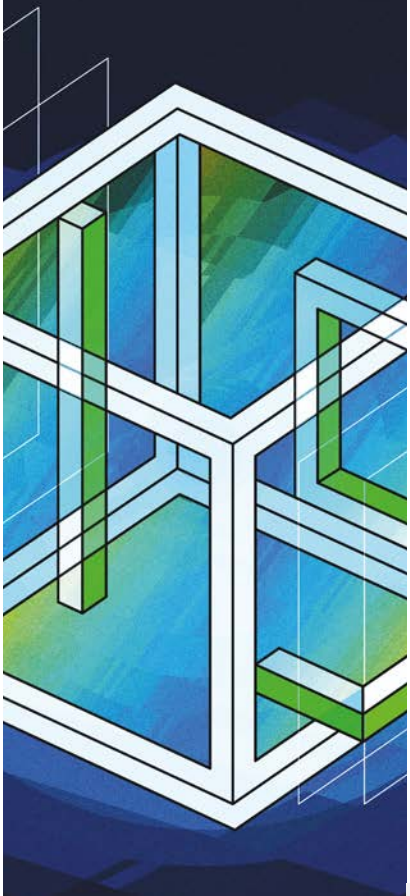
annual report 2022

Centre for Quantum Technologies

CONTENTS



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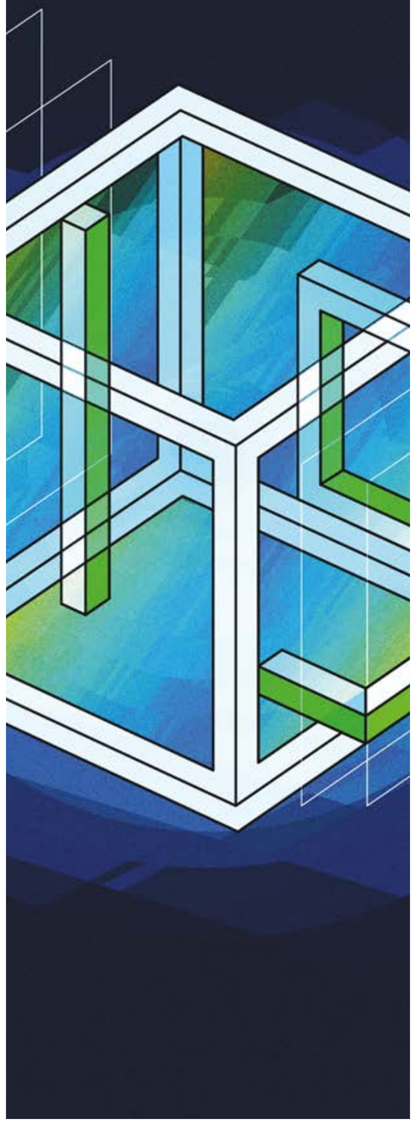
CQT AT A GLANCE



The Centre for Quantum Technologies (CQT) is a Research Centre of Excellence in Singapore. We bring together physicists, computer scientists and engineers to do basic research on quantum physics and to build devices based on quantum phenomena. Experts in this new discipline of quantum technologies are applying their discoveries in computing, communications, and sensing.

The Centre was established in December 2007 with support from Singapore's National Research Foundation and Ministry of Education. CQT is hosted by the National University of Singapore and also has staff at Nanyang Technological University, Singapore and the Agency for Science, Technology and Research.

DISCOVERY

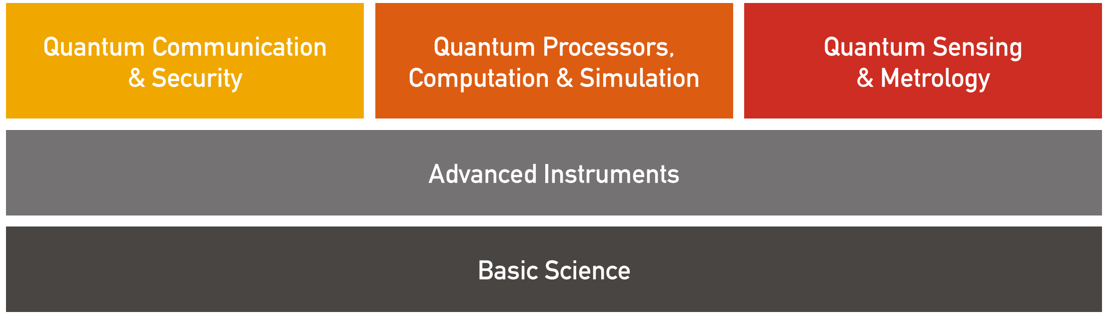
We pursue insight into the physics that describes light, matter, and information. We develop novel tools to study and control their interactions. Our research goals range from understanding the properties of materials to working out new encryption schemes.

TECHNOLOGY

We build technologies for secure communication, quantum computing, and precision measurement. We create our own software and control systems that push the boundaries of what's possible. We collaborate and consult with industry.

EDUCATION

We train people from undergraduates to postdoctoral fellows. Our quantum technologists are skilled in planning and problem-solving, with diverse skills such as coding, circuit design, and systems engineering. Our alumni have moved on to jobs in academia and industry.



Quantum Communication & Security

We have expertise in quantum key distribution and post-quantum cryptography for secure communication. We also explore quantum communication in networks, towards a quantum internet.

Quantum Processors, Computation & Simulation

The promise that quantum computers can tackle problems beyond the reach of today's most powerful supercomputers is driving research worldwide. We work on a broad array of research problems in quantum computing and simulation.

Quantum Sensing & Metrology

With exquisite control over single atoms and photons, we aim to build measurement tools of unprecedented precision for magnetic fields, gravity and time.

Advanced Instruments

To push the boundaries of technology, researchers in CQT labs design and build their own instruments, from electronic controllers to photon detectors.

Basic Science

We work not only on known applications of quantum technologies, but also on the unknowns, to deepen humanity's understanding of the behaviour of light, matter and the universe.

VIEW FROM THE DIRECTOR

Sometimes we need to take stock of where we are and how we got there, before we start the next stage of a journey. The Centre for Quantum Technologies is at such a moment.

In December 2022, CQT turned 15 years old. We had plenty to celebrate – not just our scientific achievements (2,596 papers and counting) and the people we've nurtured (including 100 PhD graduates and another 84 enrolled) – but the kindling of a quantum ecosystem in Singapore.

Like in other countries around the world, there is growing attention from industry sectors ranging from finance to defence. We applaud the quantum startups founded by our staff and alumni and the public-private partnerships forged in the national quantum platforms.

But it's a time of transition for us too. We have maxed out the lifetime allowed for a Research Centre of Excellence (RCE) under Singapore policies. When CQT was established in 2007, it was the first such RCE in the country, as well as being one of the first centres dedicated to quantum technologies in the world.

As an RCE, we have offered researchers a strong community, long-term funding and dedicated admin support. We encouraged our Principal Investigators to do basic science, as well as empowering them to do translation when it suited their work. We built an international reputation.

For CQT to continue on a successful trajectory, we want to keep these same ingredients. We now have a two-year bridging grant, and we're involved in shaping a national quantum strategy for Singapore that will set out plans for our future.

I did not witness the start of CQT, but I've heard stories. My predecessor Artur Ekert, who became CQT's Founding Director, came to Singapore in 2000 to speak about quantum computing at a Millennium Conference on Frontiers in Science.

