Framework for quantum technology driven research and innovation in South Africa: the South African Quantum Technology Initiative (SA QuTI)

Prepared for: Department of Science and Innovation (DSI)
Complied by: National Working Group for Quantum Technology
Updated: 20 January 2021
Version: 0.8

science & innovation

Department:
Science and Innovation
REPUBLIC OF SOUTH AFRICA

Executive Summary

Quantum mechanics is a theory that has been in existence for almost a century and has given birth to disruptive technologies such as the laser and the transistor. Recent advances in the engineering of quantum states have given hope for a “second quantum revolution”, to realize new technologies, e.g., enhanced medical imaging, efficient light-harvesting materials (clean energy), secure optical communication networks, exponentially faster computers (quantum computers), and more precise measurement systems (metrology).

Quantum computing, quantum communication and quantum metrology and sensing are core technologies of the Fourth Industrial Revolution and closely related to groundbreaking developments in fields such as artificial intelligence (AI) and cybersecurity. A very high activity in the international research in quantum technology is clearly noticeable. National and regional strategies have been developed in the past few years by the European Union, the United States of America, China, Brazil and India, to name but a few, with investments at the many billions of Euro level. Governmental funding is not only for universities and research institutes, but also for the development of quantum information technologies at commercial companies.

South Africa has a long tradition of theoretical quantum physics and a more recent history in experimental quantum science, spanning approximately two decades. Over the last 10 years an active academic community working on topics related to quantum computing, quantum communication and quantum sensing and metrology has emerged, and is keen to compete with the global players in this vibrant area of research and innovation.

South Africa has several strong centres in quantum computing and quantum technology that cover 13 higher-education institutions and several other national research facilities. The growing network of researchers, mostly of young academics, has an excellent track record of publication. Also, postgraduate students are increasingly attracted to the area.

Currently there are no commercial companies that are directly involved in the development and commercialization of quantum information technology in South Africa. However, there is already some evidence from the financial sector. The South African industry is diverse enough to benefit from entering the quantum information technology market.

To create the conditions for a globally competitive research environment in quantum technology and to grow a local quantum technology industry in south Africa, the following recommendations are made:

Recommendation 1: Education and training programmes
Curricula development and deployment at Honours and Masters level in quantum technology.

Recommendation 2: Stakeholder awareness campaign
An active awareness campaign to disseminate information on quantum technologies to key stakeholders, including the public, government and industry. A strong public engagement is necessary to familiarize the citizens and other stakeholders with the foundations and principles of Quantum Technology. Also, it will be crucial to inform the key stakeholders of the opportunities for economic development that Quantum Technology offers.

Recommendation 3: Research chairs
Create critical mass in quantum technology research leadership across the country through senior and emerging research chairs.

Recommendation 4: Governance and coordination

Establish a governance structure for national coordination, particularly of synergetic activities, and to drive legislative, standardisation and certification activities. The South African Quantum Technology Initiative (SA QuTI) will be a consortium of five Universities, three main centres (SU, UKZN, WITS) and two emerging centres (CPUT and UZulu), and the Centre of High Performance Computing (CHPC), as the provider of the quantum computing infrastructure. The QuTI will exploit synergies with the Converging Technologies Platform for the National System of Integration. Wits University will act as the main contracting site.

Recommendation 5: Flagship programmes

Establish one flagship programme in each of the three focus areas, distributed across national nodes.

Recommendation 6: Establish new emerging centres

Support new participants in quantum technologies with the aim of diversity in demographics, geographics, and in focus.

Recommendation 7: Quantum technology seed fund

Support the establishment of a quantum industry through strategic and financial support for technology development and deployment.

Recommendation 8: Quantum technology legislation and validation

Provide a national context for a quantum enabled future through government interventions in the form of local economic clusters, legislation with respect to the transition to and adoption of quantum technology, and formalise the need for validation.

Recommendation 9: Interface with the Converging Technology Platform

Engage with the Converging Technology platform and become one of the enabling emerging technology pillars.

Quantum technology will be integrated in the National System of Innovation. The Converging Technology Platform (CTP) has been initiated by the DSI, as the tool to increase the collaborative efforts between emerging technologies and maxime synergies and socio-economic impact. The Quantum Technology Consortium will engage with the CTP and become an essential player in the field of innovation.

Potential impact and the multiplicator factor (leapfrog benefit)

Although the recommendations appear to follow a traditional development path, they are constructed to have maximum impact when delivered *together*, i.e., the sum is greater than the parts. The plan is not to simply have "more of" the present. To this end, **recommendations 1, 3, 5 and 6** will see the rapid growth of a quantum community in South Africa, addressing critical mass at existing nodes, succession planning at all major nodes through emerging chairs, and the establishment of new centres at previous disadvantaged institutes through the placement of new chairs and emerging chairs. The plan is that well trained post graduates from existing centres could become the next generation of emerging chairs at previously disadvantaged institutes, thus transferring and building capacity. **Recommendations 2 and 8** will see an awareness and outreach campaign, not only to the public but also to government and industry stakeholders. For example, in addition to the usual public outreach programmes and initiatives (such as working with SAASTA and other similar bodies), recommendation 2 and 8 also speak to lobbying government for legislative changes, working closely with standards institutes to drive quantum validation and certification, and establishing industry clusters in quantum technology, to give a voice to industry through self-organised representation. Together with **recommendations 1, 5 and 6**, we should see a growing quantum awareness in South Africa, and a well trained youth. To turn "trained youth" into a "young workforce" we make **recommendations 5, 7 and 8.** Recommendation 8 seeks to have government ministries on board to create an environment for the deployment of quantum technologies, e.g., that encryption should become quantum by some agreed date based on detailed discussion, that an economic zone is created for quantum technologies to encourage local production, and that South Africa's NMISA becomes the driver for quantum standards in Africa. These are but examples. The established quantum industry cluster (recommendation 2) will give a voice to the economic participants in this conversation. That sets the scene for a technology pull (recommendation 8) and a technology push through recommendation 5, with recommendation 7 acting to accelerate the change from science to technology. Key to the initiative is where to fund quantum, and this is largely dictated by the flagship projects. **Recommendation 5** takes the incoherent SA quantum community and brings their abilities together to save decades in time and money. In a quantum computing flagship, the idea is to not build a quantum computer but to build quantum “apps”, quantum software - a faster and cost effective way to make an impact that leverages on our capabilities in software development. In a quantum communications flagship, the idea is to focus on technology integration from partner institutes across SA, comprising sources, detectors, protocols and networks, to establish local quantum secure links between universities, key government sites, and strategic industry locations such as banks. We have a competitive advantage in access to unused SANREN links that will fast track quantum deployment by decades. In a quantum sensing flagship the focus is on quantum imaging technology, to tap into SA’s long history and well developed and sophisticated medical industry. **Recommendation 7** is key, and it is suggested that like the UK programme, the seed fund should be spent by the quantum nodes on industry partner projects. Thus this becomes an industry led endeavour. The impetus for doing so is ensured by **recommendation 8**, which also provides industry with a means to validate their solutions, bringing in metrology and standards institutes in SA. Of course, the interface to the Converging Technology Platform (**Recommendation 9**) ensures the embedding of quantum technology in the national efforts for innovation.

The aforementioned synopsys makes clear the importance of coordination, because the multiplicator factor is only possible if the programme is deployed holistically. Each recommendation alone will achieve little in advancing SA’s quantum aspirations. But with careful and attentive management of this programme, engagement by all stakeholders the impact can be very high, and the saved time and money to enter the quantum race telling.

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Acknowledgements

The National Working Group would like to thank all those members of the community who have contributed to this document, including:

- The DSI staff members, particularly, Dr Daniel Adams, Dr Sagren Moodley, Dr Charles Mokonoto, Dr Daniel Mokhohlane, Dr Mmboneni Muofhe and Dr Matholdi Mathebula for their support and strategic input to this document;
- The IBM staff, particularly Dr S Assefa, Dr Ismail Akhalwaya and Mr Kugendran Naidoo for inputs on quantum computing;
- Dr Herman Uys, one of the co-initiators of the roadmap;
- The participating members of the various national workshops and surveys, with special thanks to Prof. Thomas Konrad and Prof. Kessie Govender;
- The University of the Witwatersrand Research Office for administrative and logistical support.

1. Introduction

1.1 Background

Quantum Mechanics was developed about 100 years ago to describe the behaviour of Nature at the microscopic level. The laws of quantum physics allowed several technological breakthroughs. The Laser and transistor are the most prominent ones and were the basis for the start of the Information Age.

In 2003 the term Second Quantum Revolution [1.1] was introduced to exploit the “spooky” properties of quantum physics (superposition principle, entanglement) for technological gain. Arguably, this second quantum revolution started in the Seventies, when single quantum objects could be manipulated for the first time.

Since those groundbreaking experiments, achievements in the field have been rewarded with several Nobel Prizes:

- In 1997 the Nobel Prize in Physics was awarded jointly to Steven Chu, Claude Cohen-Tannoudji and William D. Phillips "for development of methods to cool and trap atoms with laser light."

- In 2001 it was awarded jointly to Eric A. Cornell, Wolfgang Ketterle and Carl E. Wieman "for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates."

- In 2005 the Nobel Prize was divided, one half awarded to Roy J. Glauber "for his contribution to the quantum theory of optical coherence", the other half jointly to John L. Hall and Theodor W. Hänsch "for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique."

- In 2012 it was awarded jointly to Serge Haroche and David J. Wineland "for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems."

The technologies of the second quantum revolution explicitly address individual quantum objects and exploit the *spooky* properties of quantum mechanics: superposition and entanglement.

The technologies emerging from the interaction of quantum physics and information technology can broadly be described as quantum information processing and communication. It can be further divided into the disciplines of *quantum computing*, *quantum communication* and *quantum sensors and metrology*. They are summarised in the figure below. Ultimately, the vision is to develop a quantum internet.

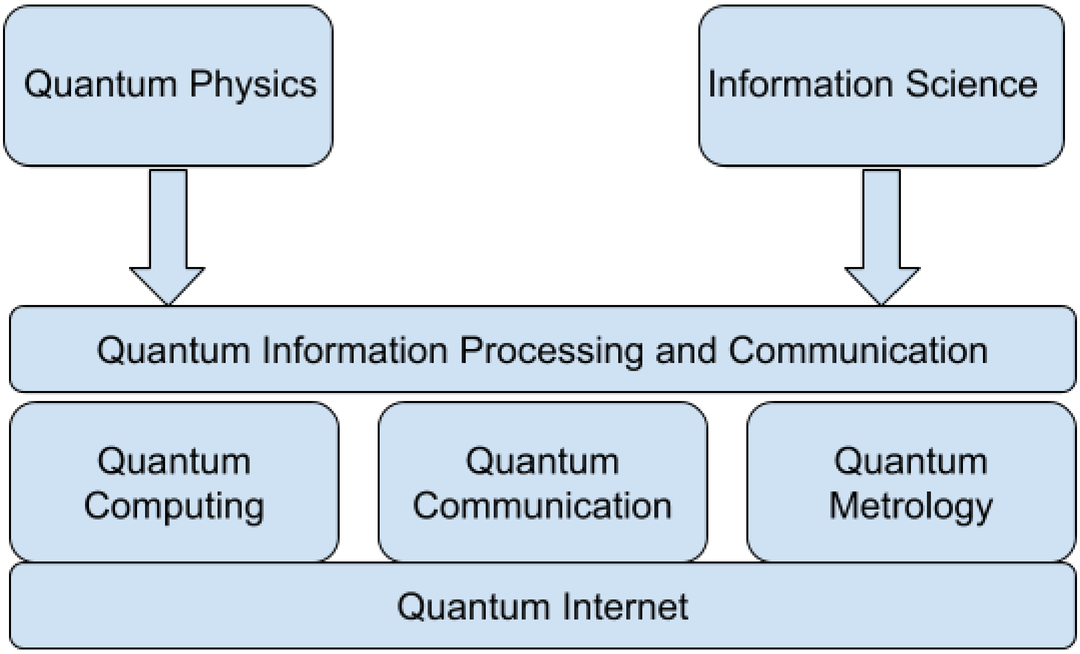

Figure 1.1: The emergence of a new discipline and its main drivers.

• *Quantum computing* – Devices that allow efficient computation of certain classes of mathematical problems much faster than traditional computers, by exploiting the quantum mechanical phenomena of superposition and entanglement. This is expected to impact machine learning, artificial intelligence, image recognition, database searching, analysis of big data, optimization problems, and facilitate new developments in chemistry and materials science.

• *Quantum communication* – Devices that allow provably secure communication, i.e., not based on the computational complexity of breaking an encryption code but rather on the laws of quantum mechanics. In such devices, the communicating parties immediately know when their message is being intercepted. Secure communication is a mature technology and has countless applications both in the civil, government and military environments.

• *Quantum sensors and metrology* – Devices that can detect very small effects with ultra-high precision such as tiny accelerations, magnetic-, electric- or gravity fields, image with ultra-high precision, or make very precise measurements of time and frequency. These devices have applications in metrology, non-destructive testing, geo-surveying, navigation, and medical imaging. Utilising quantum effects, quantum metrology helps define essential standards, such as time, mass, resistance, voltage and current via fundamental constants of nature, increasing the accuracy of measurement and uncertainty traceability. Due to its relationship with quantum measurement and the fact that quantum technology is reliant on it, quantum control can also be included under quantum metrology.

Quantum research in South Africa goes at least as far back as the 70s. Initially, this research focussed on nuclear physics, which led to the establishment of an accelerator facility for medical applications and the establishment of nuclear research facilities. More recently, research groups focussing of quantum information technologies were established among others at the University of KwaZulu-Natal (UKZN), University of Pretoria (UP), Stellenbosch University (SU), Cape Peninsula University of Technology (CPUT), the University of the Witwatersrand (Wits) and the National Metrology Institute of South Africa (NMISA). Over time, these groups made numerous achievements.

In 2016, IBM Corporation announced the opening of a new research lab in Johannesburg, South Africa. Researchers at this IBM lab are involved in quantum computation research by contributing to a Python-based Software Developers Kit (SDK) called QISKit. In 2019, a 20-qubit IBM Q was made accessible to South African and African universities through an IBM-Wits initiative. The South African community has started to make use of the facility with UKZN, SU and Wits the active participants (at the time of writing).

In the field of quantum metrology NMISA was the first in South Africa to set up quantum Hall and Josephson junction systems for the establishment of resistance and voltages standard measurements respectively. More recently, the University of Cape Town has established a NanoElectronics group where research on the quantum Hall effect and work towards a new quantum standard for electrical current is ongoing. NMISA is currently building a Kibble balance to establish a primary standard for mass in South

Africa. All this ensures that South Africa remains up to date with the latest industry and research metrological standards.

1.2 Our Quantum Future and the National Objectives

The main objective is to provide a framework (or road map) for the establishment of a quantum technology economic sector in South Africa. In other words, it not only addresses the support of academic research for quantum information technologies, but also addresses the support of the entire innovation chain from academic research all the way to the industrialisation and commercialisation of quantum information technologies so that it would form part of the South African economy. It is not expected to involve all quantum information technologies to the same extent as it exists in the developed economies of the world. Instead, it is envisaged that South Africa will become involved in niche markets where it can play a necessary role for the future needs of South Africa.

As agreed at its first meeting, the focus of the National Work Group for Quantum Computing and Quantum Technology is to conduct a Strength, Weakness, Opportunities and Threats (SWOT) analysis of quantum computing and quantum technology in South Africa. The SWOT analysis should address all relevant aspects, including:

- The development of human capital and research capacity,
- The development of technology capacity and capability,
- The availability and need for research and innovation infrastructure,
- The potential industrial uptake of quantum computing and quantum technology,
- Partnerships and networks,
- Collaborative platforms and institutional landscape.

1.3 The constitution of the National Working Group

The National Working Group on Quantum Computing and Quantum Technology was constituted on 26 September 2019 during a meeting held at the Meraka Institute (CSIR, Pretoria).

The meeting was organised by DSI and the following officials attended:

- Dr Daniel Adams, Daniel.Adams@dst.gov.za
- Dr Charles Mokonoto, Charles.Mokonoto@dst.gov.za
- Dr Daniel Mokhohlane, Daniel.Mokhohlane@dst.gov.za
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- Dr Matholdi Mathebula, Matlhodi.Mathebula@dst.gov.za

The scientific members of the Committee are

- Prof Zeblon Vilakasi (WITS), Zeblon.Vilakazi@wits.ac.za (present at the inaugural meeting)
- Prof FrancescoPetruccione (UKZN), Petruccione@ukzn.ac.za (present at the inaugural meeting)
- Dr Happy Sithole (NICIS, CHPC), hsithole@csir.co.za (present at the inaugural meeting)
- Prof Andrew Forbes (WITS), andrew.forbes@wits.ac.za (present at the inaugural meeting)
- Dr Claudia Zander (UP,)claudia.zander@up.ac.za (present at the inaugural meeting)
- Dr Stef Roux (NMISA), froux@nmisa.org (present at the inaugural meeting)
- Dr Kessie Govender (CPUT), govenderk@cput.ac.za
- Dr Hermann Uys (SU), hermann@sun.ac.za (present at the inaugural meeting)
- Prof Mark Blumenthal (UCT) mark.blumenthal@uct.ac.za (present at the inaugural meeting)

- Prof Tim Gibbon (NMU), Tim.Gibbon@mandela.ac.za (present at the inaugural meeting)

Dr Hermann Uys has left the Stellenbosch University since the inaugural meeting. His substitute is Prof Mark Tame, also from the Stellenbosch University.
Industry is represented trough

- Dr S Assefa, IBM, sassefa@us.ibm.com

The Secretariat of the National Working Group is run by WITS through

- Robin.Drennan@wits.ac.za (present at the inaugural meeting)
- Kasturie.Sanasy@wits.ac.za

1.4 The process

The formal process started on 26 September 2019 with the constitution of the National Working Group.

Prior to this meeting the quantum computing and quantum technology community in South Africa had already drafted a Roadmap document.

The first meeting of the community to discuss a roadmap was held on 7 July 2017 at the South African Institute of Physics (SAIP) conference in Stellenbosch. About 40 researchers and students attended and a first vision for the roadmap was discussed.

On 10 July 2018 a first version of South African Roadmap for Quantum Computing and Quantum Technology was submitted by the consortium to the DST.

On the 12th of July 2018 a Workshop on Quantum Computing was held at the IBM Research lab in Braamfontein to discuss the potential and the way forward for quantum computing in South Africa. This resulted in a proposal for a distributed Centre of Excellence in Quantum Technologies which was sent to the DST on 26th November 2018.

The community came together again at the Quantum Africa 5 conference, which was held in Stellenbosch from 2 to 6 September 2019. The Conference included a Quantum Computing Training Workshop organised jointly with IBM.

