sector.

3.1 Provide more small grants for upstream research in quantum technology

Outstanding questions remain in the realisation of the full potential of quantum technology across all domains. To increase the rate of discovery and to uncover new approaches, it is recommended that more grants be given out in smaller amounts, creating more exploration opportunity. Specifically, more funding in the region of existing Ministry of Education Tier 2 grants (up to 1 million) would assist agile upstream research which can then benefit downstream research. Helpful changes would include having Tier 2 thematic grant calls for quantum technology and allowing applications from senior research fellows and other early-stage independent scientists based in Singapore.

3.2 Encourage small-team collaborations when reviewing proposals

If we look around the world, the most impactful results in quantum science research come from collaborations between experiment and theory at the small team level, consisting of two or three PIs. Existing funding structures like Tier 3/CRP tend to encourage large teams of PIs to go for large sums of funding; when this team structure is not a natural alignment, the projects can lack coherence. Focused proposals supporting collaboration between one experimental PI and one theory PI can be enough to spark a very productive setup.

At the moment, the step in funding size grows from SGD 1 million (Tier 2) to SGD 25 million (Tier3/CRP). A step towards promoting small-team collaboration is to consider an intermediate funding regime capped at SGD 5 million, and to have quantum-themed calls at the Tier3/CRP level.

3.3 Increase the number of PhD positions in quantum science and technology

There is increasing demand for quantum-related expertise from both public and private sector organisations. This demand can be addressed by revising upwards the number of junior research positions. In general, people trained in the physical sciences are highly adaptable problem-solvers and are in demand as Singapore grows its deep technology sector. It would be very helpful if PhD targets were set for the subject areas of physics and quantum technologies, instead of having a single number for all science subjects.

3.4 Boost community engagement

We recommend there be stronger engagement between government stakeholders and researchers, for example through cross-institution bodies, in discussing the direction and support structures for quantum research in Singapore.

3.5 Support the links between research and the deep-tech ecosystem

Organisations like SGInnovate and Temasek Foundation are investing in deep technology startups and spin-offs in quantum technology. This is on top of university-level support for entrepreneurial scientists. We welcome more of these activities. These efforts distill relevant use-cases of quantum technology and show a career path for researchers beyond academia. Many junior researchers and students are excited about the prospects of applying their skills in companies.

3.6 Engage the deep-tech sector when funding applied research

Applied funding in Singapore sometimes requires private sector participation, as in the NRF's Central GAP fund. Such practices should be encouraged in growing applied funding for quantum technologies. Engaging the domestic deep-tech sector can help to ensure market relevance, supporting cost-effectiveness.

3.7 Maintain broad and flexible support

There is a temptation to propose 5- or 10- year plans to structure and drive research directions. Cherry picking quantum technologies at an early stage of technical maturity runs a serious risk of excluding fast-developing solutions. An example is superconducting circuits for quantum computers -- this approach was not considered a serious solution for quantum computers until recently. Maintaining broad support, open-minded to changes in direction, can help to avoid such pitfalls. A broad local talent pool will also act as a resource to evaluate emerging technologies and to support translational outcomes.

3.8 Seize opportunities to join international research efforts

Many developments in quantum technologies are taking place in international collaborations. As a small country, we can use our peaks of excellence to earn access to projects that need broad expertise. This approach has a few advantages. It naturally focuses financial support in areas where local expertise is of international calibre. It also gives local scientists access to the know-how of the international group. The community is confident that there is a critical mass of strong domestic teams that can join efforts such as the European Quantum Technologies Flagship or the US National Quantum Initiative.

A bottleneck to international collaboration is the fact that local funding cycles cannot be coordinated with international cycles; whereas established bilateral calls are often too restrictive in scope to capture emerging opportunities. To encourage international collaboration, mechanisms for enabling emergent international opportunities could be explored.

3.9 Simplify administration of intra-national collaborations

Collaboration between local research groups could be enhanced to enable sharing of resources and manpower. Mechanisms should be put in place to overcome institutional barriers to improved scientific collaboration.

3.10 Enhance support for quantum algorithms and software

Singapore could capitalise on its current position as a quantum software pioneer, integrating with the local deep-tech sector to become a key player in the world arena of quantum software development in the next decade. Quantum algorithms are expected to have applications in diverse industries such as logistics, financial services, materials and pharmaceuticals. There is a growing demand from both private and public sectors seeking employees trained in developing quantum software at different levels. Scaling up funding in this area would also help meet this demand.

3.11 Enhance support for post-quantum cryptography

The existence of quantum algorithms for code-breaking is driving the development of post-quantum cryptography (PQC), with a standardisation effort led by the US National Institute of Standards and Technology. A Singaporean proposal was submitted to this process. Although this proposal is no longer under evaluation, it is important to maintain local expertise in the field. Singapore will need to understand the future PQC landscape and prepare for the transition efforts expected in secure communications technology.

3.12 Enhance support for full-stack experiments in quantum computing

Small universal quantum computers are already being realised in academic and commercial environments. Because this technology has strategic importance, Singapore needs to support the development of full-stack quantum computing platforms. That means supporting all levels from quantum hardware through machine language to software for general applications. Given Singapore's existing expertise in different quantum systems, it could realise more than one full-stack approach. This would mitigate the risk of failure in any one system and keep exploratory directions open. This is important because access to quantum hardware developed in other countries may be restricted by proprietary issues or legislative controls.

3.13 Exploit Singapore's size and connectivity to build quantum networks

Public sector organisations are in the process of forming proof-of-concept quantum key distribution networks aimed at investigating system reliability. We hope this will be a first step towards a nationwide quantum network. Singapore's small size, fiber connectivity and the density of end-users make it an ideal test-bed for this technology. The research community could adopt the proof-of-concept network once trials are complete for further upstream research on topics such as quantum-based clock synchronisation and entanglement storage that might later be deployed on commercial networks.

3.14 Enhance support for development of quantum communications standards

Singapore can become an active participant in the development of emerging standards for communications technology, and in particular for quantum communications. Various efforts are ongoing at the international level on quantum key distribution, post-quantum cryptography and quantum random number generators. Funding support for local developers from academia and the deep-tech sector to participate in the standards development could be increased to ensure that Singapore has an insight on the proposed development of these strategic technologies. In turn this builds up a domestic knowledge base which benefit Singaporean public agencies during the translation phase. This will also allow Singapore to play the role of a hub in the deployment of downstream quantum technologies in the region and beyond.

3.15 Enhance metrology-related research

Singapore could consider combining its quantum research in precision measurement and metrology under a single umbrella. Furthermore, the link between metrological research and services could be enhanced following the examples seen in other advanced industrial nations, where such activities often take place within a single institute (e.g. the National Institute of Standards and Technology operated by the US Department of Commerce). This benefits the overall organisation by upgrading the overall quality of services that can be offered, as well as in spearheading the adoption of new techniques.