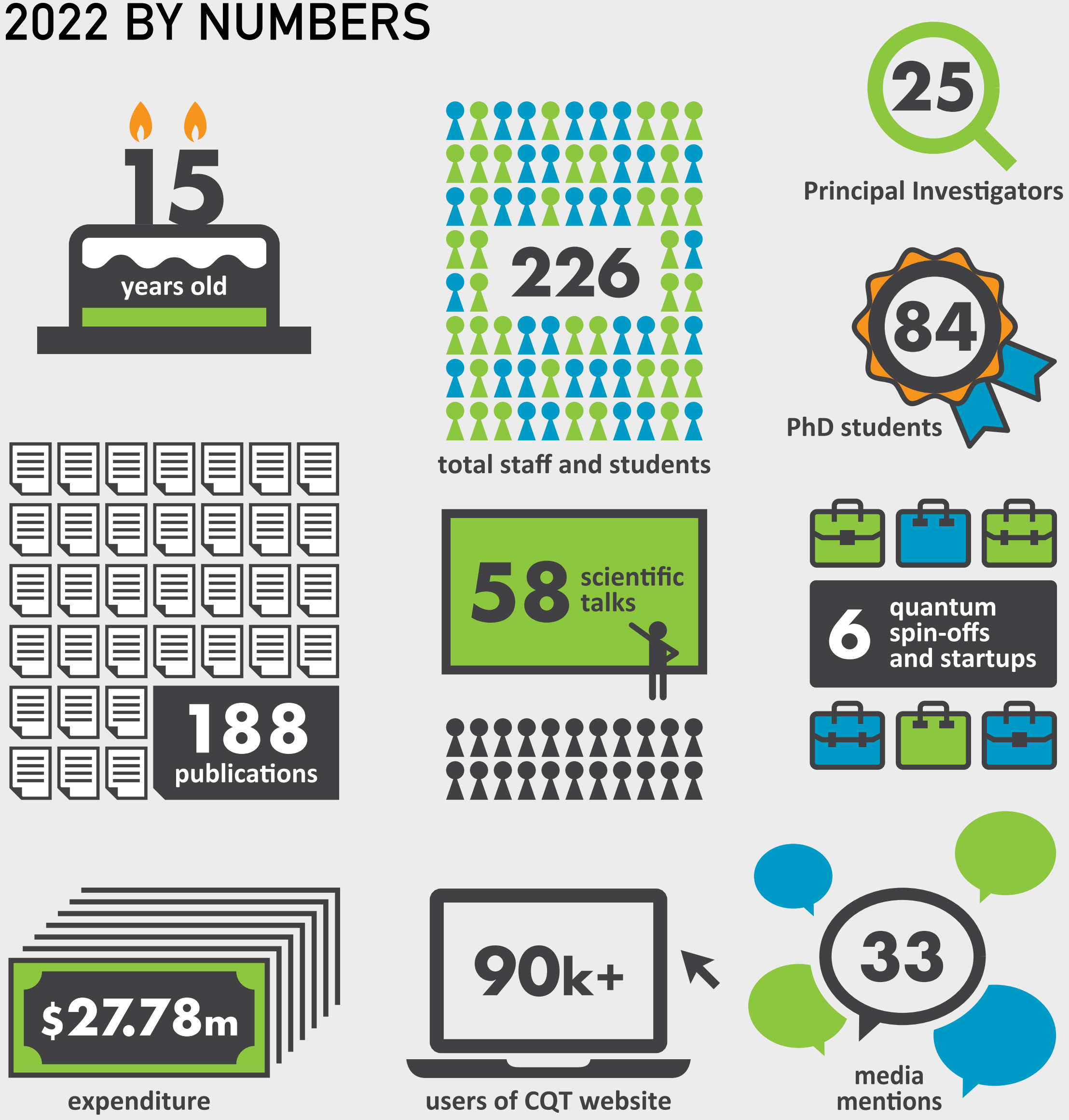
As he tells it, during that visit he enjoyed a long conversation with Tony Tan, who was then Singapore's Deputy Prime Minister and Minister for Defence (and would in future be Chairman of the National Research Foundation and then President of Singapore). He also got to know a small group of local theoretical physicists who were excited about quantum information.

Momentum built from there. Artur accepted a local professorship and joined forces with these physicists. They won a small grant that attracted more researchers. Then came the successful RCE application. The team crafted policies for this wholly new kind of centre, and the science got underway.

There are parallels for our circumstances now. We need a combination of top-down understanding and bottom-up enthusiasm to chart the next phase of CQT. I believe we have both. The path ahead will not always be smooth, but we are prepared and raring to go.

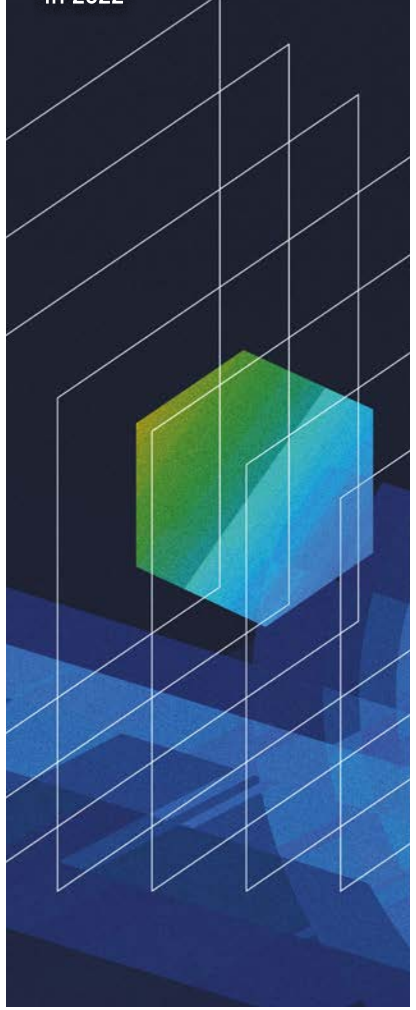
José Ignacio Latorre

2022 BY NUMBERS



OUR PROJECTS

Highlights of CQT's work in quantum technologies in 2022



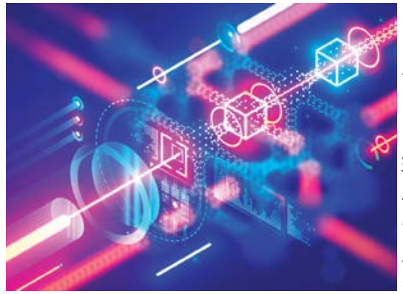
Omelchenko/Shutterstock.com

Algorithms for noisy quantum computers reviewed

The group of CQT's Kwek Leong Chuan teamed up with overseas collaborators to survey over 800 papers about algorithms for noisy, intermediate-scale quantum (NISQ) computing devices. The 14 co-authors distilled their work into a 91-page, comprehensive review.

The review provides a compilation of the available algorithms suited for the NISQ era and which could deliver results in the near-term. A major goal is to demonstrate quantum advantage for useful problems. In the review, the researchers write that advances on three fronts are necessary – hardware developments; designing algorithms to suit the device hardware and algorithms for error mitigation; and identifying applications suited for NISQ devices. CQT alumnus Kishor Bharti, who drove the work in Singapore, says, "This review is like an encyclopaedia for the NISQ era, a one-stop place for the work of many people."

Rev. Mod. Phys **94,** 015004 (2022)



Andrey Suslov/Shutterstock.com

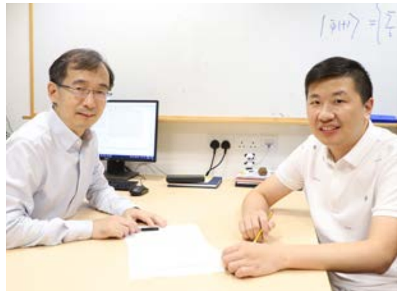
QKD goes device-independent

An international team including CQT's Charles Lim and Valerio Scarani were among three groups to implement device-independent quantum key distribution (DIQKD) in 2022, a form of QKD that is secure even if the users are not privy to the underlying quantum hardware. Charles, formerly a CQT PI, now works in the private sector.

The experiment used a new DIQKD protocol invented by the Singapore theoretical team. An extra set of key-generating measurements for users makes it more tolerant to noise and loss. The experimental team in Germany created high-quality entanglement via quantum swapping, where independent photons from photon-atom entangled pairs are transmitted over 700 metres of optical fibre and mixed in a joint measurement scheme. They carefully balanced entanglement quality, generation rate, and system noise. Charles' team performed security analysis to confirm the setup's DIQKD capability.

Nature **607,** 687 (2022)

SCIENCE UPDATES

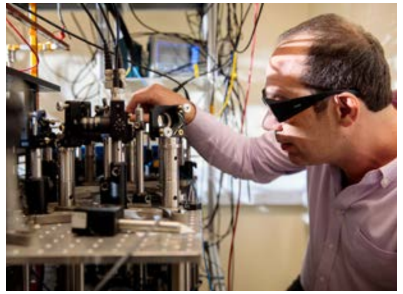


Quantum switches manipulate light emissions

Constructive or destructive interference can affect light emission from quantum emitters, leading to phenomena known as superradiance and subradiance. CQT's Gong Jiangbin and group member Qiao Lei found that making a photon interfere with its own emission process can amplify both effects: either superradiance becomes hyperradiance or is strongly suppressed to become a new form of subradiance. Besides developing physicists' fundamental understanding of spontaneous light emission, the effect could be useful in reading and storing quantum information.

A key point in the researchers' scheme is controlling when there is constructive or destructive interference. This depends on the relative phase of the photon as it self-interferes. The researchers propose one way to adjust this is with tunable 'switches' made from coupled superconducting resonators with transmon qubits.

Phys. Rev. Lett **129,** 093602 (2022)



Trembling signals from cold atoms

The group of CQT's David Wilkowski took a new step towards simulating high-energy physics, traditionally probed in the extreme conditions of a particle collider, on a tabletop. They measured an oscillation of ultracold atoms that falls into the category of a 'Zitterbewegung' effect, or relativistic trembling motion. This effect has never been observed in a real particle yet, but experiments have sought to simulate it with non-Abelian gauge fields.

"Non-Abelian gauge fields are interesting because they are fundamental in nature, and lead to different dynamical behaviour than their Abelian counterparts," says David. In their work, the researchers let ultracold strontium atoms move in a constant SU(2) non-Abelian gauge field. When the atoms were given a nudge, instead of moving along a straight line, the atoms oscillated because of the way the non-Abelian gauge field acts on the spin of the atoms.