At the 13th Annual Conference of the Centre for High Performance Computing (CHPC) on the 12th of December 2019 a session was dedicated to Quantum Computing in South Africa. The Session was opened by Dr Daniel Adams (DSI) and Dr Happy Sithole (CHPC) and was followed by presentations of the South African Roadmap for Quantum Computing and Technology by Prof F. Petruccione and Prof. A. Forbes.

From 2 to 10 December 2019 WITS hosted a Summer School on Quantum Computing that was followed by the QISKIT Camp Africa organised by IBM in the Pilanesberg.

In February 2020 the Centre for High Performance Computing and the National Institute for Theoretical Physics organised a joint Summer School in Saldanha Bay on Foundations of Theoretical and Computational Science, which included an introduction to Quantum Computing and some of its applications.

The National Working Group reconvened at the Meraka Institute on 9 March 2020. Three sub-groups were formed in charge of drafting materials for the final Framework Document.

On 29 May 2020 the first draft of the Framework document was shared to the National Working Group.

On 17 November the National Working Group reconvened to finalize the last version of the framework document.

References to Chapter 1

[1.1] J. P. Dowling and G. Milburn, Quantum Technology: The Second Quantum revolution. (2003) https://doi.org/10.1098/rsta.2003.1227

2. Quantum Technology Status and Drivers

2.1 Quantum Technology Objectives

2.1.1 Quantum Computing

Quantum computing as an alternative to classical computing was proposed by Richard P. Feynman in a paper published in 1982 [2.1]. From the observation that Nature at its fundamental level is quantum, Feynman realised that ultimately Nature will best be simulated by a computer obeying the laws of quantum physics. The development of the idea of a quantum computer rested upon the work of Rolf Landauer, who already in the Sixties proposed that information is a physical entity and can be processed according to the laws of physics. Inspired by this insight, it was ultimately David Deutsch in 1985 who outlined the theoretical basis of quantum computing, by suggesting that unitary “quantum gates” could replace the binary logic gates of conventional computers in a quantum computer [2.2].

While conventional digital computers are based on the manipulation of binary digits (bits), that can be either in state 0 or in state 1, quantum computers process two-dimensional quantum objects, called quantum bits, or qubits. A qubit is best represented as a vector that points from the centre of a sphere of unit radius to its surface, with state $|0>$ being the North pole and state $|1>$ being the South pole. Because of a peculiarity of quantum mechanics -the quantum superposition principle- , any point on the sphere represents a possible qubit state. In particular the qubit can be in a so-called superposition state $(\frac{1}{\sqrt{2}}(|0> \; + |1>)$.

The qubit is the fundamental building block of quantum computers. A number of qubits forms a qubit register. A quantum register of n qubits can be in 2^n different states at the same time. Any quantum computation can be implemented as a series of quantum logic gates operating either on a single qubit or on two qubits.

Besides the universal quantum gate model of quantum computing sketched above, there are other models of quantum computing:

- Adiabatic quantum computing, based on the concept of quantum annealing;

- One-way quantum computers, based on the preparation of an entangled initial state and a subsequent series of single qubit measurements;

- Topological quantum computers, are so far a theoretical concept, based on the realisation of qubits as two-dimensional quasi-particles, which guarantee better stability and noise tolerance.

What hardware do we have?
It took about twenty years from the intuition of Feynman to experimentally realize a quantum computer. In the year 2000 Isaac Chuang and co-workers demonstrated a 5 qubit quantum computer using a NMR technology, implementing an algorithm for order finding [2.3].

Of course, the processing power of a quantum computer is determined by the number of qubits. Over the years, exploring various physical systems for the construction of qubits, quantum computers with more qubits could be constructed. Currently, the “mainstream” physical systems used to realize qubits are:

- superconducting Josephson junctions,
- trapped ions,
- neutral atoms,
- spins.

The following table summarizes some of the quantum computers available today.

Company	Computer Model	Technology	# of qubits
IBM	gate	superconducting	53
Google	gate	superconducting	53/72
Intel	gate	superconducting	49
Rigetti	gate	superconducting	32
USTC (China)	gate	superconducting	10
IonQ	gate	trapped ions	10
IQOQI	gate	trapped ions	20
Intel	gate	spin	26
Univ. of Wisconsin	gate	neutral atoms	49
D-Wave	annealing	superconducting	2040

Table 2.1: Number of qubits for various quantum computer architectures. The data are from the Quantum Computing Report and were updated on 2 April 2020.

It has to be stressed that the number of qubits is not necessarily an indicator of the power of a quantum computer. The stability (quantum coherence), quality (error correction) and connectivity of the qubits plays a fundamental role as well.

In order to describe quantum computers with 50-100 qubits that will be available in the near future, John Preskill coined the term of Noisy-Intermediate State Quantum (NISQ) Computer [2.4]. Such quantum computers will have the power to outperform classical super-computers. These computers have noisy quantum gates, as not enough qubits are available, to implement quantum error correction, so that the size of quantum circuits will be limited. In the same publication, John Preskill, provides us with three very good reasons for thinking that quantum computers will surpass the capabilities of classical computers:

- Quantum algorithms for classically intractable problems,

- Complexity theory arguments,
- No known algorithm can simulate a quantum computer.

The field of quantum computing gained enormous momentum with the availability of quantum computers in the cloud. IBM launched the IBM Q Experience in 2016 with a 5 qubit quantum computer and a quantum composer. This was followed by the launch of Qiskit, a Python based quantum computing software development platform. Cloud-based quantum computing is now widely used for research and teaching.

Currently, there are at least six quantum computing cloud platforms that make various hardware available. These are listed in Table 2.2.

At the end of 2019 Noisy Intermediate-Scale Quantum (NISQ) Computers achieved the milestone of “Quantum Supremacy” [2.5]: A quantum computer built by Google performed a calculation that would have been impossible on a conventional computer. Refined quantum supremacy arguments reveal that instantaneous Quantum Polynomial-Time (IQP) circuits with 208 qubits and 500 gates, Quantum Approximate Optimization Algorithm (QAOA) circuits with 420 qubits and 500 constraints and boson sampling circuits (i.e. linear optical networks) with 98 photons and 500 optical elements are large enough for tasks that are intractable with conventional computers [2.6].

Hardware Provider	Quantum Computing Cloud Platform					
	Amazon	D-Wave	IBM	Microsoft	Rigetti	Quantum Inspire
Alpine Quantum Technology			X			
D-Wave	X	X				
Honeywell				X		
IBM			X			
IonQ	X			X		
Quantum Circuits Inc.				X		
Rigetti	X				X	
Quantum Inspire						x

Table 2.2: Overview of Quantum Computing Cloud Platforms. Data from Quantum Computing Report retrieved on 2 December 2019.

Recently, HPC simulations on Summit, the fastest computer in the World, revealed another very promising feature of quantum computers. The energy consumption of NISQ quantum computers is orders of magnitude smaller than for a Supercomputer solving the same problem [2.7].

What algorithms do we have?
Quantum algorithms are algorithms that run on a quantum computer and achieve a speedup, when compared with the best possible classical algorithm, thus making

possible the solution of problems of a higher complexity. It is useful to remind us of some complexity classes useful in the characterisation of quantum computing algorithms.

Complexity class	Definition
P	Can be solved by a deterministic classical computer in polynomial time.
BPP	Can be solved by a probabilistic classical computer in polynomial time
BQP	Can be solved by a quantum computer in polynomial time
NP	Solution can be checked by a classical computer in polynomial time
QMA	Solution can be checked by a quantum computer in polynomial time

Table 2.3: Complexity classes of importance for quantum computation [From: [2.8]]

Historically, probably three quantum algorithms induced intensive theoretical research in quantum computing and motivated the efforts to develop quantum computing hardware.

In 1994 Peter Shor proposed a quantum algorithm that solves the integer factorisation problem in polynomial time. [2.9] This is the algorithm that makes quantum computers a threat to conventional cryptographic schemes, like the RSA (Rivest-Shamir-Adleman) public-key cryptosystem.

In 1996 Lov Grover devised a search algorithm that finds a marked entry in an unstructured database using a number of queries on the order of the square root of the number of entries only, instead of a number that is of the same order as the number of entries, which is required by conventional classical algorithms [2.10].

It was again Peter Shor who discovered the first quantum error correction code in 1995 [2.11]. This discovery was crucial to demonstrate that quantum information can be protected from errors due to decoherence and quantum noise and, thus, that large scale fault-tolerant quantum computers can be built in principle.

Since these pioneering results many more quantum algorithms have been proposed. Currently, the “Quantum Algorithm Zoo” website [2.12] lists more than 400 different algorithms, grouped into four categories:

- Algebraic and number theoretic algorithms,
- Oracular algorithms,
- Approximation and simulation algorithms,
- Optimisation, numerics, and machine learning algorithms.

All quantum applications/algorithms have a structure illustrated in the cartoon below.

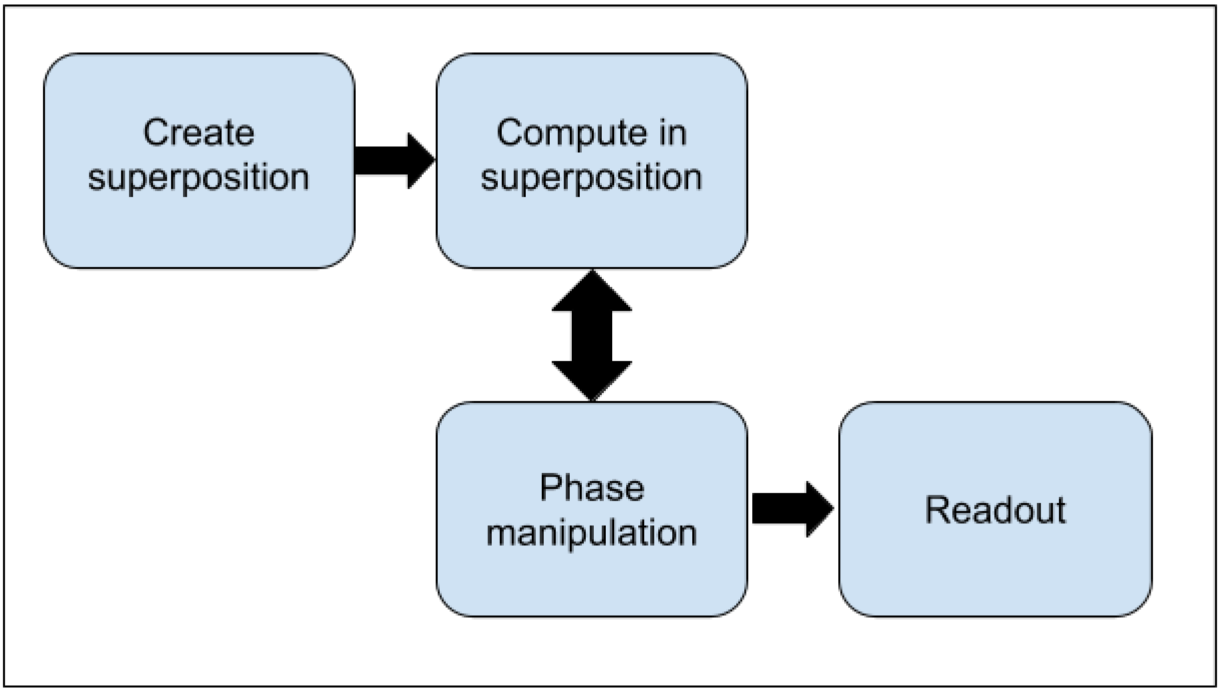

Figure 2.1: A high-level view of the structure of a quantum algorithm (inspired by Reference [2.13]).

At a high-level view quantum algorithms can be reduced to a toolbox of QPU primitives, which are listed in the table below.

QPU primitive	Example
Digital logic	Quantum adder
Amplitude amplification	Grover's algorithm
Quantum Fourier Transform	Shor's algorithm
Quantum walks	Element distinctness
Quantum simulation	Quantum chemistry simulation
BQP-complete problems	Linear systems of equations
Quantum data types	QRAM

Table 2.4: List of "primitive" quantum algorithms and examples of their use.

The richness and diversity of currently known quantum algorithms is an invitation to apply them to the solution of yet unsolved problems.

What software do we have?

We have discussed the available quantum computing hardware and the great variety of existing quantum algorithms, we now need to look at the programming tools available to arrive at a full-stack solution for quantum computing.

For brevity we limit our overview to the typical workflow on a gate-model quantum computer, as illustrated in Fig. 2.2.

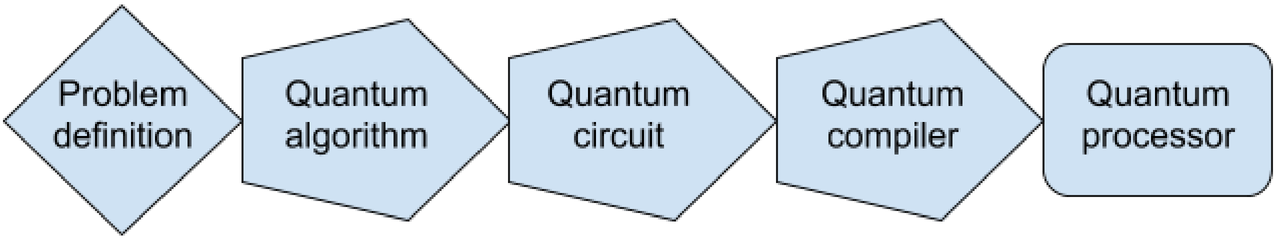

Fig. 2.2: Visualization of a full-stack quantum computing workflow for a circuit-model quantum computer.

Solving a problem on a quantum computer requires the user to specify a quantum algorithm in terms of a sequence of quantum gates (quantum circuit). Typically a QPU (Quantum Processing Unit) implements only a limited number of quantum logic gates. Thus, the necessity of a compiler that translates the abstract quantum circuit to the actual gates available in the quantum hardware.

Interestingly, most quantum computer producers have opted for open source software solutions. A few popular open-source quantum software development kits (SDKs) are listed below.

SDK	**Company**	**Programming language**
Qiskit	IBM	Python
Forest	Rigetti	Python
Q#	Microsoft	C#
ProjectQ	ETH Zurich	Python
t|ket>	Cambridge Quantum Computing	Python
Ocean	D-Wave	Python

For a full classification of quantum computing languages we refer to the website of the Quantum Open Source Foundation (QOSF) [2.14].

2.1.2 Quantum Communication

Quantum communication is a field that has developed quickly since the early 1980s, exploiting principles from quantum mechanics. The objective is to make data transmission secure regardless of the adversary. This is in contrast to mathematical encryption approaches which assume the algorithm is immune to decoding by an adversary in some reasonable time. History has shown that this approach is never fundamentally secure, e.g., the Enigma machine from world war II. In that example, it was the advent of a computer that was the undoing of the encryption. Today, the threat is the quantum computer – once the realm of science fiction, now already demonstrating an advantage over classical computing. The answer is to use quantum mechanics for fundamentally secure communication too, by virtue of two principles: quantum states cannot be perfectly cloned, and any measurement of a quantum state alters it. The consequence is that if a message is intercepted, the message is altered in some measurable way, while it is not possible to clone a message and make undetectable measurements on the copies. To ensure the security, the information must be sent as quantum states, which in practical deployment means entangled or single particles. In the remainder of this document we will assume photons (single particles of light) are used, so that the quantum communication is photonic-based. Photons are in fact ideal for quantum communication, fast and weakly interacting, just as they are for "normal" or "classical" communication, and have all but replaced electrons: rather than electrons down copper wire for communication, we now have photons down fibre optic.

The most common form of quantum communication is photonic quantum key distribution (QKD). Here the scenario is two parties who wish to share a secret key that can later be used to encrypt information and send it down a classical channel. There are many protocols to do this, but perhaps the most common is the BB84 protocol. The sending party, Alice, prepares a particular state of the photon and sends it to the receiver, Bob. Bob then choses how he wishes to make the measurement. By comparing results (what type of state Alice selected and what type of measurement Bob made), they can sift out a secret key. This approach has been demonstrated extensively with the polarization of light, allowing an information capacity of 1 bit per photon. There are several alternatives to QKD, including quantum secret sharing and entanglement steering, and many variants on the protocol just described, but all work on a similar principle to ensure the message is fundamentally secret.

The simplicity of the physics hides many technical challenges to realizing deployable technologies, captured by the simple questions:

- How far can we send a message?
- How fast can we send the message?
- How integrated can we make the technology?

How far?

Because cloning of a quantum state is not allowed, so too is amplification forbidden. This means that, in contrast to classical communication, losses cannot be compensated for. The medium, and the states sent down the medium, therefore play a major role in how far one can go. In fibre, the losses are exponential with distance – this is why fibre networks have repeater stations every 100 km or so. Such amplification stages are not allowed in the quantum world, limiting the fibre link distance between nodes. In free-space the losses are far less (roughly quadratic with distance), but the atmosphere introduces other unwanted perturbations and communication must be line-of-sight. It is not surprising then that the longest quantum link has been between satellites in pristine outer space.

To push the distance farther, studies have to be conducted into the states to be used, the evolution of such states in a given medium, and the correction of quantum errors. Next, to get beyond the distances limited by loss, quantum repeater technology needs to be developed, including entanglement swapping and quantum teleportation tools. The types of states also affect the distance that can be travelled before the channel is no longer secure, with high-dimensional states promising to be more robust to noise than low-dimensional states. The technologies to push the distance are therefore very much in their infancy.

How fast?

Polarisation encoding is limited to 1 bit of information per photon, but has a reliable toolkit. High-dimensional encoding allows much higher information capacity per photon, unlimited in principle, but has an almost empty toolkit: we do not know yet how to easily create, manipulate and detect such states. Next, the key rate is also dependent on how many photons can be produced per second, requiring devices for fast random number generation, fast and on-demand single photon sources, single photon counting units with small dark counts and short dead times, and so on. Most of this technology is available but only at speeds much slower than their classical counterparts, restricting key rates to the equivalent of a very slow internet connection.

How integrated?

Assuming the hardware and protocols would allow for fast quantum communication over some desired distance, there remains the issue of integration. Quantum communication solutions should integrate seamlessly into classical networks. This requires development on software platforms, protocols, on-chip photonic solutions, for a hybrid classical-quantum architecture. Integration also refers to seamless connections from free-space to fibre, from bulk to on-chip connections, from photonic to electronic. Presently only isolated connections have been deployed with custom made devices. Tellingly, the UK's Quantum Communications Hub at the University of York has as its stated objective to address the price, size, weight and power limitations of present technologies in order to deliver practical systems that will open broader markets – engineering and packaging the technology.