Phys. Rev. Lett **129,** 130402 (2022)

Aki Honda

The emerging field of atomtronics

Atomtronics involves the manipulation of ultracold atoms to build circuits for devices. Ultracold atoms flow through guides made of laser light or magnetic fields, analogous to electrons zipping through conventional wires in electronic circuits. Atomtronic circuits can be harnessed for fundamental research, such as the study of quantum transport, and for applications such as quantum sensing, simulation and computing.

CQT's Kwek Leong Chuan and Luigi Amico and their collaborators provided a concise and up-to-date summary of the emerging field. "A pedagogical review is timely since there has been growing interest in this area coupled with beautiful experiments with atoms, both bosons and fermions, in toroidal optical traps," Kwek says. The review covers the state-of-the-art trapping technologies supporting atomtronic circuits, coherent effects, and atomtronic components and applications.

Rev. Mod. Phys **94,** 041001 (2022)

CQT charts new phase of growth

Renewed support for the Centre comes as Singapore plans for a national quantum strategy

On 7 December 2022, the Centre for Quantum Technologies celebrated its 15th anniversary and began a new phase of growth.

CQT was awarded a two-year bridging grant by the National Research Foundation (NRF), Singapore to support a transition towards a national centre with expanded roles and membership.

"Singapore is deeply invested in understanding and preparing for the transformative impact of quantum technologies. As one of the pioneers of research in quantum science in Singapore and ASEAN, CQT plays an important role in supporting the nation's ambitions in this area. The transition of the Centre of Quantum Technologies into a national-level platform is a testament to this, which will not only build on the vibrant innovation ecosystem, but also nurture and ensure a continuous pipeline of talent to support both academia and industry," said NRF's Marvin Lee, Director, Smart Nation & Digital Economy.

When CQT was established in 2007, it was Singapore's first Research Centre of Excellence (RCE). The RCE scheme was launched by NRF and the Ministry of Education to enable world-class investigator-led research aligned with the long-term strategic interests of Singapore (see box **How it began**).

RCEs are limited to 15-year terms, but quantum technologies have only grown in strategic importance since the Centre got started. Public and private investments in quantum computing, quantum communication and other quantum technologies have soared around the world.

In 2022, Singapore established a National Quantum Office (NQO) at the Agency for Science, Technology and Research (A*STAR) that will define a national quantum strategy for the country including a vision for CQT.

Research visions

"Through its first 15 years, the Centre for Quantum Technologies has been relentless in educating talent, built international connections, collaborated with industry and produced startups. The conditions are right to grow Singapore's quantum ecosystem, and we can do that from our deep roots in basic science," said CQT Director José Ignacio Latorre. He has been appointed to the National Quantum Steering Committee guiding the NQO.

CQT remains hosted at the National University of Singapore (NUS) while planning growth and taking national responsibilities. CQT is already involved in the three national platforms announced in 2022: the National Quantum-Safe Network, the National Quantum Computing Hub and the National Quantum Fabless Foundry (see pp.19–23).

> *"Singapore is deeply invested in understanding and preparing for the transformative impact of quantum technologies."*

Growth will include a search for new Principal Investigators (PIs) and the appointment of CQT Fellows. CQT currently has twenty-five PIs including seventeen co-appointed with NUS, four with the Nanyang Technological University, Singapore, and two with A*STAR. Four of these PIs joined CQT in 2022 (see pp.14–16). The Centre aims to admit 20 to 30 PhD students per year.

The Centre also announced some leadership changes in 2022. In September, CQT PI Valerio Scarani was promoted to Deputy Director following the retirement of the former position-holder, Lai Choy Heng, who is now an NUS Emeritus Professor (see p.12). Under the new bridging grant, the Centre's independent Governing Board (GB) was reformed. See the box **Steering Singapore's quantum ecosystem** for views from the board's new Chair.

How it began

The topic of "Quantum Information Science and Technology" was announced as the focus for Singapore's first Research Centre of Excellence (RCE) at a press conference on 2 May 2007. Reporting on the news, Singapore's *The Straits Times* quoted CQT Founding Director Artur Ekert as saying the Centre "would create a culture of basic science and make things happen". RCEs were intended to spur research excellence in the local universities. CQT was the first of six to be established.

Dr Tony Tan Keng Yam, President of Singapore from 2011 to 2017, was then Chairman of the National Research Foundation. The same news article from 2007 reports him saying the RCE "represents a shift from establishing an industry based on what other people discover, to preparing ourselves to be in the forefront of an industry which will be developed in around 10 years".

Pictured is the kick-off event for the RCE on 7 December 2007. A student contest to design the Centre's logo gave rise to the identity still used today.

Steering Singapore's quantum ecosystem

CQT welcomed Low Teck Seng as Chair of CQT's Governing Board (see p.28) in December 2022. He took over from Quek Gim Pew, Senior R&D consultant to MINDEF, who was Chair since November 2016. The two experienced leaders co-chair the National Quantum Steering Committee.

Formerly Chief Executive Officer of Singapore's National Research Foundation (NRF) from 2012 to 2022, Teck Seng is now Professor and Senior Vice President (Sustainability & Resilience) at the National University of Singapore (NUS). This Q&A with him is abbreviated from a longer interview published at quantumlah.org.

How do we take quantum in Singapore to the next bound?
Globally, a lot of money is being poured into quantum. Singapore will need to have a strategic approach in using the limited resources we have to enable us to compete. We see the opportunity to move CQT to a national entity, coordinating and facilitating the growth of the quantum science and technology knowledge ecosystem. I see it as the only way forward. Once we have this in place, we can build partnerships with the many different groups that we need to work with to support our quantum ambitions.

You are also co-chairing the National Quantum Steering Committee with a national quantum strategy in the works.
CQT is a very important piece of the national quantum strategy. At the national level, we see the basic science that needs to be done and continue to be funded. This will continuously give new things for us to build on in a pathway to translation. Other important pieces are the development of the national platforms and a strategy to develop industry. Without an industry receptacle for our best science, our national resources will not accrue benefits to Singapore. All this in totality will be driven by the National Quantum Steering Committee that is supported by the National Quantum Office.

What would be some outcomes of a successful strategy?
For me, there are three key outcomes that will show some measure of success. One obvious initial outcome is the continued vitality of our research ecosystem which can be measured by publications for example. That is a proxy measure to ensure that we're competitive with the best research groups in the world.

The next is the vibrancy and effectiveness of our translation. For example, a lot of our basic science in quantum key distribution has been translated into a company like SpeQtral and corporate work in the NUS-Singtel Cyber Security R&D Lab.

Lastly, how has the quantum industry developed? It is measured by how many big quantum companies come to Singapore and invest here; how many foreign quantum startups see the vitality of our ecosystem, come here and develop their businesses from Singapore; how many companies our universities and CQT are working with; and how many startups there are.

All these are quantitative and qualitative proof. You can count the number of companies, but the qualitative aspect is the vitality of these companies and the breadth of things that they do with our research ecosystem.

The quantum ecosystem is still nascent now.
Quantum is still very nascent, but we have all the necessary pieces here and we need to capitalise on that. With nascent areas, Singapore can be in the leading pack. In the past – in microelectronics, magnetics, chemicals – we always started from behind the curve, but we learnt fast.

RESEARCH IN FOCUS

NUS

Meet the Deputy Director

A Principal Investigator at CQT since 2007, Valerio Scarani stepped up to serve as the Centre's Deputy Director from September 2022

"After benefitting so long from the structure of CQT and the environment, I'm happy to be able to serve and maybe to contribute to the future of CQT that is being designed right now," said Valerio Scarani on his appointment as the Centre's Deputy Director.

Valerio is one of the Centre's pioneering PIs – arriving in Singapore just as the decision to set up CQT as Singapore's first Research Centre of Excellence was announced. He takes the leadership role on top of his responsibilities as a CQT PI and Professor in the NUS Department of Physics. He was also previously Deputy Head for the Department of Physics.

He succeeds founding Deputy Director Lai Choy Heng, who is now an Emeritus Professor in NUS. Choy Heng had played a key role in kindling interest in quantum information in Singapore from the late 90s, starting from a small journal club group that met Friday evenings to talk about physics.

When the changes were announced, CQT Director José Ignacio Latorre said: "I greatly benefited from Choy Heng's experience and wisdom after I moved to Singapore to head CQT in 2020. On behalf of generations of CQTians, I thank him for his long service to the Centre. I now look forward to Valerio's advice and support in leading CQT at this important time, when quantum technologies are soaring around the planet. CQT must strive for continued scientific excellence."

Valerio shares some of his perspectives on the Centre's future and life beyond research in the interview that follows.

What did you expect when you first arrived in Singapore?

I was supposed to come to the "Quantum group" of the physics department. Pretty much when I landed in Singapore from Europe, I was told that this big grant had been accepted. It was a bit surprising for everybody. At the time it was not called CQT of course. That name came later and was duly serious, though some of us had proposed more playful ones. My name suggestion was Qurian, like durian, and the logo would have been a 'Q' with the two yellow fruit inside.

Photo: In October 2022, CQT Deputy Director Valerio Scarani (left) hosted a visit by Emeritus Senior Minister Goh Chok Tong (centre), former Prime Minister of Singapore, together with NUS President Tan Eng Chye (right). At the end of the visit, Valerio presented ESM Goh with a copy of the introductory quantum textbook he co-authored with two NUS High School students.

How do you feel about becoming Deputy Director?

When I was Deputy Head for Education in the Physics Department, from 2017 to 2020, I mostly took care of curriculum matters. The part that I enjoyed was being at the service of students and sometimes of my colleagues who needed help with the logistic of teaching and exams. For my new role, I think the main task is really to make CQT a thriving place and keep it as such, to support the Director's efforts. From our discussions, the scientific direction of the Centre is a primary concern.

What are the goals for CQT's scientific direction?

Fifteen years ago, when we started CQT, we were one of the first centres for quantum technologies. Although the word 'technology' was already there, it was clear that our task was to be a bit visionary, to see what can be done with these new tools.

Now, in the last few years, something amazing has happened. Tasks that were then just done by a couple of postdocs and some PIs in a university are now taken up by whole companies. We've come out of the pandemic, and some things that used to belong to academia don't belong here anymore.

To make a comparison: the engines of Formula One cars are certainly thermodynamics, but you don't expect the physics or engineering department in a university to develop them. Very specialised, dedicated teams of engineers are optimising these objects. Quantum computers are not yet there, but some sectors of the field are already at that level. This is a sign of the maturity of the field.

With this preamble, I think that CQT should not become a car manufacturer: it should remain a physics and mathematics and computer science environment, stay academic. Our task is to keep finding what may become technology in 10 or 15 years.

What are you excited about in your own research at the moment?

One of the most promising directions is a new idea to certify the quantumness of physical systems based on their dynamics. Now, the idea is clearly new and there is science to be discovered. We are also exploring the links between logic and thermodynamics, treating physical irreversibility in the same way as one treats the impossibility of recovering all information from the past.

> "Our task is to keep finding what may become technology in 10 or 15 years."

Then there are singular projects. I am excited about one on simulating quantum correlations with bounded communication. One of my students, using machine learning, intuited a major result that was not known before. Unfortunately, so far, we have not yet been able to extract any analytical proof from those data. Meanwhile, some people in Vienna have an analytical proof of part of the parameter regime. We have not given up the hope to be the first to solve the problem in full.

Do you have any favourite memories from the early days at CQT?

We had this exciting work that led to a National Science Award for a few of us, and I was building up little by little my group. There are many nice memories. When the number of people was small, many of us would go for dinner every Friday. We played football every week – one of my latest successes is that we are doing it again.

What about other interests?

I do some formation and charity work in the context of a Catholic group. My religion connects to my work in the sense that I'm trying, with many failures, to work as a Catholic should work – to respect people, be serious in my work and try to work well.

RESEARCH IN FOCUS

New arrivals

CQT welcomed four new Principal Investigators in July 2022. They will lead groups working across the Centre's research areas of quantum processors, computation and simulation, quantum communication and security, quantum sensing and metrology, advanced instruments and basic science.

Gong Jiangbin

Jiangbin is a theorist who brings to CQT a wealth of experience in quantum dynamics. He is also Provost's Chair Professor and Head of Department at the NUS Department of Physics, where he has researched a variety of topics including quantum dynamics control, quantum simulation, topological phases of matter, quantum thermodynamics and quantum chaos.

Jiangbin was drawn to quantum during his PhD at the University of Toronto in theoretical chemical physics, which considered how to use quantum effects to control chemical reaction dynamics or molecular dynamics. He became interested in puzzles such as why the evolution of quantum systems could be described by classical physics even when quantum physics says properties of the underlying system are undefined until measurement. "It is a fundamental question asking at which point does classical reality emerge from the quantum world," he says.

Some of his group's work has applications in mind. For example, topological phases of matter can offer quantum states useful for encoding quantum information in a robust way. "In topological lattices, there are some states localised at the edge of the material, for example an array of cold atoms, that are very robust. We say they are 'protected by topology'," explains Jiangbin. But he appreciates the support for basic science in CQT: "I think it's very important to have the freedom to do research where we are not bounded by too specific goals…We hope that by freely exploring, you can get something you did not expect, which could be highly original and have a lasting value."

Patrick Rebentrost

Patrick's research interests are in quantum computing, quantum algorithms, quantum machine learning, learning theory, and mathematical finance. He was promoted to Principal Investigator and Research Assistant Professor from the position of CQT Senior Research Fellow.

Before he joined CQT in 2018, Patrick was keeping an eye on the Centre. "I had already heard about CQT around the time it was founded, and it was always a place I was considering to be at," he recalls. Now he is one of the Centre's five PIs in computer science, who run a collective group with regular meetings and seminars.

Patrick first ventured into research on quantum computing for machine learning during a postdoc with Seth Lloyd at the Massachusetts Institute of Technology in the US. He divides his current research across three pillars:

(i) on fault-tolerant quantum computing, looking at optimisation, machine learning and algorithmic building blocks;
(ii) on noisy intermediate-scale quantum computing (NISQ), on what he calls "post-variational" algorithms and
(iii) quantum information-related topics, especially machine learning for quantum states and quantum extensions of finance.

"While I think that the most immediate application of quantum computing would be in the simulation of quantum systems such as molecules, we are also thinking about how quantum computing can or cannot be used in finance," says Patrick.

> *"Finance uses a lot of computational resources. Every little speed up can make a big difference for risk management, pricing derivatives or portfolio optimisation."*

"Finance uses a lot of computational resources. Every little speed up can make a big difference for risk management, pricing derivatives or portfolio optimisation." Patrick leads a grant from the Quantum Engineering Programme on "Computer science approaches to quantum computing for finance."

Patrick's hobbies include travel and playing chess.

Steven Touzard

Steven is building a new experimental group at CQT working on quantum network technologies. He shares an appointment as a Presidential Young Professor at the NUS Department of Physics and Department of Materials Science and Engineering.

Formerly a CQT Research Fellow, he received a Fellowship from the National Research Foundation, class of 2022, for research on "Building quantum networks of superconducting circuits mediated by telecom photons". He was also named to the 2022 list of MIT Technology Review's "Innovators under 35" for the Asia-Pacific region (see p.31).

"A lot of time when we think of quantum technologies, we divide them into quantum computation, quantum communication and quantum sensing. Quantum networks is at the interface of these three pillars. Essentially, the idea is to remotely entangle quantum processors, such as small quantum computers, to one another. But it is something that is extremely hard to do because you need to be able to send quantum signals over long distances," explains Steven. Renovation of his group's experimental space at CQT was completed in 2022. He expects the team to complete their setup in 2023 and be set to achieve innovative results in 2024.

Steven is balancing work with being a new father. "That it is common in Singapore to have help with childcare is something positive because otherwise a parent, usually the mother, would have to put their career on hold. My wife, who is also a professor, and I are really grateful for the help."

Gao Weibo

Weibo has expertise in quantum photonics and quantum materials. At the Nanyang Technological University, Singapore, where he is Associate Professor and Provost's Chair Professor in Physics, Weibo has established an experimental group working on two-dimensional materials, quantum information and quantum optics based on solid state systems.

Weibo made his start in physics as an undergraduate at the University of Science and Technology of China (USTC), then joined the lab of Professor Jianwei Pan at USTC as a PhD student. There he contributed to leading experiments in the world such as creating a six-photon entangled state and demonstrating topological error correction.

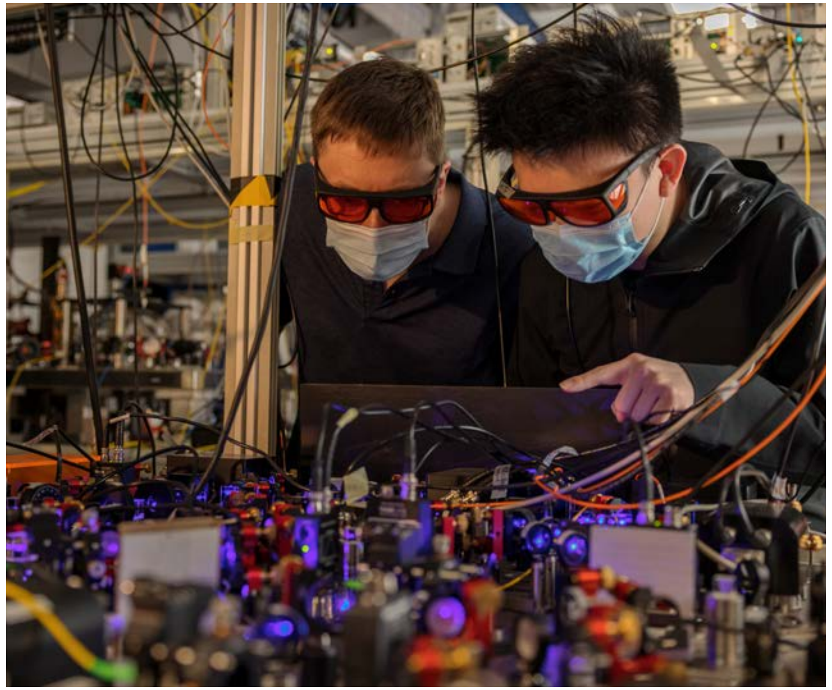
His favourite types of research involve both new techniques and new physics. "Science and technology are both important, but if you combine them into one piece of work, there will be some beautiful improvement," says Weibo.