From challenge to opportunity

There has been progress in each aspect of the core challenges outlined above, but so far each is tackled largely in isolation. For the most part, high-dimensional state preparation for secure communication has not considered integration issues, integrated solutions have not addressed the speed of connection, and pushing distance has been achieved without a clear roadmap on scalability. For example, quantum random number generators have good speed, but become noisy when integrated into classical circuitry. QKD works excellently between two parties, but fails to ensure authentication, and so is vulnerable to man-in-the-middle attacks. Because of this, and due to lack of integration with classical systems, the UK National Cyber Security Centre (NCSC) “does not endorse the use of QKD for any government or military applications, and cautions against sole reliance on QKD for business-critical networks, especially in critical national infrastructure sectors.”

There is significant work worldwide going into addressing these challenges. To overcome this will require multi-disciplinary research with inputs from physics, mathematics, engineering, industrial design, computer science and IT. Thus, although quantum communication is a mature topic, there remains significant scope to advance and deploy it nationally for strategic and economic benefit, while making an international impact through science and technology development.

2.1.3 Quantum Metrology and Sensors

Quantum metrology and sensors represent the largest collection of existing and potential commercial quantum information technologies [2.15]. It includes atomic clocks; gravimeters; quantum metrology standards for voltage, current and resistance; inertial motion sensors; and a range of quantum imaging devices, to name but a few. It is also considered to be the most established category, because several of these products that are based on quantum phenomena have existed for decades. Such quantum information technologies are widely applied in navigation, timing, medical imaging and many other applications.

The benefit of quantum information technologies in this category can be summarized as the general improvement in accuracy that it provides compared to devices based on classical physics. Coherent and entangled quantum states allow measurements that are more accurate than the shot-noise limit would allow in classical measurements. A notable example where this property is being applied is in the LIGO system for the sub-shot-noise measurement of gravitational waves [2.16] .

Quantum clocks

While the SI second has for a number of decades been based on the microwave clock transition between two hyperfine ground states of cesium-133 atoms, recent advances in laser cooling of atoms, frequency comb laser and stable resonant cavities. As a result, the measurement uncertainty for frequency determination on the basis of optical atomic clocks has been brought down to 2x10e-18 [2.17]. It thus follows that the definition of the second is set to change in the near future.

Optical atomic clocks enable accurate timing and navigation devices for defence, telecommunications and finance industries. They are expected to become more widespread over the next five to ten years.

In South Africa, the highest requirement for accuracy in timing is probably that which is required for the SKA. It is estimated that an accuracy of only a few nanoseconds is required by the SKA for timing measurements involving pulsars, which is currently planned to be provided by global positioning satellite (GPS) signals. However, this limit may have been imposed more by the restriction of current technology than by what the science requires.

South Africa does not currently have an activity in the development of an optical atomic clock. However, some of the enabling technologies for such an activity does exist in the country.

Quantum sensors for electromagnetic quantities (metrology triangle)

There are various electromagnetic quantities that can be measured by quantum sensors and devices. This category includes SQUIDs and colour centres in diamond for the measurements of very small electric and magnetic fields. Applications of such sensors include medical diagnostics and high resolution imaging for microbiological studies, especially of the inner workings of single cells. Other uses include charge sensing in low temperature detection and scanning applications, with the potential for imaging individual charges that may be used in the design and testing of new types of materials.

Today, in some electrical measurements, experimental calibration is required at the level of 0.01ppm. Throughout the world, countries with economies dependent on technology and industry will have scientific centres dedicated to the calibration of equipment to the levels required by the scientific community. In the field of electrical metrology, the desire to close the quantum metrological triangle [2.18] has led to much interest in single electron pumps [2.19]. At present, electrical resistance is defined via the quantum Hall effect [2.20] and voltage through the Josephson effect [2.21]. The electrical current is derived via these representations of voltage and resistance via Ohm's law. An independent representation of electrical current would enable an examination of the self-consistency of these representations of the SI electrical units through the closure of the metrological triangle, with all measurements based on fundamental constants.

South Africa remains an active player in this role with the development of the Kibble mass balance, which will be installed in South Africa in the coming years, together with a new quantum Hall resistance standard and Josephson voltage standard. The Kibble balance requires the accurate measurement of electrical standards such as resistance, current and voltage. South Africa will therefore remain an active participant in this essential field for the foreseeable future.

Quantum biosensors

In the biological and chemical sciences it is vital to have sensors that can measure bacteria, virus and protein characteristic properties accurately. These sensors enable scientists to gain a better understanding of the biochemical processes involved in a given scenario and use this, for example, to develop drugs for improved health care, monitor chemical and biological reactions in agriculture and forestry applications, improve food safety, detect pathogens and perform environmental monitoring in climate-change research. Quantum sensors offer a significant improvement in the accuracy of sensing in these applications, which can reveal previously unclear diagnostics and the true effectiveness of protocols. They may also enable new pathways for optimizing biochemical processes, such as in catalysis.

Quantum biosensors are attracting a growing interest from research groups and companies internationally. In South Africa, there is already some expertise in this area at Stellenbosch University and the University of Pretoria. Groups at these institutes are developing quantum techniques for biosensing using a combination of photonics and solid state systems. The research is aimed at improving drug development techniques and the efficiency of biochemical processes for solar cell technology. This work may eventually be commercialised and contribute towards a future quantum economy in South Africa, with devices focused on problems unique to the country, such as in HIV and Tuberculosis drug research, green energy and in quality control protocols in agriculture and farming.

Quantum sensors for gravimetry and inertial measurement

The gravity field and its gradient can be measured accurately by dedicated quantum sensors, which are expected to emerge over the next decade. Being able to produce a 3D map of the density of the material around them, these devices are expected to have a disruptive impact on construction and the oil and gas industries.

Quantum sensors for inertial measurements can determine acceleration a thousand times more accurately than current technology. As a result, they provide an alternative to navigation by GPS. These quantum sensors are also expected to appear over the next decade.

Quantum imaging

There is a wide variety of quantum imaging technologies, ranging from quantum ghost imaging, which is able to image an object with photons that never encountered that object, to quantum illumination, which can significantly improve the signal-to-noise ratio in imaging. Quantum imaging can be applied in medical diagnostic applications, especially in scenarios which are challenging to image. It is expected that these quantum imaging technologies will start to appear within the next decade.

Quantum control

Most if not all quantum technologies require a high degree of control of quantum systems. While quantum measurements are an integral part of closed-loop control schemes, where feedback is applied according to the deviation of measurement results from a set point, they can be seen as the translation stage between the quantum and the classical world, projecting superposed properties into definite outcomes. There are as many different measurement and control techniques as there are different quantum systems, and their theory is well established. As a result quantum measurement and control form an essential part of quantum metrology and sensors. For example, there is an intricate technique to cool and indirectly measure the “ticks” of the aluminium ion clock at the National Institute of Standards and Technology (NIST) in the US, using a partner magnesium ion. Improving the control of the system over the last decade led 2019 to a world record in precision: the clock would neither gain nor lose a second within 33 billion years. Measurement and control also plays a vital role for benchmarking of quantum technologies. The technologies for quantum control are expected to appear concomitantly with the technologies that employ them. Therefore, commercial implementations of quantum measurement and control are expected to emerge over the next decade.

2.2 Quantum Computing and Quantum Technology Drivers

2.2.1 Quantum Computing

Potential Market and Impact

It is very difficult to estimate the Total Addressable Market (TAM) for the emerging quantum computing industry. Several such TAM estimates -ranging from $300M to $3B- in 5 years have been proposed, but the detailed reports are behind expensive paywalls [2.21]. A recent study of the Boston Consulting Group [2.22] expects the economic impact of quantum computers to be in the range of

- $2 billion - $5 billion in 3-5 years (NISQ Computers),
- $25-$50 billion in 10+ years (Broad quantum advantage),
- $450 billion - $850 billion in 20+ years (Full-scale fault tolerance).

Deloitte Insights estimates that the quantum computing market of the future will be about the size of today's supercomputer market, i.e. $50 billion. For comparison, the current "classical" computing market (from consumer smartphones to enterprise supercomputers) in 2019 was in the order of $1 trillion [2.23].

The difficulty in predicting the commercial impact of quantum computing stems also from the complexity of building and using a quantum computer. The following graphic elucidates the various steps from a quantum chip to running a quantum code.

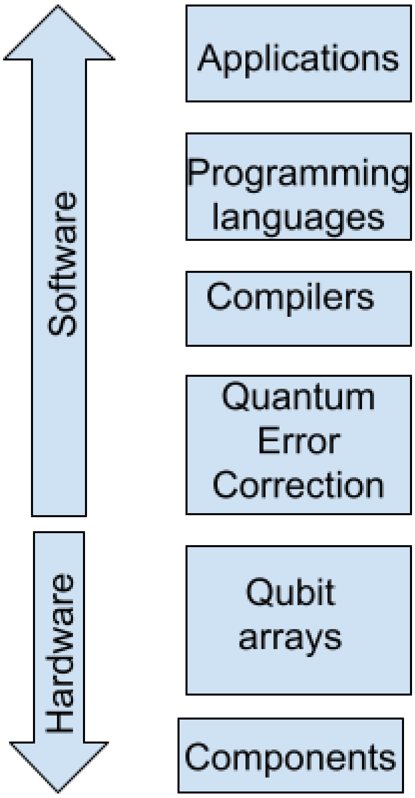

Figure 2.3: The layers of a typical quantum computing stack.

Each of the above layers offers, of course, opportunities for research, development , and commercialisation. In fact, it is evident that a whole quantum computing “eco-system” is emerging. In this section we will focus on the “software” layers and leave the “hardware” layers to the following quantum technology section.

In the “software” context the physics community has been predominantly interested in the development of new quantum algorithms. However, there are lots of opportunities for computer scientists and mathematicians as well.

Driver: High Tech industry

The high-tech industry will be one of the first beneficiaries of quantum computing. The seamless integration of quantum computing with machine learning and artificial intelligence opens up great opportunities, with applications ranging from air traffic control to generative models in unsupervised learning have been identified as examples of intractable machine learning tasks that can be handled on NISQ Computers. Also, datasets with intrinsic quantum-like correlations, will be studied advantageously on NISQ computers. [2.24]. Hybrid algorithms in which just one intractable step is executed on a quantum computer also show great potential. For example, it is already known that specific quantum devices can be used as special purpose AI accelerators, to evaluate kernels used in classical machine learning [2.25].

Driver: Material design and drug discovery

Quantum chemistry has been identified as one of the ”killer” applications of quantum computing [2.26]. With the rapid development of NISQ quantum computers exact simulations of large molecules with complex electron behaviour are possible. The applications range from the development of new materials for solar cells and other clean energy processes, to the modelling of biological nitrogen fixation in nitrogenase, with the potential discovery of cheaper and more efficient fertilizers [2.27].

Driver: Financial services

The financial industry is an early adopter of high-tech solutions. Many of the typical problems of this sector are perfect matches for quantum computing applications. Portfolio optimisation and risk management problems can lead to very complex optimisation problems that are perfectly suited for quantum algorithms. Also, the simulation of Markov chains on quantum computers (quantum walks) will improve on the performance of traditional Monte Carlo approaches of financial markets simulations. For example, quantum amplitude estimation can result in a quantum speed-up for Monte Carlo sampling, with applications in the pricing of derivatives and risk analysis [2.28],

Driver: Transportation and Logistics.

At the core of the computational challenges of the transportation and logistics industry are optimization problems. A paradigmatic example is the Travelling Salesman problem. Quantum computing algorithms will lead to efficiencies in route optimization, fleet management, network scheduling, and supply chain optimization [2.29].

Example: Manufacturing

We conclude this section with an example of various applications of quantum computing in the manufacturing industry, to show the ubiquity of potential uses. In a recent report IBM has identified use cases of quantum computing for the manufacturing industry [2.30]. The document analyses four categories: discover, design, control, and supply. The following are examples of how certain industry sectors will benefit from the use of quantum computing:

- Materials with more advantageous strength-to-weight ratios
- Batteries that offer significantly higher energy densities
- More efficient synthetic and catalytic processes that could help with energy generation and carbon capture.

The simulation and optimization abilities of quantum computing can facilitate the design of many products characterised by complex hardware features, as for example in the automotive or aerospace industry. The control and scheduling of production flows and processes is an ideal area of application for quantum optimisation algorithms. The same can be said of supply chains and risk modelling.

2.2.2 Quantum Communication

Potential Market and Impact

According to a recent market survey with projections out to 2020 [2.31], the estimated 2017 global quantum-cryptography market size was US$ 285.7 million, with a 27% Compounded Annual Growth Rate (CAGR), and estimated to be US$ 943.7 million in 2022. Network security is estimated to comprise a 43.5% share of this market, with the quantum cryptography server market taking 49.9% and consulting services 36.6%. Government and defence, as well as Banking, Financial Services and Insurance made up 42% of the market size in 2017. CAGR of government and defence is expected to be highest, at 30%. The market projected to be the biggest is in North America, with 44.4% of the global share.

Quantum communication cannot be taken in isolation as it must integrate into optical communication solutions. The classical optical communication and networking market is expected to grow from US$ 13.85 billion in 2016 to US$ 24.12 billion by 2023, at a CAGR of 8.1% between 2017 and 2023. The estimated 2017 free space optical communication market size was US$ 212.4 million, with a 41.4% Compounded Annual Growth Rate (CAGR), in accordance with a Markets & Markets report. The market size is therefore to grow to US$ 1,2 billion in 2022. Free-space optical solutions are presently a niche market with little data available. However, following the launch of Micius, it was reported that “quantum communications is expected to be widely used in government, energy, finance, broadcasting and TV sectors and is to create a market worth more than 50 billion Yuan (£5.71bn)” by 2021. Additionally, it was also reported that the military market alone was expected to be worth £3.4bn.

Trends:
Over the last decades there has been relentless and exponential growth in demand for data services, in particular video. According to a 2017 CISCO White Paper [2.32], global IP traffic will increase nearly threefold from 2016 to 2021. Overall, IP traffic will grow at a CAGR of 24% from 2016 to 2021. Business IP traffic will grow at a CAGR of 21% from 2016 to 2021, led by increased adoption of advanced video communications in the enterprise segment which will cause business IP traffic to grow by a factor of nearly 3. With increased data use, the need for increased security, especially in view of technological advances in the quantum computing space, will also increase.

Drivers:
As mentioned above, the advancements in quantum computing is a key driver of the quantum cryptography market. Although the risk is real, there is to some degree a lack of understanding of the risk and for many, this risk is deemed to be a future risk. Other key drivers, as set out in a Quantum Security Markets & Markets report, are discussed below:

Increasing data security and privacy concerns:
With increasing volume of data generated, enterprises demand better security that do not leave such enterprises vulnerable to corporate surveillance and data breaches. With

an increase in the number of systems, many security and privacy issues are expected to arise, and every endpoint, gateway, sensor, and smartphone is expected to become a potential target for hackers. As some systems in enterprises have limited memory, processing capacity, and battery power, classical IT security mechanisms are often found inadequate to cope with the unique security situations that may arise. Quantum cryptography provides its commercial customers with solutions for exchanging encryption keys efficiently and securely. If attackers try to tamper with the message, quantum cryptography destroys the entire message.

Growing incidents of cyber-attacks:

There is a rapid migration to digital forms on open and globally interconnected technology platforms. As the number of connected devices increases, the risk of safeguarding data on these devices is also rising. Due to data proliferation and continually evolving unknown cyber-attacks, probabilities of data breaches are growing considerably. Presently, the internet has become part of critical infrastructure for both businesses and individual users, making its security a critical issue. With security being an important aspect, implementing quantum cryptography enables cryptography keys to be shared over optical fibre and free space and used in a general cybersecurity framework. Due to this threat landscape of cyber-attacks, an adoption of quantum cryptography hardware and services is expected.

Rising adoption rate of cloud storage and computing technologies:

Cloud services have become important due to the rise of high-capacity networks as well as the decreased cost of computers and data storage devices. Cloud storage allows users to utilize, centralize, and share resources (both hardware and software) over a network, but with that large amount of data being stored off-site and in the cloud, it affects the security of the enterprise IT system. Quantum cryptography, using QKD techniques, secures data transmitted over a public network between the user and the cloud. Moreover, it provides strong encryption, quantum-safe server, endpoint encryption, and network infrastructure security.

Spurt in demand for security solutions across verticals:

The Banking, Financial Services, and Insurance and government sectors are adopting security solutions to secure their transactions. As online business witnesses massive growth, offering enhanced convenience to consumers, the demand for security solutions is also rising sharply. Similarly, financial institutions are providing the facility of online banking and online transactions to their customers, which is again expected to boost the payment security market. In banking transactions and applications, it is important to protect the client and proprietary information. Moreover, as government firms need to transmit enormous amounts of confidential data securely at a global scale, the possible chances of cyber-attacks increase. Quantum cryptography offers the best practices in key generation for highly secure crypto operations and banking solutions. It generates keys for security applications and crypto operations such as authentication, digital signatures, and secure access control. Furthermore, it helps protect mission-critical data for the government and provides high-performance layer encryption. Increase in demand for security solutions across verticals is thus expected to provide new business opportunities for the quantum cryptography market.

Constraints and challenges:
Commercializing quantum cryptography, especially outside the government, defence and finance-related markets is a challenge due to the lack of customer awareness, as knowledge is among the key drivers for market growth. As quantum cryptography is a new concept, various challenges are surfacing, such as failure to obtain sufficient and relevant market information, failure to use it properly, insufficient knowledge about the market, and the inability to locate local and international sales and distributions centers. Therefore, proper customer awareness of quantum cryptography solutions is needed to implement the successful deployment of quantum cryptography solutions.

2.2.3 Quantum Metrology and Sensing

Quantum metrology and sensing covers a large collection of different applications. It also includes imaging applications. Moreover, due to its importance in metrology and sensor systems, optical sources are also included here.

Here we identify potential markets in this category:

- NMISA is mandated by law to maintain the National Standard. This mandate also applies to those standards that are related to quantum technologies and infrastructure that will eventually be implemented in South Africa.
- One can distinguish two different ways in which quantum information technologies are relevant to metrology. On the one hand, quantum information technologies could be used in the implementation of measurement standards as they apply to any technology. For example, entangled photons can be used to perform sophisticated photometric calibrations. On the other hand, metrology is required for quantum information systems. For example, a quantum communication system would have to adhere to certain national standards that would include the calibration of quantum equipment.
- South Africa is already, via the research facilities at UCT, one of only a few labs around the world that has the facilities to produce and measure single electrons. This work is already actively contributing to the development of a new standard for electrical current, the last stand-alone measurement from the quantum electrical triangle. A new stand-alone standard of electrical current would be incorporated into the definition of the Ampere among the SI units and be utilised by countries worldwide.
- Metrology requires hardware. In those cases where one uses quantum technology to implement measurement standards, such technology would include quantum sensor systems, which contain sources, detectors, imaging devices, etc.
- Sensors and imaging are relevant for diagnostics in health-related applications. The health sector is a strong industry in South Africa. It provides several opportunities for quantum-based sensors and imaging systems. It also provides opportunities of other quantum information technologies. For example, the use of quantum computing for drug-discovery.
- Sensors are used in mining and the construction industry for structural and seismic sensing applications. Mining and construction are strong industries in South Africa.
- Sensors are used for climate change monitoring (for example, water contamination and other impacts), sustainable living (for example, water purity),

electrochemical monitors for renewable energy storage optimisation (for example, energy and power constraints). As some of these applications are more relevant for South Africa than other countries, it gives South Africa an opportunity to become the world leader in the quantum technologies for these applications.