He leads two projects launched since 2021 under the Quantum Engineering Programme, which supports translational research in Singapore. The first project "Island-wide quantum key distribution using electrically driven single photon emitters" aims to develop a true single-photon source to replace attenuated lasers in quantum communication tasks.

The second project "Quantum sensing for health science based on NV centers in diamond" will advance this kind of sensor technology, which is already seeing commercial investment. "They can do fantastic things, for example, detect single molecules or proteins. We hope they can eventually detect a single viral particle," says Weibo.

Outside of work, Weibo enjoys playing basketball to relax.

> *"Science and technology are both important, but if you combine them into one piece of work, there will be some beautiful improvement."*



Newcomer among ultracold atoms

Indium debuts for quantum research in pioneering work at CQT

Ultracold atomic physics has regular haunts in the periodic table. Most labs use either atoms with one or two valence electrons, known as Group I and II, or dipolar atoms. These all have distinct experimental capabilities. The group of CQT Principal Investigator Travis Nicholson entered new territory in 2022, becoming the first to trap and cool indium atoms, which sit in Group III. Group III atoms are new to ultracold physics and have many novel research prospects.

"This is just the beginning – just demonstrating that indium can be trapped and cooled shows that it is a viable species for ultracold research," said Travis after his paper was published as a Letter and Editors' Suggestion in *Physical Review A* in June[1]. The paper was also featured as a research highlight in *Nature*. "We have seen an extraordinarily positive reaction to our work," said Travis.

Travis worked on the project with PhD students Yu Xianquan, Mo Jinchao and Lu Tiangao, and former Research Assistant Tan Ting You.

When cooled to ultracold temperatures, atoms can act as building blocks for technologies such as quantum simulators, quantum processors and atomic clocks. Most ultracold atomic research has been done with Group I atoms, such as lithium and rubidium, also called alkalis, or Group II atoms, such as calcium and strontium, also called alkaline earths (see box **The atoms of CQT**)

Indium, with atomic number 49, is in the main Group III of the periodic table. Like the alkali atoms, Group III atoms are expected to have magnetic Feshbach resonances. This property allows researchers to tune interactions between the particles with a magnetic field, giving precise control over quantum many-body states. Like the alkaline earths, the Group III atoms are expected to have 'clock transitions'. Clock transitions are used in highly accurate atomic clocks and can

Photo: CQT's Travis Nicholson (left) leads the team including CQT PhD student Mo Jinchao (right) that has built the world's first ultracold atoms setup for the element indium.

[1] X. Yu *et al*, Magneto-optical trapping of a group-III atom, *Physical Review A* **105,** L061101 (2022)

act as precise probes of an atom's internal states and interactions. Having these two properties means that Group III atoms can be probed with the precision of an atomic clock while offering the many-body control of alkalis.

To build the project from scratch took the group about three years. "Since indium is part of a new group of atoms, we had to investigate many things ourselves," says Xianquan, who is first author of the paper. "Standard cooling techniques for Group III atoms have not been developed yet."

A magneto-optical trap (MOT) uses lasers to trap and cool atoms to millikelvin temperatures, approaching absolute zero at -273.15°C. The technique uses a 'cooling transition', an atomic transition between two internal energy states of the atom. Group I and II atoms have a cooling transition out of their ground state – the most stable state where atoms spend most of their time. For indium, there is no workable cooling transition to the ground state. The group identified a suitable transition to a 'metastable' state instead.

After optimising parameters, the group achieved a magneto-optical trap with 5 × 10^8 indium atoms, competitive with traps for alkali and alkaline earth atoms, with temperatures of order 1 mK. The group's techniques could also apply to other Group III atoms. "It is exciting to be working on a new particle like this," says Travis. "Every small thing – every state, interaction, transition – has never been really talked about before in the context of ultracold science. We are still learning about the possibilities."

The atoms of CQT

For many quantum experimentalists, atoms are a tool of their trade. They may use atoms to store quantum bits of information, simulate materials, or act as precise sensors. Some groups make ultracold clouds of atoms, others arrange atoms precisely in lattices, and some tear off electrons to make ions which can be trapped by their charge. Typically, the work involves using lasers, electric fields and magnetic fields to manoeuvre the atoms and control their energy levels. Which element a team chooses depends mostly on the structure of the atom's energy levels and available lasers. These are some of the isotopes employed in CQT, ordered by their atomic number.

Isotope	Description
6 Li 3 Lithium-6	Cooled together with two other atomic species to make ultracold molecules and in lattices for quantum simulations
23 Na 11 Sodium-23	Trapped with optical tweezers in a lab that will use arrays of cold atoms for quantum simulation and computation
40 K 19 Potassium-40	Paired with lithium (see above) to make LiK molecules to study the physics of quantum many-body systems
87 Rb 37 Rubidium-87	A popular choice, used in various groups for experiments from shaping photons to measuring gravity
87 Sr 38 Strontium-87	One of the two labs using ultracold Sr is simulating high-energy physics (see **Trembling signals from cold atoms**, p.7)
115 In 49 Indium-115	Trapped and cooled for the first time at CQT. Read the main article (**Newcomer among ultracold atoms**, pp.17–18)
133 Cs 55 Caesium-133	A joint project with the Centre for Disruptive Photonic Technologies at NTU aims to trap caesium atoms in subwavelength optical tweezers for quantum information applications
138 Ba 56 Barium-138	Trapped as ions for quantum information processing and searching for dark matter interactions
171 Yb 70 Ytterbium-171	Used in one lab to make a five-ion quantum processor operating with qubits and continuous variable quantum states
176 Lu 71 Lutetium-176	A CQT group identified Lu ions as a novel candidate for high-precision optical atomic clocks and is collaborating with A*STAR's National Metrology Centre to benchmark its timekeeping

Launched: three national quantum platforms

The three platforms in quantum computing, quantum-safe communication and the manufacturing of quantum devices are led by CQT researchers

Singapore's quantum ecosystem got a boost from the launch of three national quantum platforms in 2022. The three platforms were established in key areas:

- NATIONAL QUANTUM COMPUTING HUB SINGAPORE — National Quantum Computing Hub (NQCH) led by CQT Director José Ignacio Latorre
- NATIONAL QUANTUM FABLESS FOUNDRY SINGAPORE — National Quantum Fabless Foundry (NQFF) led by CQT Principal Investigator Manas Mukherjee, co-appointed with A*STAR's Institute of Materials Research and Engineering
- NATIONAL QUANTUM-SAFE NETWORK SINGAPORE — National Quantum-Safe Network (NQSN) led by CQT Principal Investigator Alexander Ling

"Our investment in quantum computing and quantum engineering is part of our approach of trying to anticipate the future, and proactively shaping the future that we want," said Deputy Prime Minister, Coordinating Minister for Economic Policies, and Chairman of the National Research Foundation (NRF), Mr Heng Swee Keat, when he spoke on the initiatives in his opening address at Asia Tech x Singapore, the region's flagship tech event, in May 2022.

Singapore's Quantum Engineering Programme (QEP) has committed $23.5 million to the three platforms for up to 3.5 years, with further support coming from across the research landscape. QEP is a national programme launched in 2018 by NRF to apply quantum technologies for solving user-defined problems. Read on to find out more about the platforms.

Quantum Engineering Programme, Singapore

Photo: CQT is one of three founding members of the National Quantum Computing Hub. Pictured are representatives from the three partner organisations at Singapore's ASPIRE-1 supercomputer. From left are Ye Jun, IHPC; Papani Venkatesh, NSCC; and Han Rui, CQT.

National Quantum Computing Hub

Quantum Engineering Programme, Singapore

Quantum computers have the potential to outperform today's supercomputers in speed and energy efficiency for some tasks – spurring a global effort to develop the technology and harness its power.

The NQCH pools expertise and resources from CQT, A*STAR's Institute of High Performance Computing (IHPC) and the National Supercomputing Centre (NSCC) Singapore to build capabilities and community in quantum computing in Singapore. The heads of the three organisations drive the initiative – see the box **Leadership on quantum computing**.

Researchers at CQT and IHPC are developing quantum computing hardware and middleware. They also explore applications with industry collaborators in fields such as finance, supply chain, and chemistry. Meanwhile, NSCC will provide the supercomputing power needed to develop and train algorithms and, ultimately, host a quantum computer too.