- The South Africa National Space Agency [2.33] has identified key areas to address, all of which require sensing and imaging from space. There are two ways in which quantum technologies can be of service here. One is to develop quantum sensors to be incorporated into satellites. The other is to employ quantum methodologies to calibrate the sensors that are used on these satellites.
- The Square Kilometre Array (SKA) telescope in South Africa has the need for ultra-precise phase-drift monitoring between telescopes. This could be enhanced using quantum sensors.
- Maritime and Navigation in South Africa could benefit from quantum sensors such as gyroscopes, which would improve navigation and network coordination.
- Thanks to the increased international activity in quantum sensors, there are more opportunities to identify niche markets where South Africa can produce quantum-based products for the international market.
- Quantum devices require new ways of testing and certifying that they perform as required. For example, it is critical to guarantee that a quantum key distribution (QKD) system is secure against eavesdropping. Self-testing enables prepare-and-measure devices, as well as quantum channels, to infer the properties based only on correlations in experimental data. Benchmarking of quantum processors is an important task, because the results from quantum computations often cannot be tested with classical computations. As the international market for quantum technology grows, there will be an increasing need for independent certification. This certification would be done by NMISA, but South African companies and university laboratories could also be involved. Certification and self-testing would require dedicated hardware, including quantum sources and detectors.

2.3 Conclusions

Here we identify the following conclusions:

- South Africa has a strong academic activity in quantum computing, quantum communication and quantum metrology and sensors.

- The academic activity is strongly focussed in physics departments at universities, with some activity in other university departments such as chemistry.

- There is very little activity in the research and development of these quantum technologies in engineering departments at universities.

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3. Benchmarks for Quantum Technology Frameworks

Quantum technologies are no longer only the purview of laboratory experiments as private industry has quickly adopted the most robust ideas into applications. For example, atomic clocks are a very mature technology: cutting edge laboratory clocks would not gain nor lose a second in 40 billion years, while chip scale manufacturing technologies have led to the development of extremely miniaturised clocks that are now commercially available. Technologies working on similar principles to atomic clocks allow for the detection of weak magnetic fields and have been used to fabricate atomic vapour sensor arrays used for brain wave detection. Similarly, the geo-surveying industry is benefitting from commercial gravimeters based on laser-cooled, magneto-optically trapped atoms, while quantum random number generators are available off-the-shelf for quantum encryption. On the quantum computing front, Google, IBM, Microsoft and Lockheed Martin all have quantum computing development projects, with D-wave offering a commercially available quantum computer based on an adiabatic quantum computing architecture with several hundred qubits.

3.1 Overview of International Frameworks for Quantum Technology

The aim of this section is to provide a concise overview of quantum technology strategies and investments world-wide. These efforts are motivated by the current race to develop the world's best quantum technology. Arguably, the two biggest contestants are the USA and China [3.1]. All strategy documents stress the need of the joint effort of academia and industry to develop the full economic benefits of these new technologies.

Developed nations have invested heavily over the past two decades in establishing a vibrant research community studying quantum computing and quantum technology related physics [3.2, 3.3]. Many policy documents on national efforts to develop these technologies have been compiled [3.4-3.9], and more recently, governmental funding in many of these countries have been increasingly funneled toward transforming laboratory successes into marketable technologies according to well-defined roadmaps [3.10-3.12]. It is clear that a new industry is on the horizon with many opportunities to contribute [3.13], ranging from being a full-scale quantum computer and technology manufacturer to a supplier of enabling technologies and quantum computing software solutions for international companies.

United Kingdom

The United Kingdom was a pioneer in the establishment of national initiatives. Its Strategy was published in 2015 and has invested more than £1bn since then [3.14]. In 2014 the UK's National Quantum Technologies Programme [3.15] was launched, with The Quantum Communications Hub led by the University of York [3.16]. The programme was renewed again in 2019 for a further 5 years, with investments in four quantum technology hubs: Sensors and timing, Quantum enhanced imaging (QuantIC), Quantum computing and simulation, and Quantum communications Technologies (Quantum Communications Hub). This has led to significant advances having been made on the technology front, including chip-to-chip QKD, fibre based QKD over ~100 km, and wireless QKD between a handheld device and a wall mounted terminal. The investment in Quantum Computing covers the full stack of hardware and software, from core technologies to potential applications including the discovery of novel drugs and materials, quantum-enhanced machine learning, and carbon reduction through resource optimisation.

European Union

In 2016 the European Union published a Quantum Technology roadmap [3.17] and a Quantum Manifesto [3.4] that formulated a common strategy for Europe to stay at the front of the second Quantum Revolution. These documents also induced a €1 billion european initiative in Quantum Technology. The current Quantum FET Flagship was launched in October 2018, has a timeline of 10 years and involves approximately 5000 scientists in total.

In 2019 several EU member states have signed a declaration in which they commit to exploring the development and deployment within 10 years of a quantum communication infrastructure in the EU [3.18], with “a first stage goal of securing government and critical infrastructure communication across the European Union, and in a second stage prepare the connection of quantum computers and sensors in a full Quantum Information Network”. “This quantum communication infrastructure will be used for data transit and storage in a highly secure way. It will ultimately link sensitive public and private communication assets all over the EU, such as banks and administrations [3.19].”

On 6 March 2020 the European Union presented the Strategic Research Agenda of the Quantum Flagship Project [3.20]. The document was prepared in consultation with more than 2000 Quantum Scientists over an 18 month period. The executive summary of the document starts with the following statement:

> “It is now widely understood that the mastery of deep technologies will determine the future prosperity of countries and regions across the world. Sovereignty over these technologies will become the critical building block for the future economic development and digital self-determination of societies.“

The document then clearly expresses 5 goals:

1. Quantum Europe - Engage all stakeholders/create an innovative ecosystem.
2. Financing the growth - Build a sustainable quantum industry.
3. From lab to fab to market - Provide the necessary Infrastructure.
4. Strengthening Europe - Create a European IP and standardisation strategy.
5. Education and outreach - Train a quantum-aware workforce and society.

China

Under its 13th five-year plan, introduced in 2016, China has launched a “megaproject” for quantum communication and computing, “which aims to achieve major breakthroughs in these technologies by 2030, including the expansion of China’s national quantum communications infrastructure, the development of a general quantum computer prototype, and the construction of a practical quantum simulator" [3.21] . China is also setting up a National Laboratory for Quantum Information Science in Hefei, a project led by Prof Pan Jianwei [3.22] . The total investment is reported to be in the order of $10bn.

China is presently the leader in quantum communications, with the launch of the first QKD satellite (Micius) in 2016 and a low key-rate link over 3000 km. This is the culmination of a decade of research, with an estimated national quantum budget of just short of US$1 billion, building on initial work from 1998 to 2010 with a budget of US$150m [3.23]. Quantum communication featured strongly from the start, with key national projects in long distance QKD as well as space based QKD. The experience showed the importance of national flagship projects with directed aims through science, e.g., the "Beijing-Shanghai quantum secure communication backbone" project, funded to the tune of US$490m from 2011-2015 and covering a total distance of 2000 km. Key rates remain low, ~ 10 kbps, but the distance is impressive. Interestingly, funding has been found both from national and regional governments, and has been distributed across all the core technologies needed for a complete network, both photonic for transmission and solid-state for memory.

The University of Science and Technology of China is expected to achieve a 60-qubit quantum computer, based on superconducting technology, with 99.5% fidelity superconducting quantum system this year. The ambitious plan is to have a 1000 qubit quantum computer in 5 years.
[http://quantumhermit.com/chinese-team-lead-by-pan-jianwei-is-expected-to-realize-a-60-bit-quantum-computer-this-year/].

Other BRICS countries

In terms of BRICS countries, Brazil was off the mark early and has had a sustained investment totally ~US$10m since 2001 [3.24], with a healthy portion dedicated towards quantum communication technologies. In its latest budget (2020) India has allocated 80 billion rupees (about US$1.12 billion) to quantum technology research over the next 5 years. This is a considerable increase on the previous commitment in 2018 of US$27.9

million over five years, as part of the National Mission on Interdisciplinary Cyber-Physical Systems. Also Russia [3.25, 3.26] has started such programmes, investing in the order of US$1 billion in quantum technologies as a part of the Digital Economy National Program. Quantum technologies are in the list of nine cross-cutting directions of the program with a total announced budget around 25 billion EUR. The final budget specifically for quantum technologies is not yet defined, but the amount requested by experts is close to 1 billion EUR. But by far the most successful so far, and an early starter, is China.

United States of America

In December 2018 the National Quantum Initiative Act was approved in the USA [3.27]. This law devotes more than US $1.2 billion to a national effort dedicated to quantum information science over the next 10 year. The funding will go to the National Institute of Standards and Technology (NIST), National Science Foundation (NSF) Multidisciplinary Centers for Quantum Research and Education and to the Department of Energy (DOE) Research and National Quantum Information Science Research Centers.

As part of this investment, the DOE has committed to fund $625 million over the next five years to establish two to five multidisciplinary Quantum Information Science (QIS) Research Centers in support of the National Quantum Initiative. Indeed, the DOE's Argonne National Laboratory announced that it has launched a new, 52-mile testbed for quantum communications experiments, which will enable scientists to address challenges in operating a quantum network and help lay the foundation for a quantum internet.

In the 'National Strategic Overview for Quantum Information Science' [3.28] the USA has identified 'grand challenge opportunities':

> *"Quantum approaches motivated by Grand Challenges show promise for providing new capabilities and tools for sensing and metrology, communication, simulation, and computation. This is vital for fundamental research and promotes security, health, and the economy. For example, quantum sensing holds the promise to provide advanced sensors for military mission impact, to develop new*

measurement science and quantum-based standards, to improve navigation and timing technologies, and to environmental sensing in novel settings. Single-photon detectors may become possible at far infrared and microwave wavelengths to expand the range of discovery of the dark universe, while non-classical emitters could be integrated for sensing, communication, and computing systems at room temperature.

Today's noisy intermediate scale quantum (NISQ) technology will offer insight into the scientific and technological advances that can address QIS Grand Challenges in areas such as machine learning, simulation of many-body systems for materials discovery, chemical processes, quantum field theory, and dynamics of biological processes.“

It is important to note that all of these programmes have a strong focus on developing national capabilities, this is due to the strategic importance of security and defence, and the role that quantum computing and quantum technology is already playing in this.

Germany

European countries are developing their own quantum computing and technology frameworks, in parallel to the joint european one. Just to mention an example, in 2018 the German Government announced a €650Mio investments in its Quantum Technologies Programme, with the explicit aim of bringing these technologies to market [3.29].

Ireland

Finally, it might be worth mentioning that the Tyndall National Institute of Ireland, a country with a GDP similar to South Africa (approx USD 334bn), has also recently released a document entitled “Positioning Ireland for the Quantum Opportunity” [3.30]. The authors of the study see the opportunity to:

- establish quantum technologies as a key driver of the country's innovation strategy,
- develop quantum technology hardware utilising the country’s strengths,

- establish infrastructure for quantum computing and quantum technology,
- invest in educating quantum scientists and engineers.

3.2 Quantum Technology in Africa

The African continent is working hard to increase its stake in quantum computing and quantum technology. To increase the collaboration on the continent since 200x a Quantum Africa conference series has been held every couple of years. The first two editions of the conference were held in South Africa. Quantum Africa 1 took place in Durban in 2010 held in Durban in 2010, and was followed by Quantum Africa 2 in Drakensberg in 2012. The conference moved out of South Africa for the first time in 2014, when Quantum Africa 3 was held in Rabat, Morocco. Quantum Africa 4 took place 3 years later in Tunis, Tunisia. Quantum Africa 5 came back to South Africa in 2019 and was held in Stellenbosch. The next edition will take place possibly in 2021 in Kigali, Rwanda. The conferences are coupled to school to train the next generation of researchers in the field.

The agreement on Quantum Computing between IBM and WITS was a great boost for the field on the continent. Wits University as the first African partner on the IBM Q Network and acted as the gateway to quantum computing for academics in South Africa and from the 15 universities who are part of the African Research Universities Alliance (ARUA). In December 2019 IBM organised a first Quantum Computing Hackathon in Pilanesberg.

Countries like Egypt, Morocco and Tunisia have an emerging community of researchers working in the field of quantum computing and quantum technology.

The African Institute for Mathematical Sciences (AIMS) has launched "Quantum Leap Africa" with the vision to place Africa on the leading edge of quantum science and technologies for the future. Quantum Leap Africa is funded by the government of Rwanda and by private donors. The Quantum Leap Africa facility at the AIMS Rwanda centre hosts about 20 researchers and 60 postgraduate students.

One Quantum, a leading Quantum Tech community has opened an African Chapter as well (https://onequantum.org).

There is strong evidence that a vibrant quantum technologies community is emerging on the continent.

3.3 Industry investments in Quantum Technology

Next to the huge investments of governments in quantum technology, established industries and startups have started to position themselves in the space with equally important investments.

The coordinated international effort to develop quantum technologies is systematically leading to the birth of a new high-tech industry. Already it is estimated that the current market for components supplied to primarily researchers in quantum technologies is on the order of 100 million pounds. The long term growth projects new industries with upper limit annual worth of up to 400 million pounds in component technologies, up to 200 million pounds for atomic clocks, 300 million pounds for quantum sensors, 500 million pounds for navigation sensors, 300 million pounds for quantum communication, 200 million pounds for quantum-enhanced imaging and 300 million pounds for quantum computing. The technologies themselves will allow better protection of state and citizen privacy, create new tools for geo-exploration, new methods of non-destructive testing of advanced manufactured components and instruments, solve challenging problems such as the design of new drugs, potentially save many lives through new medical imaging applications, and ultimately impact everyday consumer applications.

The interest of large listed companies in quantum computing and related quantum technologies goes back almost 20 years. Table 3.1 lists some of the years some selected public companies started investing in quantum computing and quantum technology.

The industrial “Quantum Gold Rush” started approximately around the year 2012, as can be seen in the two figure below from a recent publication in Nature [3.31]. Over the last 10 years a large number of quantum technology start-ups was successful in raising substantial amounts of venture capital funding, mainly in the areas of quantum computing and related software.

Year	Public Company	Quantum Computing & Technology Activity
2001	SK telecom	R&D in quantum communication
2005	Microsoft	Starts StationQ UC Santa Barbara
2011	Lockheed Martin	Buys D-Wave Quantum Computer
2013	Google	Absorbs UC Santa Barbara group of John Marininis
2014	IBM	Investment of $3Billion in quantum computing
2015	Intel	Invests in QuTech Delft to build quantum computer
2015	Aliyun (Alibaba Cloud)	Quantum Computer
2017	Honeywell	Ion Trap Quantum Computer
2017	Accenture	Quantum Computing
2018	Baidu	Quantum Computing Algorithms
2019	Infineon Technologies	Ion Trap Quantum Computer

Table 3.1: Year some public listed companies entered the quantum computing and quantum technology arena.

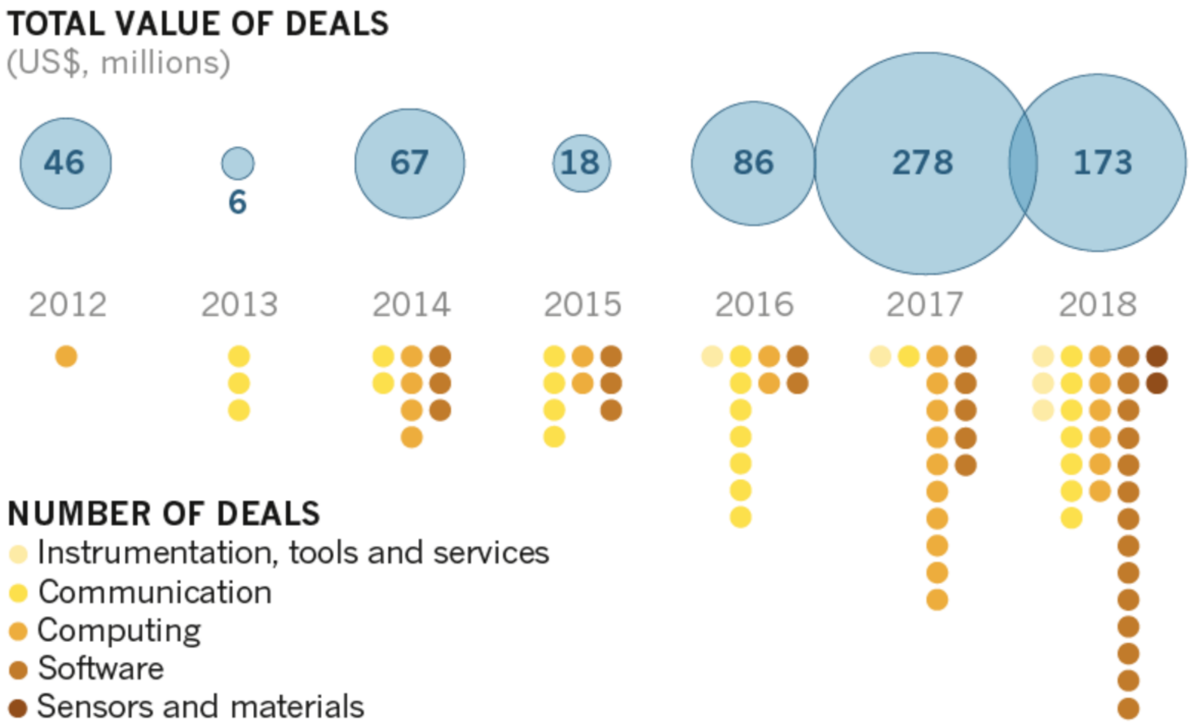
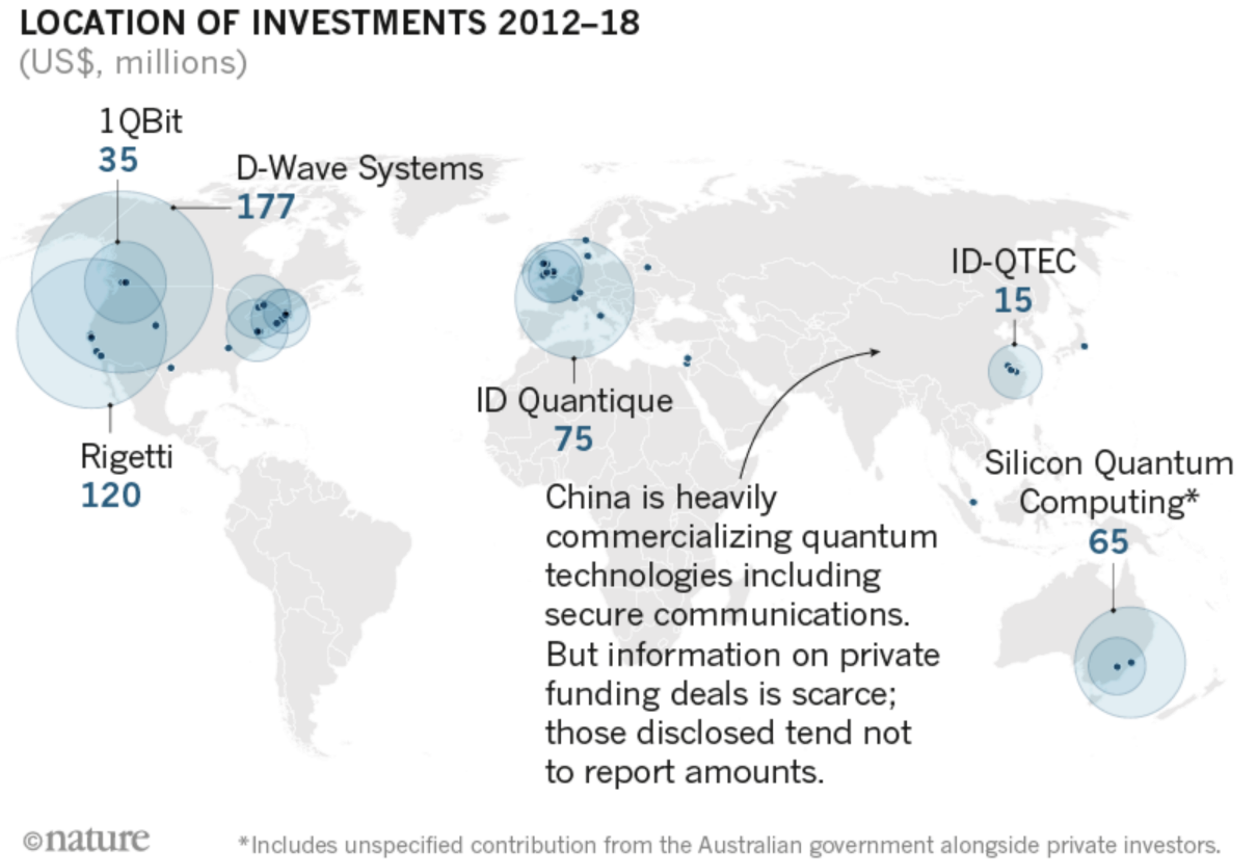