CQT's teams at both the National University of Singapore and Nanyang Technological University, Singapore, are involved. Principal Investigator (PI) Rainer Dumke and Senior Research Fellow Christoph Hufnagel are working on superconducting quantum processors, while PIs Dimitris Angelakis and Patrick Rebentrost do research on applications and help coordinate access to commercial quantum computing services.

For the middleware, CQT Director José Ignacio Latorre, who also serves as lead PI for the Hub, champions an open-source offering called Qibo. Middleware serves as the backbone of a software stack, transforming high-level code into operations on qubits. Qibo will go from advanced programming interfaces for promising targets such as optimisation problems down to control of different hardware platforms. IHPC researchers have joined international partners in developing Qibo (learn more at qibo.science).

*Photo: A team led from CQT is developing hardware for NQCH. Pictured are CQT Senior Research Fellow Christoph Hufnagel (left) and scientist Senthil Kumar Karuppannan (right) from A*STAR's Institute of Materials Research and Engineering, who specialises in the microfabrication of quantum devices with the National Quantum Fabless Foundry (see pp.22–23).*

The hub will also build international collaborations and train new talent to address skills shortages in the emerging industry. CQT PI Kwek Leong Chuan is part of the team looking at internationalisation, while CQT PI Berge Englert has taken the lead for talent plans. Berge is working with experts hired at CQT to design an online learning platform and in-person training programmes. These are expected to launch in 2023.

Singapore's National Quantum Office kicked off international collaborations on a visit to Finland in September 2022, inking a memorandum of understanding with VTT Technical Research Centre of Finland, IQM Quantum Computers, and CSC – IT Center for Science (Finland). They agree to explore and promote research and development collaboration in areas including quantum technology hardware components, algorithms and applications, and quantum-accelerated high-performance computing.

www.nqch.sg

Leadership on quantum computing

"Quantum computing is coming. The question is not about 'when', but about 'who' will be ready to use this technology. The approach taken in Singapore is to combine the expertise from our researchers with the needed support to such a mission."

José Ignacio Latorre
Director, CQT and Lead Principal Investigator, NQCH

"Quantum computing is a revolutionary technology that promises a significant shift in how information is processed and analysed to solve complex problems traditionally limited by classical computers. We are pleased to contribute our expertise in computational science, high performance computing, artificial intelligence and optimisation."

Su Yi
Executive Director, IHPC, A*STAR, and Co-Principal Investigator, NQCH

"Supercomputers will be a key resource in accelerating quantum computing research and developing the tools and algorithms needed to support the new technology. The partnership between NSCC, IHPC and CQT reflects a whole-of-research commitment that covers the entire value chain for the development of the quantum computing ecosystem in Singapore."

Tan Tin Wee
Chief Executive, NSCC, and Co-Principal Investigator, NQCH

National Quantum Fabless Foundry

Quantum Engineering Programme, Singapore

A successful quantum industry will need the capabilities to build quantum devices, beyond the know-how to design and understand them. That's the idea behind the NQFF, which aims to support micro and nanofabrication of devices such as quantum processor chips, electronics, and micro-sized structures for ion traps.

NQFF is hosted at the Institute of Materials Research and Engineering (IMRE) at the Agency for Science, Technology and Research (A*STAR).

"Take the analogy of today's computers: you could build a computer with reliable parts from different producers and developers, but knowing how to build the system does not mean you have the skills to produce the parts and devices needed," says Manas Mukherjee, NQFF Director. Manas is a CQT Principal Investigator co-appointed as Senior Scientist and Head of the Quantum Technologies for Engineering department at IMRE.

"Our vision is that with time, we will have the intellectual property to develop devices," says Manas. "We think we would be able to contribute to the economy locally and to spin out some of these device fabrication methods through startups or licensing."

The Foundry's three pillars are design, fabrication and characterisation, which involves testing how well a device works. The design and fabrication teams are distributed between IMRE and the Institute of Microelectronics (IME) at A*STAR while the characterisation team is based fully in IMRE. NQFF has about 20 staff based in the two institutes who work closely with the device end-users at different research organisations.

Manas says, "We want to bring on board various types of expertise to support the local ecosystem of researchers. In the process, as we learn more and can produce better devices, we will also want to contribute to the global ecosystem, which is still very nascent."

Singapore has a head start thanks to its long-term investment in quantum technologies research and the country's well-established infrastructure for micro and nanofabrication. The process typically requires operating sophisticated machinery in a cleanroom environment. NQFF gives researchers access to Singapore's existing network of cleanrooms including those at IMRE and IME, at the Nanyang Technological University, Singapore (NTU Singapore), and at the Centre for Advanced 2D Materials and E6NanoFab at the National University of Singapore.

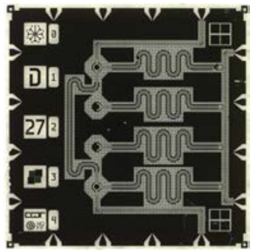
*Photo: The NQFF enables researchers to design, build and characterise quantum devices in Singapore. It coordinates access to cleanrooms such as this one at A*STAR's Institute of Materials Research and Engineering*

NQFF will also augment the cleanrooms with new tools. For example, NQFF first installed an integrated angled evaporator and oxidation chamber in CQT Principal Investigator Rainer Dumke's laboratory at NTU under a pilot programme. It is currently in the process of ordering newer versions of the tool for the cleanrooms at A*STAR. This tool is used to produce Josephson junctions, which are integral parts to realise superconducting qubits for quantum computing. With it, Singapore has the full process line to produce Josephson junctions which did not exist before.

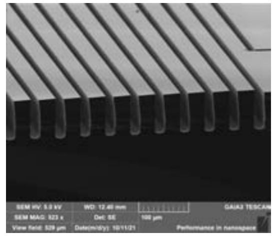
In addition to manufacturing superconducting qubits, NQFF is also developing fabrication processes for three other quantum technology platforms. They are integrated ion traps, photonic integrated circuits and site-specific donor on silicon.

www.nqff.sg

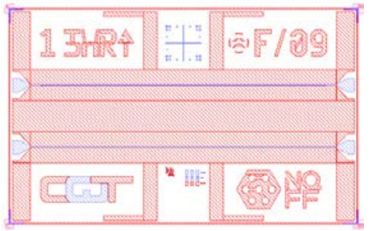
The micro parts of quantum devices



Superconducting quantum processor
The left image shows two qubits on a sapphire substrate – zoom in, and you would see a Josephson junction across the small circles. Two such transmon qubits coupled in a superconducting circuit form the basis for implementing quantum gates and algorithms.



Microfabricated electrodes
A cross-sectional image by a scanning electron microscope of a surface ion trap. Trapped ion chips offer long coherence times and scalability, making them a promising technology for realising practical quantum computing systems.



Circuit design
A design file for a traveling wave parametric amplifier based on the interaction between a strong pump signal and a weak input signal within a nonlinear medium. Manufacturing of this circuit would use processes including photolithography, electron beam lithography, double-angle metal deposition and metal etching.

National Quantum-Safe Network

Photo: One node on the NQSN is located at CQT. Haw Jing Yan (front) and Hao Qin (back) are Quantum Communications Technologists for the network.

The public-key encryption that protects some of the billions of bits of data exchanged each day is known to be vulnerable to attacks by quantum computers. While today's quantum computers are too small to break encryption, calls to address the cybersecurity threat become more urgent as the technology advances.

The NQSN was established to conduct nationwide trials of quantum-safe communication technologies that promise robust network security. It kicked off in February 2022 with more than 15 collaborators (see box **In the network**).

Quantum-safe communication technologies are designed to counter the threat of quantum computing with specialised hardware and new cryptographic algorithms. They could secure communication systems for governments, critical infrastructure such as energy grids, and companies handling sensitive data in areas such as healthcare and finance.

The NQSN is providing both quantum key distribution – a hardware approach to quantum-safe communication requiring the installation of devices to create and receive quantum signals – and post-quantum cryptography, which means upgrading software to run new cryptographic algorithms perceived to be resistant to attacks by quantum computers. Its team is also contributing to the development of standards for these emerging technologies (see box **Setting standards**).

CQT Principal Investigator Alexander Ling is the network's lead PI. His co-PIs are CQT's Christian Kurtsiefer, Biplap Sikdar from the National University of Singapore (NUS) Department of Electrical and Computer Engineering and Nelly Ng from Nanyang Technological University, Singapore. Joining them as co-coordinator of the network is Michael Kasper, CEO of Fraunhofer Singapore and a cybersecurity expert. The NQSN has additional dedicated technical staff at CQT.

The project's former lead Principal Investigator, Charles Lim, also previously a CQT PI, took leave of absence from his NUS faculty position to become Global Head of Quantum Communications and Cryptography at the financial services firm JPMorgan Chase from July 2022.