Fig. 3.1: Total value of deals in quantum computing and quantum technology. From Reference [3.31]

It is also interesting to look at the location of said investments.



Source: *Nature* analysis, including data from Quantum Computing Report, Boston Consulting Group, PitchBook and Crunchbase

Fig. 3.2: Location of investment in quantum computing and quantum technology. From Reference [3.31]

It has been reported [3.32] that at the end of 2019 the quantum computing start-up PsiQuantum has raised about $230 Million, which is possibly the largest VC investment in Quantum Computing so far. PsiQuantum, based in the USA and the UK, is planning to build a silicon-based photonic quantum computer, based on technology developed at the University of Bristol. PsiQuantum is promising to build “the first useful quantum computer” with about a million qubits.

The website Quantum Computing Report [3.33] currently lists (information retrieved on 26 April 2020) more than 150 private/start-ups companies operating in the segments of hardware, software, communications and consulting. Some private/start-up companies operate in multiple segments and a few work in areas such as incubators and IP-development. The ratio of companies operating per sector is depicted below.

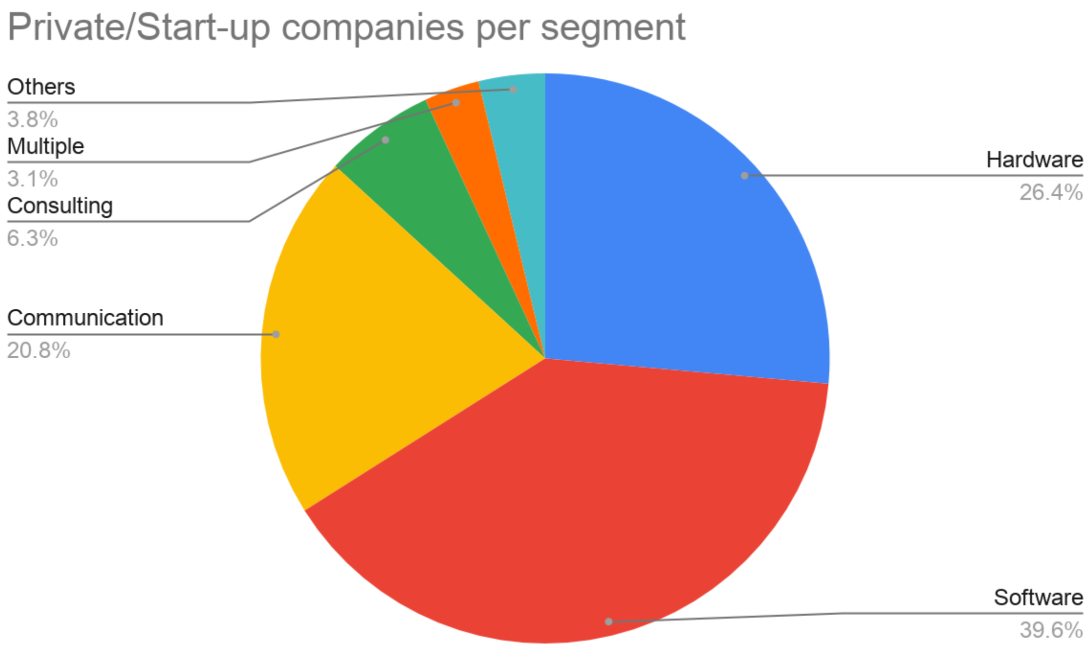


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Figure 3.3. Private/Start-up companies per segment.data retrieved from Quantum Computing Report on 25 April 2020 [3.33].

In the following we portrait some successful start-ups in the areas of quantum computing, quantum communication and quantum sensing and metrology.

Players in the quantum computing segment include hardware and software start-ups. Among the most promising hardware start-ups we will briefly profile Xanadu, PsiQ and IonQ, while among the software start-ups we will profile Zapata and ProteinQure. ProteinQure deserves special mention, as it was co-founded by a current UKZN MSc student, Mark Fingerhuth, who serves as Head of Research & Development at the company. The company uses quantum computing and artificial intelligence for the computational design of protein-based drugs. It leverages quantum computing, molecular simulations and reinforcement learning to engineer novel protein-based therapeutics.

Xanadu

Founded: 2016

Location: Toronto, Canada

Products: Xanadu is a photonic quantum computing company that integrates and designs quantum silicon photonic chips. It also develops software solutions: Pennylane is a cross-platform Python library for quantum machine learning, automatic differentiation, and optimization of hybrid quantum-classical computations and Strawberry Fields is a full-stack Python library for designing, optimizing, and utilizing photonic quantum computers.

Funding: $35.6M

Website: https://www.xanadu.ai

IonQ

Founded: 2016

Location: College Park, Maryland, USA

Products: IONQ develops general-purpose quantum information processors. Its unique trapped ion approach combines unmatched physical performance, perfect qubit replication, optical networkability, and highly-optimized algorithms to create a quantum computer that is as scalable as it is powerful and that will support a broad array of applications across a variety of industries. It is offering the first commercially available trapped ion quantum computer.

Funding: $75M

Website: https://ionq.com

PsiQ

Founded: 2016

Location: Palo Alto, USA

Products:	It is building a general purpose quantum computer using silicon photonic qubits produced in a conventional semiconductor fab.
Funding:	$660M
Website:	https://psiquantum.com

ProteinQure
Founded:	2017
Location:	Toronto, Canada
Products:	computational biophysical models with statistical and machine learning approaches to enable search across vast spaces of protein therapeutics.
Funding:	$4.6M
Website:	www.proteinqure.com

Zapata
Founded:	2017
Location:	Boston, USA
Products:	Orquestra, a unified quantum operating environment, that allows quantum-enabled workflows across a full range of quantum devices and is already used by leading hardware interfaces. Zapata also offers solutions, such as quantum proof of concept and assessment, and custom quantum software, quantum capability building.
Funding:	$31.4M
Website:	https://www.zapatacomputing.com

Players in the quantum-cryptography market include ID Quantique, Magiq Technologies, QuintessenceLabs, Qasky, Quibitekk, PQ Solutions and Nucrypt. These competitors mostly provide quantum-crypto solutions catering for quantum key generation, quantum key delivery and quantum safe network encryption for fibre communication links. None of the solutions are for the Free-space communication market.

ID Quantique

Founded: ~2001 (as spin-out of the Group of Applied Physics of University of Geneva)

Location: Geneva Switzerland

Divisions: Quantum Safe Cryptography Division; Photon Counting Division; Quantum Random Number Generation Division

Current products: Quantis range of random number generation, Centauris range of quantum-safe network encryption products, QKD generators

Funding: In 2003, IDQ raised one million Euros from i2i, a venture capital fund, which allowed the company to develop the first QKD products for data centres and conduct the first test implementations. In 2013 IDQ raised $4.5 million from QWave Capital, a venture fund, in order to expand its market presence in different geographic and vertical markets. In 2016 another $4 million to develop the world's smallest (5x5mm) Quantum Random Number Generator based on technology and know-how licensed from IDQ. In April 2018, ID Quantique raised US$ 65 million from SK Telecom, intended to develop IDQ's quantum technologies for the telecom and IoT markets.

Website: https://www.idquantique.com/

MagiQ Technologies

Founded: ~1999

Location: Somerville, Massachusetts

Products: Novel solutions for a wide range of applications, including in the fields of Nonlinear Optics and Quantum Information (Quantum Cryptography Systems, Entangled Photon Sources), contracting directly with private firms and with government agencies such as the Air Force, Navy, Army, DARPA, DOE and NASA.

Website: http://www.magiqtech.com

QuintessenceLabs

Founded: 2008

Location: Canberra, Australia (following research at The Australian National University)

Products: Novel solutions for a wide range of applications, including in the fields of Nonlinear Optics and Quantum Information (Quantum Cryptography Systems, Entangled

Photon Sources), contracting directly with private firms and with government agencies such as the Air Force, Navy, Army, DARPA, DOE and NASA.

Funding: Westpac Group, a major investor, extended two rounds of funding to QuintessenceLabs in 2015 and 2017, respectively. In July 2017, QuintessenceLabs received a grant of AU$3.26M from the Australian Department of Defence's Innovation Hub to develop a free-space QKD system.

Website: https://www.quintessencelabs.com/

There are no commercial quantum solutions in the free-space market, but there are several companies that could enter at some stage:

LightPointe (FSO)

Founded: 1998

Location: California, USA

Products: Aire X-Stream Series Free Space Optics

Funding: LightPointe is majority owned by Berg & Berg Enterprises, LLC, the $550,000,000 private venture arm of a Silicon Valley entrepreneur who is consistently listed on the Forbes list of billionaires

US$ 80 million in development

Website: https://www.lightpointe.com/

fSona Communications (FSO)

Founded: 2000

Location: British Columbia, Canada

Products: 155-E, 155-M, 1250-Z, 1250-E, 1250-M, 2500-Z, 2500-E

Website: http://www.fsona.com/

3.4 Conclusions

Here, the following conclusions are drawn:

- The international activity in quantum technologies is clearly very high.
- The financial support for quantum technologies from governments of both developing and developed countries is astonishing.
- These governments do not only support research through funding given to universities and research institutes, but also give direct financial support for the development of quantum technologies at commercial companies.
- In some cases, the funding of research institutes is linked to the industrial development of the technology through the establishment of such companies.

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4. Evidence-based needs analysis

4.1 A short history of Quantum Technology in South Africa

The early days (1975-2000)

Most of the "quantum" related publications until the year 2000 were devoted to problems in cosmology and astrophysics, nuclear physics, chemical physics and condensed matter physics. A few exceptions were papers dedicated to the foundations of quantum mechanics Notable are a series of publications on quantum dots.

Possibly, the first paper in the spirit of the second quantum revolution was a paper by WH Steeb and Y Hardy on "Entangled Quantum States and a C++ Implementation published in the year 2000 [4.1]. This work was followed by a series of papers by the same authors on the application of computer algebra to quantum problems. This work culminated in the publication of the books "Classical and Quantum Computing: with C++ and Java simulations" (2004) and "Problems and Solutions in Quantum Computing and Information" (2004), by the same authors. The letter book is now available in the 4th edition.

The years of growth (2000-2010)

In the year 2004 activities around quantum information started at UKZN with the appointment of Prof F. Petruccione. Initially, research was focused on applications of the theory of open quantum systems to the description of dissipation and decoherence, the two "enemies" of quantum computing. The award of an Innovation Fund grant to set up a center for quantum technology and of the SARCHI Chair in Quantum Information Processing and Communication in 2007 focused the research. Using commercial single photon quantum key distribution (QKD) technology the UKZN team made several newsworthy demonstrations, including one the first quantum communication networks, the Quantum City project and the first use of quantum cryptography at a global event in 2010, the Quantum Stadium project.

The Theoretical Physics community in South Africa played a crucial role in the promotion of quantum computing and technology in the country. A milestone was the organisation of the 13th Chris Engelbrecht Summer School in 2001 on Quantum Computing, Communication and Decoherence at the time when the topic was slowly gaining traction internationally. The proceedings of the School, edited by D Heiss, are still a wonderful introduction to the topic. To document the high quality of the School, one of the lecturers, Prof. AJ Leggett was awarded the Nobel Prize two years after the School.

The National Institute for Theoretical Physics kept the tradition of the Chris Engebrecht Summer School alive and organised further schools promoting quantum computing and technology as listed in the table below. More recently, in 2019 and 2020 NITheP partnered with the Centre for High Performance Computing and organised Schools on the Foundations of Theoretical and Computational Science, in which quantum computing and its applications played a central role.

Just after the year 2000 publications in Quantum Science and Technology have increased dramatically, from about 15 in 2001 to almost 140 in the year 2019.

Chris Engelbrecht Summer Schools on Quantum Computing and Technology	
1981	Quantum Optics
2001	Quantum Computing, Communication And Decoherence
2007	Theoretical Foundations of Quantum Information Processing And Communication
2010	Quantum Optics
2012	Quantum Biology
2017	Quantum Machine Learning
2019	Foundations of Theoretical and Computational Science
2020	Foundations of Theoretical and Computational Science

Table 4.1: Summer Schools on Quantum Computing and Quantum Technology topics organised by the National Institute for Theoretical Physics.

The last 10 years (2010-2020)

Since 2010 the community has grown significantly to cover many institutes across the country, which we summarise here in each category. The summary is that we have several strong quantum centres, several emerging quantum centres, and a large but fragmented community that would like to participate in a national programme with strategic focus.

4.1.1 Quantum Computing

Through a Wits initiative in 2019, the South African community has access to several IBM quantum computers ranging from 20 to 53 qubits. The South African community has started to make use of the facility with UKZN, SU and Wits the active participants (at the time of writing).

The availability of quantum annealing based (D-Wave) and noisy intermediate-scale quantum (NISQ) computers (IBM, Rigetti) in the cloud makes it necessary to engage with their potential applications. The Group at UKZN has pioneered the use of NISQ computers and shown, for example, how to develop and implement quantum algorithms for classification. Supervised learning on quantum computers opens the way of analysing Big Data on quantum computers.

The main centres for Quantum Computing in the country are UKZN, WITS, UP, UJ, UCT and SU. They are listed in Table 4.1 below.

Centre	Full-time researchers	Students and PostDocs	Research
UKZN	3.5	8+4	Open quantum systems, Quantum machine learning Quantum simulations, Quantum chemistry, Quantum random access memories, Open source software for QC, Quantum biology, Quantum thermodynamics, Foundations of quantum theory
WITS	3	5	Simulation of hybrid quantum systems, Quantum simulation with quantum walks
UJ	1		Quantum walks
UP	1	1	Entanglement theory
UCT	3	4+1	Chaos and complexity in quantum theory, topological quantum computation, ultra quantum matter, topological data analysis and quantum entanglement
SU/NITheP	1	3	Quantum algorithms, Quantum Networking, Open quantum systems

Table 4.1 The main centres of research in Quantum Computing in South Africa.

UKZN has traditionally capabilities in the theory of open quantum systems, including the mechanisms of dissipation and decoherence. More recently it developed capabilities in applied areas of quantum computing ranging from quantum machine learning, to quantum simulations and quantum chemistry. Foundations of quantum theory are also actively researched, as are quantum effects in biological systems. The UKZN Team has support through a Research Chair and through a node of NITheP.

WITS has capabilities in the simulation of hybrid quantum systems, the exploration of uses of quantum information processing to quantum field theory. Since the start of the collaboration with IBM, WITS has intensified its capability in quantum computing with application areas including medicine, engineering and cosmology.

SU (NITheP) has capability in the theory of open quantum systems and quantum simulators.

UP has capabilities in the theoretical foundations of quantum theory, specifically the theory of entanglement.

UJ has capabilities in the theory of quantum walks.

UCT has capabilities in chaos and complexity in quantum theory and the application of concepts of quantum information in quantum field theory.

4.1.2 Quantum Communication

Quantum communication research only began in earnest from the early 2000s. Since then, the community has grown to include theoretical and experimental activities at four centres (UKZN, CPUT, SU and Wits), theoretical-only activities at a further three (NMISA, CSIR and UP) and classical-only communication activities at a further two (UJ and NMU). Despite the small number of researchers involved (approximately 4 full-time equivalents) and the modest investment to date, the quantum communication community in South Africa has made several internationally recognised advances, including deployment of technology in the Quantum City and Quantum Stadium projects (UKZN); development of new technologies for high-dimensional quantum key distribution, teleportation, entanglement swapping (WITS), entanglement distillation (SU), fibre transport of entanglement (WITS), quantum nano-photonics and integrated waveguiding (SU); development of home-grown single photon sources, quantum random number generators, counting units and detectors (CPUT, SU, UKZN, WITS), all supported by excellent local theoretical work (UP, NMISA). There are several emerging centres that have the capability and interest in quantum communication, including SANSA for satellite deployment, HARTRAO for satellite communication and NMISA for device certification and testing, and significant potential in South Africa's very mature and sophisticated financial services sector. Further, there are a number of commercial entities who operate in the communications and security sectors who could be roll-out partners for new quantum communications technologies. Therefore, all the ingredients exist to create a quantum industry based on quantum communication.

The main centres for quantum communications research are at UKZN, Wits, SU and CPUT. The activities of these centres are summarised in the table 4.2.

UKZN has capability in experimental and theoretical aspects of quantum communication, with active programmes in QKD with entangled and single photons, both in free-space and in optical fibre. The present focus is on satellite QKD links, quantum error correction and quantum communication enhanced with bright light. The team has long term support through a research chair.

Wits has capability in experimental and theoretical aspects of quantum communication, with active programmes in quantum networks (including QKD) with entangled and single photons, both in free-space and in optical fibre. The present focus is on hybrid classical-quantum devices as well as teleportation and entanglement swapping technologies. There is a smaller condensed matter physics interest in diamond as a single photon source. The teams have no long term support.

SU has capability in photonic devices for quantum communication, with active programmes in quantum nanophotonics, entanglement distillation, quantum random number generation and single photon sources. The team has long term support through a research chair.

CPUT has capability in experimental aspects of quantum communication, with active programmes in devices. This includes sources, detectors and counting units, with the aim of developing these into QKD systems. The team has no long term support.

There is active theoretical-only work on quantum channels at the CSIR and NMISA, general quantum systems at UP, and classical communication work at NMU, UKZN, UJ and Wits, and integrated device development at UP.

Centre	Full-time researchers	Students and PostDocs	Infrastructure
UKZN	3	~10	Cold atom trap Entanglement sources QKD test-bed Application of machine learning to quantum optics
WITS	3	~7	Entanglement sources Teleportation experiment 300 m free-space link Solid-state devices
SU	1	~3	Entanglement sources Single-photon source development Nano-photonic circuitry Quantum random number generators
CPUT	1	~2	Atom trap Single photon device testbed
Other	1	0	General photonics capability (NMISA & CSIR) General fibre capability (UJ and NMU)

Table 4.2: The centres of research in quantum communication in South Africa.

4.1.3 Quantum Metrology and Sensors

The history of the development in quantum metrology and sensors in South Africa is as diverse as the quantum technologies found in this category. In metrology, the need for quantum technology grew with the international development of the Quantum SI, where the base units are today defined in terms of experimental procedures related to fundamental constants and involve quantum physics.

Apart from the SI base units, there are numerous other measurement standards, traceably linked to the SI base units, that need to be maintained. Due to the fast-paced development of technology, new measurement techniques need to be developed constantly. Quantum technology is playing an increasingly important role in such measurement techniques. An example in fundamental science is the proposed use of squeezed states for sub-shot-noise measurements of gravitational waves in the LIGO detector. Radiometric and photometric measurement techniques can also benefit significantly from the use of quantum science.

All measurements require sensors and detectors. For quantum technology, such sensors are quantum sensors. Quantum measurements also require quantum control. In South Africa, such technologies have been developed at UCT, WITS, UKZN, US, UP, UKZN and NMISA.

Historically, the primary facilities in low temperature and quantum transport measurements have been based on the highveld, with hubs at Wits and UJ. In 2008, iThemba Labs outside of Cape Town, acquired a new Physical Properties Measurement System (PPMS) from Cryogenics in the UK. The purpose of this system was to perform electron transport measurements and probe magnetic properties of devices and nanomaterials in temperatures down to 1.9K and magnetic fields up to 8T.

UCT established a group in nano-electronics in 2015 with the acquisition of a dilution fridge system and supporting instruments. The group focuses on the transport of single electrons at high frequency through quantum dots in nano sized devices. The purpose of the research is the implementation of a new electrical current measurement standard, based on fundamental constants of nature, such as the charge of the electron.

SU previously developed an ion-trapping facility, where ions were trapped for the first time in Africa. Currently, with the support of a NRF funded Research Chair, a team is working on plasmonics, nano-technology and quantum sensors.

NMISA is currently the only institution outside of academia in South Africa that is actively involved in the development of quantum technologies. The reason is that it is part of its mandate. All seven SI base units (second, metre, kilogram, ampere, kelvin, mole and candela) are currently (since 2019) defined in terms of fundamental constants and laws of nature. This new Quantum SI allows countries, such as South Africa, to maintain their own primary standards. NMISA is working toward the establishment of these primary standards and their dissemination to industry. For example, in collaboration with the National Physical Laboratory (NPL) in the UK, NMISA is currently developing a Kibble-Watt Balance as a primary standard for the kilogram in South Africa. NMISA is currently developing quantum measurement techniques to address such needs.

UP has pioneered quantum biology as an emerging research field focussing on understanding the quantum processes behind photosynthesis, using single molecule spectroscopy and ultrafast spectroscopy. The field has applications in efficient light-harvesting systems, i.e., to produce clean and efficient solar energy converters. Key advances include the discovery of quantum state switching for photosynthetic energy regulation, a ~1000-fold enhancement of light-harvesting in plants with plasmonic fields, the design of the first artificial light-harvesting protein with pre-programmed quantum features, and the development of a method for quantum coherent control of photosynthetic light-harvesting.

UKZN has a group working on quantum measurement and control since 2006. They focus on unsharp sequential and time-continuous measurements methods to monitor the state of individual quantum systems in real time.

WITS has a group working on quantum imaging, with a focus on new technologies for imaging in low light conditions, imaging light sensitive structures, and teleporting images across quantum networks. The work is geared to practical technologies.

Centre	Full-time researchers	Students and PostDocs	Infrastructure
NMISA	1	3	Entanglement source development Quantum imaging development Josephson system (Volt) Quantum Hall system (Ohm)
UCT	1	7	Nano-technology Cryogenic system Quantum Hall measurement system
SU	1	3	Entanglement sources Single-photon technology Nano-photonic circuitry
UP	1	3	Single molecule spectroscopy Ultrafast spectroscopy
WITS	1	3	Entanglement and single photon quantum imaging experiments
UKZN	1	3	Plasmonic devices for sensing

Table 4.2: The centres of research in quantum metrology and sensors in South Africa.

4.2 The Quantum Technology community in South Africa

In November and December 2019 the NWG conducted a survey of the status of the Quantum Computing and Quantum Technology community in South Africa. The intention was to reach academics operating in the areas of quantum computing and quantum technology that were not represented at the previous meetings of the community.

The resulting overview of the quantum computing and technology academic research community (excluding post-graduate students) in South Africa is illustrated in the following.

16 different institutions, including three international ones

- the Botswana International University,
- the National University of Lesotho,
- the University of Eswatini,

expressed an interest in quantum computing and quantum technology.

The following 10 South African Universities have staff and/or Postgraduate students interested in quantum computing and quantum technology:

- University of KwaZulu-Natal,
- WITS,
- North-West University,
- University of Johannesburg,
- Walter Sisulu University,
- Nelson Mandela Metropolitan University,
- Cape University of Technology,
- Stellenbosch University,
- University of Cape Town,
- Durban University of Technology,
- University of Zululand.

Also, three national facilities expressed an interest:

- CSIR,
- NMISA,
- NITheP.

The distribution of the levels of the 28 academics involved in research in quantum computing and quantum technology is visualized in Figure 4.1.

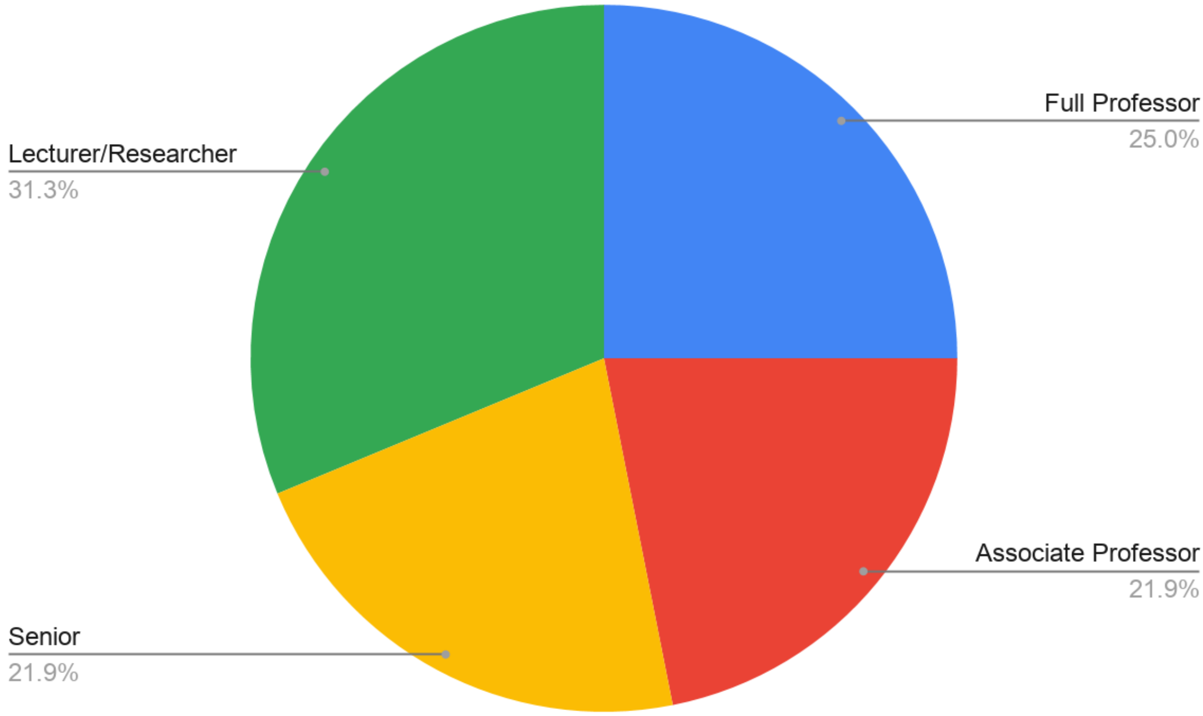

Figure 4.1: The distribution of the 32 academics working in the fields of quantum computing and quantum technology.

Notably, amongst the 8 Full Professors are one NRF A-rated researcher and 3 SARCHI Chairs. Seven Associate Professors or Senior Researchers, 7 Senior Lecturers or Researchers, and 10 Lecturers are also involved in relevant research. It is very interesting to note that the majority of Academics are at Lecturer and Senior Lecturer level, which reflects the fact that the discipline is young and flourishing. The research of the academics splits evenly between theoretical and experimental work.

Over the past decade, about 100 PhD and MSc students have graduated in topics related to quantum computing and quantum technology.

The overwhelming majority of the community would like to join a national initiative to develop a quantum computing and quantum technology research system. Also, an overwhelming majority of academics sees a need for a national training initiative in Quantum Computing and Quantum Technology.

4.3 Bibliometric analysis

A bibliometric analysis of quantum science and technology publications was performed on 13 January 2021 using data obtained from the Web of Science system (Clarvariate). The search used a strategy inspired by the one used by CSIRO in Australia for a similar study [4.2].

The search terms used to identify relevant research publications were

TS=("quantum physics" OR "quantum electronic" OR "quantum optic*" OR "quantum information science" OR "quantum key" OR “quantum cryptography” OR "quantum bit*" OR "qubit*" OR "quantum internet" OR "quantum repeater" OR "quantum radar" OR "quantum mechanics" OR "quantum tech*" OR "quantum dot*" OR "quantum simulat*" OR"quantum thermodynamics" OR "quantum biology" OR “quantum computing” OR “quantum computer” OR “quantum algorithm” OR “quantum machine learning” OR “quantum artificial intelligence” OR “open quantum” OR “quantum communication” OR “quantum network” OR “quantum sensing” OR “quantum metrology” OR “quantum thermodynamics” OR “quantum information” OR “quantum states” OR “entanglement” OR “teleportation” OR “quantum circuit” OR quantum NEAR ("error correct*" OR comput* or *communicat* OR network OR cybersecurity OR encryption OR cryptograph* OR algorithm* OR imag* OR sensor* OR sensing OR oscillator OR metrology OR measurement OR mechanic* OR tunneling OR tunnelling OR entangl* OR superposition* OR teleport* OR computer OR computing)) NOT WC=(Religion OR EDUCATION SCIENTIFIC DISCIPLINES OR HISTORY PHILOSOPHY OF SCIENCE OR Philosophy OR EDUCATION EDUCATIONAL RESEARCH)*

The search found world-wide 332622 relevant publications spanning the period from 1975 to 2019. During this period South Africa produced 1454 publications. As a comparison the total number of publications in the USA is 83818 and in China 62332. A country comparable to South Africa, like Brazil, has 6876 publications overall. Interestingly, Ireland has GDP comparable to South Africa and produces a similar number of papers. The most productive country in Africa is Egypt with 1802. This might be due to influence of the 1999 Nobel Prize for Chemistry won by Prof Ahmed Zewail "for his studies of the transition states of chemical reactions using femtosecond spectroscopy". These data are summarised in Table 4.3.

Country	**Publication output**
USA	84784
China	73841
India	17312
Brazil	7336
Austria	5220
Mexico	3324
Argentina	2049
Egypt	2025
South Africa	1591
Ireland	1427

Table 4.3: Publication outputs in "Quantum Science and Technology" for selective countries.

Figure 4.2 shows the number of publications per year. The total number of citations of the South African output is 23610. The corresponding h-index of all national publications is 66, with each publication cited 16.24 times on average. One can easily identify 3 eras:

- the early days: 1975 - 2000
- the “interest” days: 2001-2010
- the “peak” days: 2011 - today

In the early days a few individuals started getting interested in the topic. A surge in the research output started around the year 2004 and settled around 50 publications a year until the year 2010. Cleary in the current decade the interest in the topic increased further. Currently, the country is producing an output of about 150 papers per year, with a clear trend for further growth.

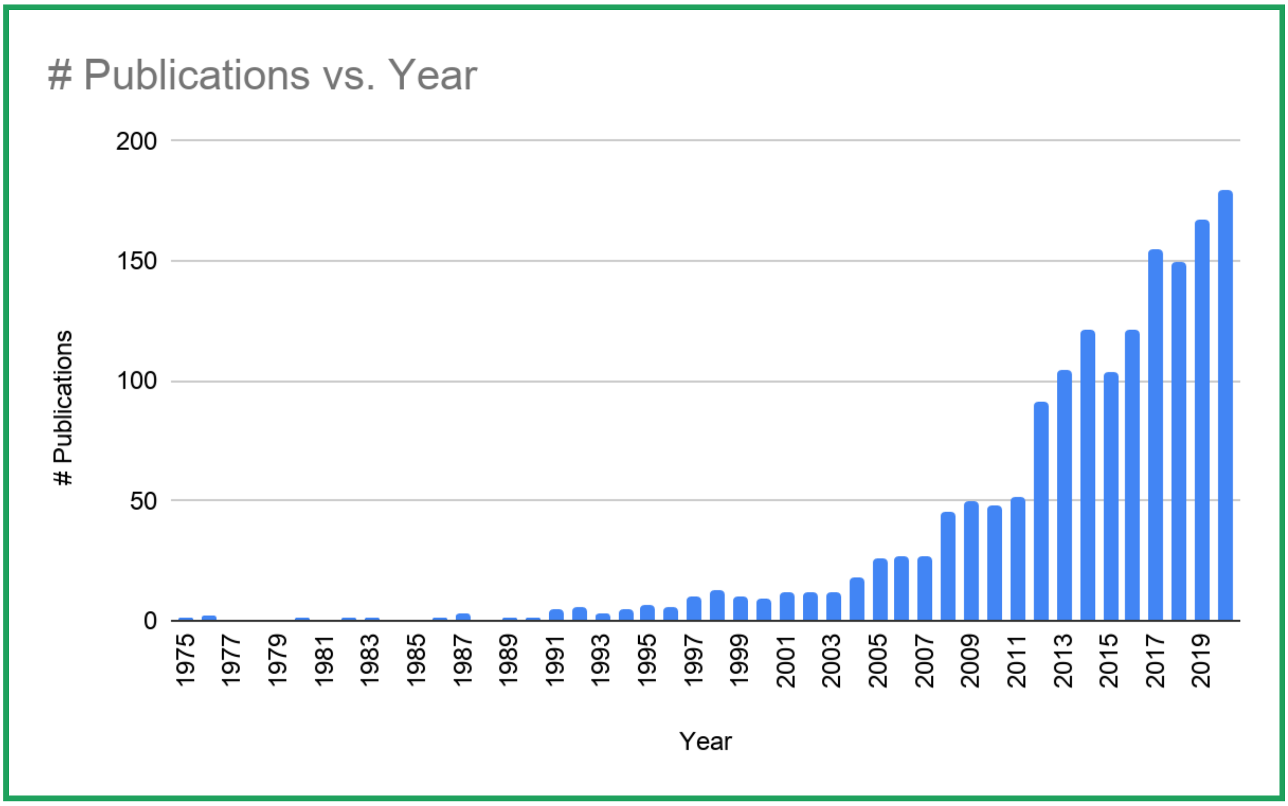

Figure 4.2: Total number of publications in Quantum Science and Technology in South Africa.

4.4 Governmental System for Innovation

In South Africa, there exists a governmental structure, the System for Innovation, that supports the innovation chain from academia to the industry. This structure will plan an important role in the establishment of quantum technologies as an industrial activity is South Africa. It includes the following governmental organizations:

- The NRF and HSRC support research at universities and government research organizations,
- TIA and the IDC provide support for technology development and industrial development, respectively,
- SAASTA provides public awareness programmes,
- NMISA maintains the national measurement standards for industry,
- SANSA and SANMMA support South Africa's space programme and nanotechnology programme, respectively, both of which are potential enablers for and users of quantum technology.

The involvement of these governmental structures in the development of a strategy for quantum information technology would enhance the achievement of the objective of such a programme. While the NRF has supported research in quantum information science for many years and thus helped to strengthen this academic activity in South Africa, this knowledge has yet to be successfully transferred to industry. Part of the reason can be found in the ignorance about the capabilities of quantum technology that exists not only in the general public but also in the engineering and industrial sectors in South Africa.

4.5 The Converging Technology Platform

Quantum Technologies as described in the previous chapters can be regarded as a platform for innovation to advance the aims of the Fourth Industrial Revolution. The applications of quantum technology range from computing to communication and sensing, and are interdisciplinary by their very nature. Also, as an emerging technology the potential for innovation and subsequent commercialisation is huge and needs to be optimally exploited for the benefit of society and to address the socio-economic challenges of the current times.