When the NQSN was announced, Ong Chen Hui, now Assistant Chief Executive (BizTech Group) of Singapore's Infocomm Media Development Authority (IMDA), said "A National Quantum-Safe Network is an important step forward as we explore advances of quantum computing and network technologies. IMDA will continue to push the boundaries in frontier technologies, to architect Singapore's digital future. Together with the NRF, NUS, as well as our industry and research partners, we will look into ways to operationalise and implement the quantum key distribution network on Singapore's extensive fibre network infrastructures."

www.nqsn.sg

In the network

- NUS, NTU Singapore and Fraunhofer Singapore provide expertise, coordination and locations for hardware.
- NetLink Trust provides access to Singapore's optical fibre network.
- Amazon Web Services, Government Technology Agency of Singapore, the National Supercomputing Centre (NSCC) Singapore and ST Telemedia Global Data Centres contribute to development of use-cases.
- ST Engineering and Thales work on network security, providing hardware for integration into the network.
- The Cyber Security Agency of Singapore (CSA) will work along with its approved Common Criteria testing labs T-Systems and UL towards formal security certification of quantum-safe technologies.
- The Defence Science and Technology Agency, HTX (Home Team Science and Technology Agency), DSO National Laboratories and Horizon Quantum Computing participate in quantum network research projects.
- The Infocomm Media Development Authority (IMDA) collaborates with institutes of higher learning, industry and research partners to find ways to operate and implement the NQSN on Singapore's fibre network infrastructures.
- The NQSN plans were developed in consultation with a working group also involving the Singapore Economic Development Board (EDB).

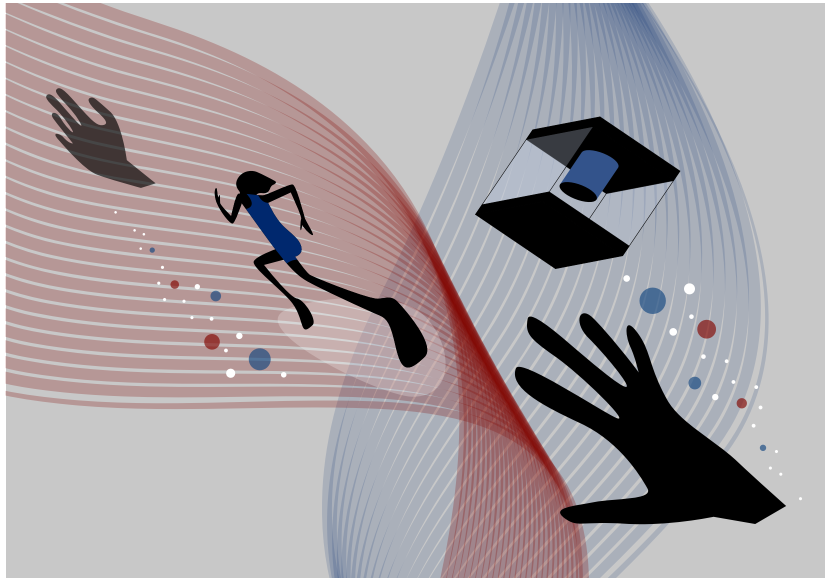
Setting standards

In November 2022, the NQSN co-hosted with Singapore's Infocomm Media Development Authority a half-day workshop organised by the International Telecommunication Union (ITU) on "Quantum key distribution protocols, security and certification".

ITU is the United Nations specialised agency for information and communication technologies. Its membership includes 193 Member States and over 900 companies, universities, and organisations. One of ITU's major roles is developing international technical standards, and its standards for quantum-key distribution (QKD) networks address aspects from architecture to key management and security.

"This workshop was the first time ITU has held discussions on QKD protocols in Singapore and South-East Asia. The workshop aimed to gather opinions from different perspectives and build up common understanding on QKD protocols to support standardisation and certification work at an international scale," says Hao Qin, Quantum Communications Technologist with NQSN and moderator for the workshop. Some 130 people worldwide registered.

The workshop was followed by a two-day discussion among experts that form an ITU standardisation working group on "Security for/by emerging technologies including quantum-based security". This was an ITU Question 15/17 Rapporteur Group Meeting.



At the intersection of science and art

Creative short films and flash fiction from the Quantum Shorts competitions reach people around the world

A quirky animated short film starring a woman travelling the multiverse claimed the first ever First Prize in the Quantum Shorts competition organised by CQT and partners – back in 2013.

Since then, CQT has continued to run Quantum Shorts under its outreach programme, encouraging people to explore quantum technologies through flash fiction and short films. The contest has alternated between annual calls in the two mediums, accepting entries from around the world.

The flash fiction contest that concluded with prizes awarded in April 2022 (see box **Fiction winners**) was Quantum Shorts' tenth round.

The best entries have engaged international audiences through the competition's website, film screenings in different countries and an anthology of shortlisted stories published in 2019, *Quantum Shorts: Collected Flash Fiction Inspired by Quantum Physics*. In 2022, the website received over 14,000 visitors.

"The Quantum Shorts competitions get people thinking about quantum physics in wildly creative ways. We have kept the series running thanks to a cast of expert judges and collaboration with excellent media, scientific and screening partners," said Jenny Hogan, CQT's Associate Director for Outreach and Media Relations. After the latest fiction prizes were decided, a new call for short films launched in September 2022.

Scientific American and *Nature* are long-standing media partners of Quantum Shorts. Scientific partners for recent competitions are the ARC Centre of Excellence for Engineered Quantum Systems in Australia; the Dodd-Walls Centre for Photonic and Quantum Technologies in New Zealand; the Institute for Quantum Computing at the University of Waterloo, Canada;

the Institute for Quantum Information and Matter at Caltech in the United States; QuTech in the Netherlands; and the UK National Quantum Technologies Programme (UKNQTP).

Singapore's ArtScience Museum at Marina Bay Sands has been among the screening partners for past film competitions, giving audiences local to CQT a chance to see the shortlisted films on a big screen.

"Being part of the Quantum Shorts community has been an incredibly rewarding experience," said Dr Georgia Mortzou, Quantum Communications Hub Project Manager at the UKNQTP. "Quantum science concepts have traditionally been thought of as challenging and pushing the limits of human imagination. By contrast, the offerings of the many creators who have participated over the years have been truly inspiring in terms of artistic quality, clarity of vision, and the range of emotions reflected in the storytelling."

An archive of shortlisted films fiction from past years is hosted at the Quantum Shorts website at shorts.quantumlah.org, along with resources on quantum physics, writing and filmmaking. The competition also offers a newsletter and shares updates as @quantumshorts on social media.

Fiction winners

The tenth round of Quantum Shorts began with a call in 2021 for stories no longer than 1000 words that took inspiration from quantum physics. As an additional challenge, writers had to make creative use of the constraint phrase "it's a lot to think about". The phrase was chosen from the winner of the previous fiction edition.

From over 400 submissions, ten stories were shortlisted and three selected for top prizes. Cora Valderas from the US bagged First Prize for "Helping Hands", a spooky story about a quantum experiment gone awry. She drew on her love for crime thrillers and horror stories. "There are many disaster stories throughout history involving sensitive equipment to draw inspiration from, and quantum physics provides a deep pool of possibilities that blur the lines of truth and fiction," she said. "It's fun to consider that there are infinite possibilities out there, and I believe it's up to the imagination to make those many universes a reality. That's what story writing is all about, manifesting every possibility into words."

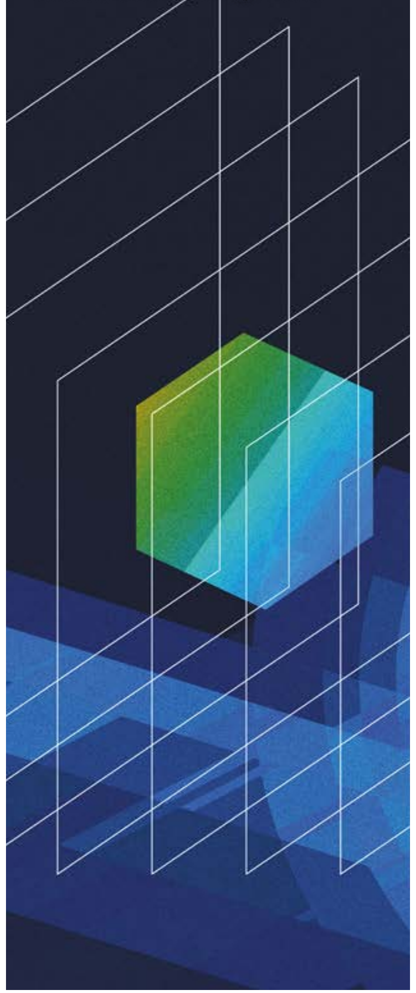
Sabrina Patsch from Germany won Runner Up Prize for "Quantum et Circenses", an account of a high-stakes quantum gameshow. Álvaro Buendía in Spain won the People's Choice Prize, decided by an online public vote on the shortlist, for "Better, Faster, Stronger, Lonelier", a tale that imagines a conversation between a classical computer and quantum computer. Sabrina and Álvaro are both PhD students studying quantum physics.