It is evident that the multi-faceted quantum technology shares the vision of the Converging Technology Platform (CTP) envisaged by the DSI. Quantum Technology aims at being one of the emerging technology pillars of the CTP. Together with photonics, nanotechnologies and other emerging technologies quantum technology will be critical in providing new solutions to problems in health, agriculture, and manufacturing, just to mention a few examples. In fact, because of the role that quantum technology will play in the future of computing, communication and imaging, it has the potential to be a critical foundational layer for cyber-infrastructure development.

The interface of quantum technology with the CTP will be critical to its success.

4.6 South Africa's Potential Quantum Industry

The big quantum computing players, IBM, Intel, Microsoft and Amazon, all have a presence in South Africa and have established a relationship with the local academic community. The agreement between IBM and WIts has already been mentioned. UKZN has an educational agreement for quantum computing training with Microsoft and is now an early adopter of the Amazon AWS Braket Quantum Cloud. The CHPC has a relationship with Intel, who shared their quantum computing simulation software for installation on a High Performance Computer.

There is presently no quantum communication-based industry in South Africa. Industry partners with an interest in developing and deploying quantum communication for encryption include Etion (www.etion.co.za), Sentech (www.sentech.co.za), Nanoteq (www.nanoteq.com), while device fabrication partners might include Insiava (a UP spin-off) and deployment partners in RF Optix (rfoptix.co.za) and Dotnetix (www.dotnetix.ai). These include (1) a hybrid classical-quantum free-space communication solution, based on Wits technology on a Parsec platform, which could be deployed commercially within a few years, (2) On-chip quantum random number generator device (UKZN and SU), (3) Single-photon source using nitrogen vacancy centre (SU), (4) locally developed single photon detectors (CPUT), and (5) a quantum fingerprint authentication device jointly under development at WITS, UKZN and NMISA.

Partners for the uptake of quantum communication technology include SANSA, the banking, financial and insurance sectors, government, the SSA and defence/military.

The following table summarizes some of the local industries that may be able to adapt to develop and commercialize quantum information technologies. It is not an exhaustive list, but indicated that there is a potential for the adaptation of quantum information in the existing industry.

Company	**Potential relevance**	**web site**
FNB	Quantum computing for finance applications	https://www.fnb.co.za
Stanlib	Quantum computing for finance applications	https://www.stanlib.com
Astrofica	Satellite based quantum sensors	[https://www.astrofica.com/]
Denel Spaceteq	Satellite based quantum sensors	[https://www.spaceteq.co.za/]
SCS Space	Satellite based quantum sensors	[http://scs-space.com/]
HENSOLDT South Africa	quantum sensors for optronics for military, security	[https://www.hensoldt.net/who-we-are/where-we-operate/hensoldt-in-south-africa/]
SGT Solutions or SAAB Grintek	quantum sensors for military	[http://www.saabgrintek.com/about.php] or [https://saab.com/region/africa/]
Simera	quantum sensors	[https://simera-sense.com/]
Etion	quantum communication	[https://www.etion.co.za]
Sentech	quantum communication	[https://www.sentech.co.za/about-us/who-we-are]
RF Optix	quantum communication	[https://rfoptix.co.za/about/]
Nanoteq	quantum security	[http://www.nanoteq.com/AboutUs/Overview.aspx]
Insiava	quantum sources and sensors	[https://www.insiava.com/] or [https://www.linkedin.com/company/insiava/about/]

Aspen	application for quantum computing	[https://www.aspenpharma.com/]
Adcock Ingram	application for quantum computing	[https://www.adcock.co.za/]
Caperay	medical diagnostic with quantum sensors	[https://www.caperay.com/]
DISA Vascular	medical diagnostic with quantum sensors	[https://www.disavascular.com/]
TiTaMED	medical diagnostic with quantum sensors	[https://www.titamed.co.za/]
Sinapi biomedical	medical diagnostic with quantum sensors	[https://www.sinapibiomedical.com/]
LifeQ	medical diagnostic with quantum sensors	[https://www.lifeq.com/]
Dotnetix	quantum communication, quantum sensors	[https://www.dotnetix.ai/]
Mintek	Advanced materials	[https://www.mintek.co.za/technical-divisions/advanced-materials-amd/]

Table 4.4: Local companies potentially interested in quantum computing and quantum technology.

4.7 SWOT Analysis

In this section we list Strengths, Weaknesses, Opportunities and Threats to Quantum Computing and Quantum Technology in South Africa. The SWOT analysis is summarised in Table 4.5.

Strengths	**Weaknesses**
● Human resources ● Active research community ● SARCHI Chairs and A-rated researcher ● Many companies with potential quantum computing and technology interests ● Synergies with NICIS and Nanotechnology infrastructure ● NMISA interested in quantum technology for standards	● Small community ● No local quantum computing and quantum technology industry ● No strategic funding resources ● No quantum engineering

Opportunities	Threats
• Significant economic potential • International academic collaboration, e.g. BRICS • Collaboration with global industry partners • Emerging local quantum industry • Untapped incentive funding programmes	• international competition • shortage of skilled workforce • South African economy under pressure •

Table 4.5: SWOT analysis for quantum computing and quantum technology in South Africa.

Strengths

- We have a strong academic community, a vibrant research activity, a good coverage of the core capabilities in quantum computing and communication, and a large and engaged student body on which to draw. The experimental infrastructure is good (if not great) and we are able to attract good researchers from abroad.

- There are currently three SARChI Chairs and one NRF A-rated researcher working in the field.

- Although South Africa cannot yet boast any significant local industry dedicated to quantum information technologies (apart from IBM perhaps), there are many companies that could potentially play a role in this field. Many of these companies fall within the classification of small, micro, and medium sized enterprises (SMMEs).

- Through the support of the Department of Science and Innovation, South Africa has developed a strong National Integrated Cyber-Infrastructure System (NICIS) to support e-research. There are strong synergies between NICIS and Quantum Computing and Quantum Technology that can be exploited for mutual benefit.

- Infrastructure that is currently being developed for the support of nanotechnology in South Africa is also relevant to quantum technologies.

- NMISA has maintained National Metrology Standards for many years. These standards include those that are required for all aspects of the South African trade and industry, ranging from time, radiometry and photometry to chemistry for food and health, which could benefit from quantum information technologies.

Weaknesses

- Currently no quantum computing and technology industry.

- Lack of critical mass in all areas.

- No strategic funding sources in South Africa dedicated to the support of quantum technologies along the innovation chain, from research through development to commercialisation.

- Currently, there are no regulations or legislation directly relevant to quantum technology in South Africa. This may result in an unpreparedness when such technologies become widespread. As an example, quantum computing may pose a threat to cyber security in future, which implies that some regulations are required to safeguard information.

Opportunities

- The new quantum information technologies represent a “second quantum revolution,” which is considered to have a significant potential for economic growth. International market values and growth point to a large economic benefit, while, for example, home-grown quantum communication technology would be ideal for national security.

- There is a significant opportunity for the government to be the first blue-chip clients that adopt quantum computing and quantum communication technology.

- We have a very well established financial and financial services sector who will need quantum computing and quantum communication technology in the future.

- Synergies can be gained by co-ordinating and by combining the expertise and technologies presently developed in isolation to one another (the sum is greater than the parts)

- Collaboration with industrial global partners can be intensified, e.g. with IBM, Microsoft, Intel, Amazon.

- Excellent international links and strategic partnerships offer significant opportunities for advancement and access to knowledge and skills.

- Since there are currently no existing quantum companies in SA, there is a significant potential for local homegrown quantum technology. The lack of competition enables first mover advantage. There is the potential to develop products for the global market.

- There is the potential to develop quantum metrology for distinct South African problems, or in industries where South Africa is globally competitive, such as mining, industrial manufacturing, defence, and agriculture and food processing. It also applies for large science projects such as SKA.

- The South African government provides various incentive programmes to support technological development, for instance, the Technology Innovation Agency (TIA) and the Industrial Development Corporation (IDC).

Threats

- Overseas competition is fierce, and it is likely that the free flow of information in quantum communication and computing will dwindle as the technologies become essential. The economic environment is poor with more pressing national needs.

- The advent of quantum computing posed a serious threat to cyber security: "It is unclear when scalable quantum computers will be available. However, in the past year or so, researchers working on building a quantum computer have estimated that it is likely that a quantum computer capable of breaking 2000-bit RSA in a matter of hours could be built by 2030 for a budget of about a billion dollars. This is a serious long-term threat to the cryptosystems currently standardized by NIST." [4.3].

- South Africa has a serious shortage in skilled workforce. This shortage leads to a lack of critical mass that can ensure sustained growth.

- The South African economy is under severe pressure for various reasons. The result is an unfavourable environment in which to develop high technology.

- There are strong quantum groups at the NMI's of developed countries. As a part of such activity at NIST, they are developing integrated systems called NIST-on-a-chip, which would provide direct self-calibration.

4.8 Conclusions

Here the following conclusions can be made:

- The South African academic activity in quantum physics research goes back several decades.

- Recently, the academic research in quantum information science in South Africa became very active, with groups at different universities becoming involved.

- A new generation of young physicists are being trained in the field of quantum information science.

- There is little to no academic activity in quantum information science in other departments. The lack of academic activity in engineering can lead to a shortage of adequate engineering manpower to drive the commercialization of quantum information technologies.

- The governmental infrastructure to support the innovation chain for quantum information technologies is largely in place, but it needs to become involved in the development for a quantum information strategy for South Africa.

- Although there are currently no commercial companies that are directly involved in the development and commercialization of quantum information technology, the South African industry is diverse enough to have several companies that can potentially benefit by entering the quantum information technology market.

References to Chapter 4

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5. Flagship Projects

5.1 Quantum Computing Flagship

5.1.1 Introduction

The quantum computing flagship is about the application of quantum computing to the solution of problems relevant to the South African context. The Flagship does not aim at developing the hardware itself, but at leapfrogging the application and use of quantum computing as an additional tool in the high-performance computing toolbox. The access to state of the art quantum computing hardware provided by the WITS-IBM agreement was a catalyst for these activities. In future, the collaboration with the Centre for High Performance Computing (CHPC) will be crucial.

In a 5 to 10 years time frame we are still expecting to see the prevalence of NISQ (Noisy Intermediate Scale Quantum) computers and the establishment of special purpose quantum hardware for simulation of quantum systems or for the solution of targeted tasks. Also in this time frame we may expect the demonstration of a quantum advantage for a problem of real practical relevance [GESDA, 2020]. It is therefore very important to use this time to prepare for the applications that will run on a large scale universal quantum computer expected in the next decade.

The main drivers for the application of Quantum Computing have been discussed in Chapter 2.2.1. They have been identified as

- High-Tech Industry,
- Material Design and Drug Discovery,
- Financial Services,
- Transportation and Logistics.

The strategy of the flagship is based upon the following steps:

- Exploiting the current strengths of research in quantum computing in South Africa,
- Training the necessary human resources in academia and industry,
- Establishing the links with the local industries that might profit most from quantum computing,
- Generating niche areas of excellence.

The current strengths of the South African quantum computing community are in quantum machine learning and quantum simulation. Capacity in the simulation of quantum chemistry problems is being developed.

South African researchers were pioneers in the field of quantum machine learning and contributed with a monograph to consolidate the field, which has already been translated to Japanese. [Maria & Francesco book. Translated in Japanese]. South African trained students won quantum computing start-up competitions and set up companies operating in the field of quantum machine learning and drug discovery.

Many training initiatives have already prepared many students to the essentials of quantum computing programming. Some South African Universities already offer Quantum Computing courses at Honours level, aimed at Physics and Computer Science students. South African students are ambassadors of the IBM QISKIT programme.

These are all activities that need to be scaled up and coordinated at a national level, may be in a fashion similar to NASSP.

The flagship envisages to focus on three work-packages:

5.1.2 Quantum Machine Learning

Quantum Machine Learning (QML) is an emerging interdisciplinary area of research and application at the intersection of quantum information science and machine learning. QML aims at designing quantum algorithms to perform machine learning tasks. It is a well-known fact that classical machine learning algorithms can require vast amount of classical computing power. It is to be expected that some of these classical algorithms will run more efficiently on quantum computers, thus opening up new possibilities of application of machine learning.

Some of the areas that Quantum Machine Learning may disrupt are

- the discovery of new materials,
- the discovery of new drugs
- pattern recognition and classification,

and these are also the areas the flagship wants to pursue.

5.1.3 Quantum Chemistry and Quantum Finance

The quantum simulation of quantum systems is a natural area of application of quantum computing. One of the most promising uses is the simulation of quantum chemistry. Several successful algorithms have been proposed and applied with great effect to the solution of important problems of quantum chemistry, such as the electronic structure of molecules. For example, Variational Quantum Eigensolver (VQE) algorithms on NISQ Computers have been successfully applied to the approximation of the ground state of physical systems.

Another area of great interest for the application of quantum simulation techniques is finance. Quantum computing algorithms for the pricing of financial derivatives have already been demonstrated to be superior to classical ones.

The aim of this work package is to start a constructive interaction with the local chemical and financial industry and start developing applications of interest to provide them with the necessary competitive edge.

5.1.4 Quantum Verification and Validation

Quantum V&V is a recent but fast developing and essential branch of quantum technology. It offers new methods that require little quantum computational power to verify efficient quantum algorithms running on quantum computers.

Because of the complexity of quantum systems, quantum technology requires for its development V&V. Moreover, especially the information security of cryptographic applications of quantum technology, such as quantum key distribution and blind quantum computing, has to be certified independently from the producer. Since quantum computers solve problems with solutions that cannot be easily checked on a classical computer, V&V is here of particular importance. QT will thus automatically produce a market for its newly developing branch of verification and validation of quantum devices and their parts.

This is a niche area in which South Africa could establish itself.

5.1.5 The resources needed

To realise the above, we suggest the following interventions specific to quantum computing:

1. Strengthen the existing community through the renewal of the existing chair at UKZN and the establishment of a new Chair.
2. Address critical mass, succession planning and redress through the creation of at least two new young emerging research chair;
3. Funding for the access to quantum computing facilities;
4. Government interventions in the form of local economic clusters, legislation with respect to the transition to and adoption of quantum technology, and need for validation.

5.1.6 The outputs and outcomes

- The beginnings of a distributed national quantum computing network
- A workforce trained in software development and applications of quantum computing
- A healthy research base consisting of senior and junior academics, collaborating on joint projects/goals and commercial opportunities
- A local quantum computing cluster to facilitate wide-spread engagement through networking events with academia, industry, national institutes and programmes, venture capital funders and government instrument co-ordinators;
- An emerging national quantum industry with international business potential
- A minimum of 20 high-level journal papers per year
- A minimum of 10 graduated students per year
- A minimum of 4 spin-out entities, license agreements or industry contracts collaborations every 3 years
- New legislation with a focus on the importance of quantum-based technologies for national security

5.2 Quantum Communication Flagship: Building the (South) African node of the global quantum internet

5.2.1 Introduction

The national and international perspective, as well as the SWOT analysis, has highlighted both the challenge and the potential for quantum communication. The challenge is to enter the race in an optimal manner, pooling resources and technologies and acting strategically. Only integration of our collective expertise will allow us to fast track the local development and deployment of quantum communication technologies. The potential is that we have all the sub-components under development (at various TRL stages), we have a large industry that could be users of quantum technology, and we have a large student body that could become a quantum workforce.

To realise this potential, we propose the establishment of a flagship in quantum communication with a focus on information security, particularly in transmission. This flagship project will be delivered through work packages covering devices, protocols, hardware & software, integrated classical and quantum technologies, with deployment in fibre, last-mile free-space links, and ground to satellite links. It will serve to integrate presently disparate activities, create critical mass in quantum communication, and drive science through to technology, allowing for faster uptake by commercial partners.

For a modest investment, the programme will produce a trained quantum workforce and prototype technologies for secure quantum communication, which we will use to move towards a national quantum network between the key quantum centres and partners (e.g., HEIs, NMISA, CSIR, HartRAO, SANSA) and stakeholder entities (banks, financial houses, government departments, defence & security, etc.), deploying quantum protocols ("software") and associated "hardware" across existing and new infrastructure. The emphasis will be on holistic technology development and deployment, bringing together disparate activities in single photon sources, detectors, random number generation, teleportation, as well as classical communication protocols and security, all to achieve a common goal. This leap from science to deployed technologies will accelerate uptake and commercialisation of quantum-inspired communication systems in South Africa, and later Africa, with initial emphasis to be placed on the banking and defence sectors in South Africa. The deployment will incorporate intra-city fibre links in the short term for commercial testing and development of South African hardware, with the potential to tap into the national dark fibre network for inter-city connections in the medium term. Free-space "wireless" links will be deployed across extended distances for building-to-building connectivity, as well as from ground to satellite to join the global quantum internet project with an African node.

We have the potential to leapfrog the long development time by leveraging on our excellent BRICS contacts to fast track our satellite quantum readiness with advanced Chinese technology, while our long history and expertise at HartRAO of satellite tracking and ranging will see us advance quickly to become an established node for the southern hemisphere. We have an extended green-fields fibre network second to none, while the free-space short range technology is based on a locally developed platform with decades of development and already commercialised in the classical regime. These are all key position points that should see us advance quickly. Finally, we envisage that the flagship will have a legislative and validation component to it, to elevate quantum-based security to a national priority. What it will take is government commitment, financial and human capital resources, and astute technical leadership to guide the community to a common goal.

5.2.2 The players

The flagship will bring together a community that includes quantum activities at UKZN, CPUT, SU, Wits, NMISA, CSIR, UZulu and UP, with classical communication activities at NMU. Deployment partners would include SANSA for satellite deployment of quantum technology, HartRAO for satellite tracking and ranging, and NMISA for device certification and testing. The flagship will seek to secure stakeholders from the financial, government and defence spheres. Further, there are a number of commercial entities who operate in the communications and security sectors who could be roll-out partners for new quantum communications technologies, including Etion (www.etion.co.za), Sentech (www.sentech.co.za), Nanoteq (www.nanoteq.com), while device fabrication partners might include Insiava (a UP spin-off) and deployment partners in RF Optix (rfoptix.co.za) and Dotnetix (www.dotnetix.ai). Therefore, all the ingredients exist to create a vibrant community, including an industry, based on quantum communication.

The flagship would also seek to engage beyond the development and deployment of technologies and include legislation and validation of the technology. Here, various spheres of local and national government will be engaged by the flagship leadership on topics such as promulgating laws on the transition to quantum-based security in the future, legislation on the integration of foreign quantum technologies with regards to national security given the strategic nature of the topic, validation of the technology to be deployed, and the rapid growth of an industry through local technology clusters. Thus, important indirect players in the flagship will include the DSI, the dti, the SSA, the CSIR, NMISA, amongst others.

5.2.3 The technology

Existing South Africa technology development projects related to quantum communication include (1) a hybrid classical-quantum free-space communication solution (Wits patent), based on Wits technology on a Parsec platform, which could be deployed commercially within a few years, (2) On-chip quantum random number generator device, based on proof-of-principle demonstration in 2017 at UKZN, which could be commercialised, (3) Single-photon source using nitrogen vacancy centre, based on proof-of-principle demonstration in 2020 at SU, which could be commercialised, (4) currently under development at CPUT are locally developed single photon detectors, (5) possible future detectors based on quantum dots at UZulu, and (6) a quantum fingerprint authentication device jointly under development at Wits, UKZN and NMISA

Further down the pipeline are advances to address the pressing quantum communication issues of the day: how fast, how far and how integrated. These are primarily based on high-dimensional states for a larger information capacity per photon (faster), mitigation schemes for addressing errors when propagating long distances (farther) and on-chip plasmonic devices for better integration. There is a wealth of local classical communications technology available which remains disconnected to its quantum counterpart.

There is the possibility to assimilate Chinese satellite QKD technology that could be used to connect to the growing international satellite links. This, together with SANSA interest in developing satellite technology and HartRAO as an established tracking and ranging station could see South Africa become an important node in the global quantum internet, with concomitant financial benefits.

5.2.4 The resources needed

To realise this, we suggest the following interventions specific to quantum communication:

1. Strengthen the existing community through new research chairs and the renewal of the existing two chairs;
2. Address critical mass, succession planning and redress through the creation of new young emerging research chairs;
3. Running and capital funding to building the infrastructure;
4. Government interventions in the form of local economic clusters, legislation with respect to the transition to and adoption of quantum technology, and need for validation.

5.2.5 The outputs and outcomes

- The beginnings of a national quantum communication network infrastructure with nodes at Johannesburg, Durban, Cape Town and Port Elizabeth
- A QKD satellite ranging station
- A workforce trained in quantum communication and optics
- A healthy research base consisting of senior and junior academics, collaborating on joint projects/goals and commercial opportunities
- Compact photonic devices for integration in quantum network nodes, including sources, detectors, repeaters, QRNGs etc.
- A local quantum communication cluster to facilitate wide-spread engagement through networking events with academia, industry, national institutes and programmes, venture capital funders and government instrument co-ordinators;
- An emerging national quantum industry with international business potential
- A minimum of 20 high-level journal papers per year

- A minimum of 10 graduated students per year
- A minimum of 4 provisional patents per year
- A minimum of 4 spin-out entities, license agreements or industry contracts collaborations every 3 years
- New legislation with a focus on the importance of quantum-based technologies for national security

5.2.6 The next step

This section of the document is a motivation for a flagship in quantum communication technology. A full proposal with work packages and participants will follow based on the available resources.

5.3 Quantum Metrology and Sensing Flagship: Quantum Imaging

5.3.1 Introduction

While Quantum Metrology and Sensing is considered to be the sector of the current Second Quantum Revolution where quantum technologies have been most successfully introduced into commercial products [5.1,5.2], the largest potential markets for sensing equipment are deemed to be those associated with quantum imaging application [5.1]. Quantum imaging is an interdisciplinary research field with diverse advantages over conventional imaging techniques. With the first proof-of-concept experiments being done more than 30 years ago, the field has achieved a level of maturity where practical demonstrations of enhanced imaging technology can start to emerge. The market for quantum imaging technology is estimated to range between 10 to 100 million EUR over the next 10 to 20 years [5.3].

There are different quantum imaging technologies. These technologies include: quantum ghost imaging, quantum illumination (quantum radar/lidar), quantum microscopy, and many more. The advantages of quantum physics in these imaging technologies take on three possible forms: Quantum physics allows imaging of objects using light that does not touch the object; it can improve the signal-to-noise ratio; and it can improve the resolution of the image. The different quantum imaging technologies emphasize different aspects of these advantages.

In South Africa, research in aspects of quantum imaging has been, and is being, conducted at different universities, including Wits, UKZN, UP, Stellenbosch and CPUT, with interest from UZulu. It is an active field of research in the country. Since quantum imaging has a strong relation to radiometry, photometry, and quantum metrology, which enables measurements to be more accurate than conventional techniques allow, it is an integral part of the activities at NMISA. As a result, NMISA has recently joined the national activity in quantum research to develop the necessary metrology standards for quantum technology.

The industrial sectors in South Africa that will benefit from quantum imaging technology include: health, military, forensics, agriculture, environment, and more. Many industrial facilities can benefit from imaging technologies that can improve resolution and can operate in noisy environments. Existing South African companies that may become interested to incorporate quantum imaging technologies in their product portfolio include: CapeRay (medical imaging), LifeQ (bio sensors) , Dotnetix (remote sensing), Astrofica, Denel Spaceteq, SCS Space, Simera (satellite based quantum sensors), HENSOLDT South Africa, SAAB Grintek (quantum sensors for military and security).

Vision: The vision of the Quantum Metrology and Sensing focus area is to establish quantum imaging technology in South Africa as a leading quantum industry, supplying quantum imaging devices to the local and international markets for applications in medical diagnostics, aerospace environmental sensing, and military surveillance. These products are to be of the highest quality and level of accuracy, complying with international standards. The local quantum industry would consist of established industrial partners, which have adapted quantum technologies into their existing portfolio of imaging and related products. It would also include new SMME's taking advantage of the fertile economic environment, established to develop quantum technologies, thereby creating a lucrative economic sector with enhanced employment opportunities.

5.3.2 Existing capability

The current situation in South Africa already contains the foundation for the development of quantum imaging as an commercial activity:

- Fundamental research in quantum imaging has been conducted by various groups at SA universities: Wits, UKZN, UP, Stellenbosch, CPUT, with interest from various emerging centres such as UZulu.
- Metrology standards in radiometry and photometry are maintained by NMISA. New metrology standards associated with quantum technologies, in particular those associated with quantum imaging, are being developed at NMISA. Due to its involvement with industry under the dti, NMISA is strategically positioned to enhance the transfer of quantum technology to the industry.
- Potential industrial partners with established market impact that may be interested in quantum imaging technology include those South African companies that are currently involved in military surveillance, medical diagnostics and remote sensing.

5.3.3 Objectives

The quantum imaging flagship project has the following objectives:

- Research in quantum imaging technologies at different university departments (physics, engineering, medical, etc.) in the country, with the intention to advance the technology to a high technology readiness level TRL.
- Develop intellectual property (IP) in quantum imaging for the South Africa context, with the help of the industrial and engineering sectors.
- Engage with the established industry to solicit interest in adaptation of quantum technology into their product portfolios.
- Develop national standards in quantum imagings to maintain quality products suitable for the export market.

- Create an ideal economic environment through government involvement (tax benefits, low interest loans, training programs, national facilities, etc.) for the establishment of SMME's in quantum imaging.

5.3.4 Outcomes

The following outcomes are expected for the quantum imaging flagship project:

- Development of South African IP in quantum imaging technologies.
- Increased employment opportunities due to the expansion of product portfolios at established companies and due to the establishment of new SMME's.
- Highly qualified human capital in the form of graduates from physics and engineering disciplines, and highly trained technical specialists.
- Revenue from export of imaging products and services to international markets.

References to Chapter 5

[5.1] Keith W. Crane, et al., "Assessment of the Future Economic Impact of Quantum Information Science", IDA SCIENCE & TECHNOLOGY
POLICY INSTITUTE, Washington, DC 20006-3602, USA (2017).

[5.2] Tom Hausken, et al., "OIDA QUANTUM PHOTONICS ROADMAP, Every photon counts," OSA Industry Development Associates, (2020).

[5.3] A roadmap for quantum technologies in the UK, Quantum Technologies Strategic Advisory Board, Innovate UK and the Engineering and
Physical Sciences Research Council (2015).

6. Conclusion and recommendations

6.1 Conclusions

In the national context, South Africa has active programmes in many aspects of quantum technology, from fundamental science through to the development and deployment of quantum technologies, and has a potential first-adopter market in the financial sectors and government. However, the lack of critical mass, lack of awareness of the benefits of quantum information technologies in the general public and the engineering sectors, and the lack of a strategic programme to bind the activities to a common goal is hindering the transition from quantum science to a quantum industry. In parallel, the rest of the world is actively engaging the second quantum revolution through strategic investment, with the hope of participating in the large industry sector that is sure to follow.

The national and international perspective, as well as the SWOT analysis, has highlighted both the challenge and the potential. The challenge is to enter the race in an optimal manner, pooling resources and technologies and acting strategically. Only integration of our collective expertise will allow us to fast track the local development and deployment of quantum information technologies. The potential is that we have:

- the expertise to develop quantum computing solutions for the local industry,
- demonstrated all the sub-components for prototype quantum communication and quantum sensing solutions,
- an innovative industry that could be users and producers of quantum technology,
- and a large student body that could become part of a quantum workforce and a pool of quantum entrepreneurs.

In view of the information provided and discussed above, the following general recommendations are made:

- focus our activity on three areas: quantum communication, quantum computing and quantum imaging (sensing),

- optimize and strengthen research and development in these three areas through strategic programmes, and in particular through research chairs,

- grow the quantum technology community through support for emerging quantum technology centres,

- inform and educate the stakeholders (public, government, industry, etc.) on the benefits of quantum technologies,

- facilitate the transition between academic research in quantum technology, on the one side, and industry ready solutions on the other side,

- establish a governing body to coordinate national activities across all sectors, from academic to industry.

The benefits of this will be:

- a diverse workforce trained in all aspects of quantum technologies,

- a healthy research base consisting of senior and junior academics in physics and engineering, collaborating on joint projects/goals and commercial opportunities,

- an innovation chain for quantum technologies linking academia and industry,

- a national industry where quantum technologies are developed and commercialized for local and international markets.

6.2 Recommendations

To achieve this we suggest the following specific interventions:

Recommendation 1: Education and training programmes
Curricula development and deployment at Honours and Masters level in quantum technology.

Dedicated curricula in quantum technology need to be developed by the community for the community. In line with the recent online learning experiences motivated by the Covid-19 crisis, one could think of a virtual programme inspired by the National Astrophysics and Space Science Programme (NASSP) model. An honours level curriculum in quantum technology could be shared by various universities, in disciplines ranging from physics, to engineering, and computer science. In addition, specialised programmes at Masters level can be introduced to accelerate the research training and address the needs of industry.

Recommendation 2: Stakeholder awareness campaign
An active awareness campaign to disseminate information on quantum technologies to key stakeholders, including the public, government and industry. A strong public engagement is necessary to familiarize the citizens and other stakeholders with the foundations and principles of Quantum Technology. Also, it will be crucial to inform the key stakeholders of the opportunities for economic development that Quantum Technology offers.

Without a significant effort to increase awareness of quantum technologies, the endeavour to develop such technologies in South Africa would have a lower chance for success. Here we propose to embark on an awareness campaign, specifically aimed at the public, government, industry and non-physics academic sectors, e.g., chemistry, computer science and engineering. This could be in the form of an active blog, webpage, other social media, position documents, guest lectures, workshops and special sessions at various conferences, possibly in partnership with other organisations, e.g., SAASTA.

Recommendation 3: Research chairs

Create critical mass in quantum technology research leadership across the country through senior and emerging research chairs.

We propose to strengthen the existing community through research chairs: two new senior chairs and the renewal of the existing three SARCHI chairs, and address critical mass, succession planning and redress through the creation of five new emerging research chairs. These should be distributed across the various national nodes as well as across the three focus areas. We recommend that the emerging chairs be paired with the senior chairs.

Recommendation 4: Governance and coordination

Establish a governance structure for national coordination, particularly of synergetic activities, and to drive legislative, standardisation and certification activities. The South African Quantum Technology Initiative (SA QuTI) will be a consortium of five Universities, three main centres (SU, UKZN, WITS) and two emerging centres (CPUT and UZulu), and the Centre of High Performance Computing (CHPC), as the provider of the quantum computing infrastructure. The QuTI will exploit synergies with the Converging Technologies Platform for the National System of Integration. Wits University will act as the main contracting site.

The SA Quantum Technology Initiative (SA QuTI) is envisaged as a collaborative research and development consortium comprising the expertise of the three pillars (quantum computing, quantum communication and quantum sensing) with the aim of

- supporting the development of local quantum technological capabilities in general,
- coordinate quantum technology projects to the benefit of South Africa,

- nurturing public-private partnerships between research communities to deliver intellectual property (IP) that can be commercialised.

The institution leading the consortium will be responsible to make the necessary contractual and financial arrangements on behalf of the consortium members. Of course, the Consortium members will make it their responsibility to include other Higher Education Institutions and National Research Facilities in the research and training programmes.

The pillar leaders will coordinate the activities of the three main hubs and engage closely with the Chairs and Flagship leaders. The Consortium may elect a spokesperson.

The Consortium will coordinate also the common training and engagement activities.

It is planned to formalize the loose community of quantum technology practitioners in the country into a Community of Practice and a national network of Associates to ensure the growth of the Initiative into a substantial and significant research and development community.

Furthermore, we propose the establishment of a national Steering Committee to direct the Consortium under the joint control of the DSI and the dti, including industry cluster bodies, representatives of the quantum technology pillars, and international experts. A particular emphasis of the Steering Committee should be to establish national and international collaborations, and seek synergies and coordinate these. The Steering Committee will also monitor the progress of the activities of the Consortium.

The Consortium will collaborate with other national stakeholders:

I. Theoretical and computational activities should exploit synergies with the existing activities of the National Institute for Theoretical Physics (National Institute for Theoretical and Computational Science) to avoid duplication,
II. Access to the Quantum Computing hardware/cloud should be placed on a sustainable basis through the Centre for High Performance Computing (CHPC).

The CHPC has the negotiating capability to secure the economically most advantageous access to quantum computing.

III. Legislative, certification and standardisation programmes should run in consultation with NMISA and the SABS.

Recommendation 5: Flagship programmes

Establish one flagship programme in each of the three focus areas, distributed across national nodes.

We recommend the establishment of one flagship programme per focus area: communication, computing and sensing, with details to be determined through submitted proposals. Each should be distributed across various nodes, have deliverable work packages, and bind the community towards a common technological goal. The programmes will serve to drive science through to technology, and allow for faster uptake by commercial partners.

Recommendation 6: Establish new emerging centres

Support new participants in quantum technologies with the aim of diversity in demographics, geographics, and in focus.

We propose to bring in new centres of quantum technology research, with an emphasis on previously disadvantaged institutions. This would be done through small seed funds to get activities started, followed later by an infrastructure expansion programme to establish a core activity. Once diversity in demographics and geographics is achieved, the programme can be used to fund diversity in focus, expanding on the initial three areas as the community and its needs mature.

Recommendation 7: Quantum technology seed fund

Support the establishment of a quantum industry through strategic and financial support for technology development and deployment

There will be a need to advance new IP rapidly toward commercialisation. It would include all the usual processes, from seed projects through to product development and finally commercial or strategic deployment. To this end, we recommend that TIA be used to support an emerging quantum industry, e.g., through a dedicated quantum desk and ring-fenced support.

Recommendation 8: Quantum technology legislation and validation
Provide a national context for a quantum enabled future through government interventions in the form of local economic clusters, legislation with respect to the transition to and adoption of quantum technology, and formalise the need for validation.

There will be a need to provide a national strategic context for quantum technologies, for example, when the time is right to legislate the need for quantum-enabled security in appropriate industry sectors. Further, the technology would need validation guidelines and standards, while the service providers, local and international, could be incentivised to develop such technologies through local economic clusters. To this end we recommend that the DSI engage with the necessary spheres of government to see through this national context.

Recommendation 9: Interface with the Converging Technology Platform
Engage with the Converging Technology platform and become one of the enabling emerging technology pillars.

Quantum technology will be integrated in the National System of Innovation. The Converging Technology Platform (CTP) has been initiated by the DSI, as the tool to increase the collaborative efforts between emerging technologies and maxime synergies and socio-economic impact. The Quantum Technology Consortium will engage with the CTP and become an essential player in the field of innovation.

6.3 Budgetary Impact

The above recommendations and interventions can be grouped, from a budgetary perspective, as follows:

Low budget items

1. Establishment of a governance structure
   This would have a clear mandate and be the voice of the community.

2. Public awareness campaign
   An active blog, webpage, other social media, and public lectures.

3. Quantum community awareness campaign
   An active blog, webpage, other social media, but more emphasis on guest lectures, workshops and special sessions in various conferences. Instruments such as SPIE/OSA travelling lecturer funds, SAASTA and KIC could be used here.

4. Stakeholder awareness campaign
   An active blog, webpage, other social media, but more emphasis on position documents and presentations that are outcome orientated.

5. Establishment of a national Honours-level course in quantum technologies
   This would be accredited and delivered as optional second semester modules by virtual presentations or visiting lecturers.

Medium budget items

6. Establishment of a quantum technologies bursary programme
   Hons, MSc and PhD scholarships per year across the country, drawn from the existing bursary programmes of the NRF and DSI.

7. Establishment of quantum certification & standards
   Begin the task of establishing certification and standards for quantum technologies: hardware, software and legislation.

8. Quantum Technology seed fund

To bring in new centres of quantum technology research, with an emphasis on previously disadvantaged institutions.

9. Quantum Technology development fund
   To rapidly advance existing IP to commercialisation; could be leveraged from TIA.

Large budget items

10. Establishment of senior research chairs
    Several senior research chairs across the main nodes, funded from the NRF SARCHI programme.

11. Establishment of emerging research chairs
    Several emerging research chairs across the main nodes, funded from the NRF SARCHI and nGAP programmes, with an emphasis on demographics, for succession planning.

12. New quantum flagship projects
    This would require a new funding scheme. One per focus area, with distributed work packages across multiple nodes to achieve a common goal that has both scientific and strategic or economic relevance.

13. Infrastructure expansion
    Bring emerging nodes to full maturity by an infrastructure spend using existing equipment instruments from the NRF.

Summary of budget estimate

A rough estimate of the budget for full implementation of the recommendations is presented in Table 6.1. Many line items could be funded from existing NRF, DSI and dti programmes.

Intervention	Quantity	Unit Price	Cost
Research Chairs	5	R2 500 000	R12 500 000 pa
Emerging Chairs	5	R1 500 000	R7 500 000 pa
Flagship running	3	R10 000 000	R30 000 000 pa
Seed fund	4	R250 000	R1 000 000 pa
Governance	1	R1 000 000	R1 000 000 pa
Bursaries	50	R100 000	R5 000 000 pa
Technology Fund	3	R1 000 000	R3 000 000 pa
Quantum Computing access fee	1	R4 000 000	R4 000 000 pa
Infrastructure	5	R1 500 000	R7 500 000
Education and Awareness	1	R100 000	R100 000

Table 6.1: Estimated budget to implement the recommendations.

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