Offline, the ten shortlisted stories went on tour in New Zealand. Scientific partner the Dodd-Walls Centre collaborated with Otago Museum, a screening partner during the film editions of the competition, to organise a tour around libraries. Jessa Barder, Science Engagement Manager at Otago Museum, said, "Comments were incredibly favourable, particularly from parents and librarians who were keen to see the connection between literature and the physical sciences."

During the tour, copies of the 2019 Quantum Shorts anthology were added to the collections of five New Zealand libraries. Physical copies of the book were already available in libraries in Singapore. The e-book was in 2022 highlighted by the National Library Board Singapore as a Librarians' Pick.

OUR COMMUNITY

We bring together top physicists, computer scientists and engineers



Governing Board

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Advisor to National Research Foundation & Senior Vice-President (Sustainability and Resilience), National University of Singapore

Chen Tsuhan
Deputy President (Research and Technology) and Distinguished Professor
National University of Singapore

Charles Clark
Fellow, National Institute of Standards and Technology, USA and Adjunct Professor
Joint Quantum Institute, University of Maryland, USA

Guan Yong Liang
Associate Vice President (Infrastructure and Programmes)
Nanyang Technological University

Andy Hor
Deputy Chief Executive (Research)
Agency of Science, Technology and Research

José Ignacio Latorre
Director, Centre for Quantum Technologies
Provost's Chair Professor, Department of Physics, National University of Singapore

Quek Yee Kian
Director (Systems & Concepts Group)
Ministry of Defence

Ling Keok Tong
Executive Director (National Quantum Office)
Agency of Science, Technology and Research

Ling San
Chief Scientific Advisor
National Research Foundation

Ong Chen Hui
Assistant Chief Executive (BizTech Group)
Infocomm Media Development Authority

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Research Director, Laboratoire Kastler Brossel, Ecole Normale Supérieure Paris

Umesh Vazirani
Director, Berkeley Quantum Computation Center (BQIC), Computer Science Division
University of California at Berkeley

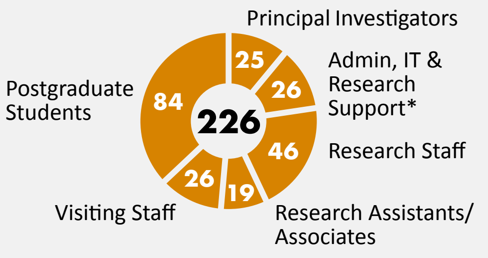
Yasunobu Nakamura
Director, RIKEN Center for Quantum Computing, Professor, Research Center of Advanced Science and Technology,
The University of Tokyo

Principal Investigators

Name	Type
Divesh Aggarwal	theory
Dimitris G. Angelakis	theory
Murray Barrett	lab
Kai Dieckmann	lab
Rainer Dumke	lab
Berge Englert	theory
Yvonne Gao	lab
Loh Huanqian	lab
Rahul Jain	theory
Gong Jiangbin	theory
Patrick Rebentrost	theory
Dagomir Kaszlikowski	theory
Christian Kurtsiefer	lab
Kwek Leong Chuan	theory
Wenhui Li	lab
Alexander Ling	lab
Dzmitry Matsukevich	lab
Manas Mukherjee	lab
Travis Nicholson	theory, lab
Miklos Santha	theory
Valerio Scarani	theory
Marco Tomamichel	theory
Steven Touzard	lab
Gao Weibo	lab
David Wilkowski	lab

theory lab

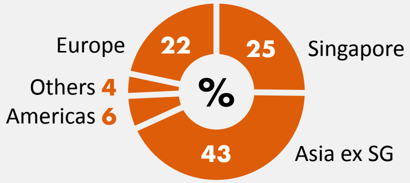
Headcount



Count of CQT staff and students as of 31 December 2022

* Admin count includes only staff directly employed within the Centre. HR, IT and procurement is supported by additional staff working across University centres

Nationalities



Nationalities of CQT staff and students as of 31 December 2022

https://www.quantumlah.org/people

The CQT Governing Board (GB) was reformed and expanded in December 2022 on the Centre's transition to new funding (see pp.8–11). This listing shows all new members serving as of 31 December 2022. The Centre acknowledges and thanks those members who stepped down: Nicholas Bigelow, University of Rochester; Ho Teck Hua, National University of Singapore; Teo Kien Boon; Ministry of Education. We are particularly grateful to former Chairman Quek Gim Pew, Senior R&D Consultant, Ministry of Defence, for his service from 2016 to 2022.

Students at CQT

84
CQT PhD students as of December 2022

10
CQT PhD graduates in 2022

100
CQT PhD graduates since CQT founded

Internships

48
CQT Interns in 2022

For students wanting to sample what research in quantum technologies is like, an internship can be a smart choice. CQT supports internships for masters students or undergraduates nearing the end of a relevant degree. Students may apply directly to the PI with whom they would like to work.

PhD programme

For students keen on a career in research or in the emerging quantum industry, a PhD can be their launch point. CQT's graduate programme offers high-quality education and opportunities to make original contributions in quantum physics and technologies, supported by a generous scholarship and travel allowance. Applications are open throughout the year to students of all nationalities. Doctoral degrees are awarded by the National University of Singapore, consistently ranked among the world's leading universities. CQT Principal Investigators also accept students funded by other sources.

"CQT enables me to thrive as a PhD student by promoting multidisciplinary research, creating spaces for lively exchange, and enabling student-led outreach."

Clara Fontaine
Experimental Physics

"I really appreciate the unique place CQT holds within the global and local community, which enables both the constant stream of visiting researchers and the Centre's many outreach efforts. As a PhD student, this allows me to place my work not just within the context of other fields in quantum research, but also that of a much broader audience—prospective students, adjacent industries, or even enthusiastic members of the public."

Zaw Lin Htoo
Theoretical Physics

Recognition

CQT's achievements are the combined efforts of all our staff and students, but we are also happy to congratulate individuals who won awards for their work and contributions in 2022. Kudos to our staff!

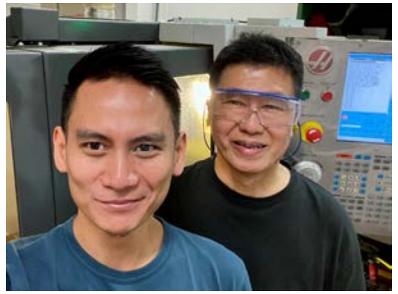
CQT Director **José Ignacio Latorre** was one of four recipients to be conferred a **Distinguished Professorship** by Singapore-based company ST Engineering in December 2022. The inaugural awards recognise researchers "with outstanding contributions to the strategic goal of achieving impactful research translation". José Ignacio is recognised for his contributions in accelerating the translation of research in quantum technologies. He is Lead Principal Investigator for Singapore's National Quantum Computing Hub (NQCH), driving efforts to build Singapore's capabilities in quantum computing. Interviewed about his work, he said: "I hope to modestly help make Singapore more relevant in the quantum landscape. This will require concrete actions, and I'm looking forward to defining projects that bring quantum solutions to the economy."

José Ignacio Latorre

CQT's **Steven Touzard** made the 2022 edition of **MIT Technology Review's "Innovators under 35" list** for the Asia-Pacific region. Announced on 14 November 2022, the list recognises 35 top talents in the region. Steven is named a pioneer for his work on quantum error correction and quantum networking. Earlier in his career, he demonstrated techniques that led to noise suppression in the so-called cat qubits and GKP qubits. Steven is jointly appointed as a CQT Principal Investigator and a Presidential Young Professor at the NUS Department of Physics and Department of Materials Science and Engineering. He also received a **National Research Foundation Fellowship** (Class of 2022) for research on "Building quantum networks of superconducting circuits mediated by telecom photons".

Steven Touzard

On Singapore's 57th birthday, two of CQT's technical support staff received National Day Honours. **Bob Chia Zhi Neng**, CQT's Mechanical Workshop Manager, received **The Commendation Medal** (Pingat Kepujian) having "distinguished himself through commendable performance and conduct, or significant efficiency, competence and devotion to duty". **Mohammad Imran** received **The Efficiency Medal** (Pingat Berkebolehan). This is presented "for exceptional efficiency or exceptional devotion to duty or for work of special significance". As a Laboratory Technologist, Imran's effectiveness in using laser cutting for plastic structures is known even beyond the Centre: during the pandemic, he helped to manufacture plastic parts for self-service kiosks in isolation facilities.

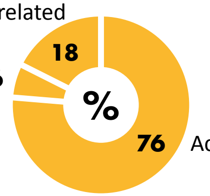


Mohammad Imran and Bob Chia Zhi Neng

Alumni

The research staff and students who honed their skills at the Centre go on to bring their expertise into a wide variety of roles. While many choose to continue in academic research as PhD students and postdocs, some are expanding their horizons in the growing quantum technologies industry in Singapore and abroad – such as the two alumni whose stories we share below. We also summarise in the chart on the right the next job types of 34 staff and students who departed in 2022.

Job types: 2022 survey

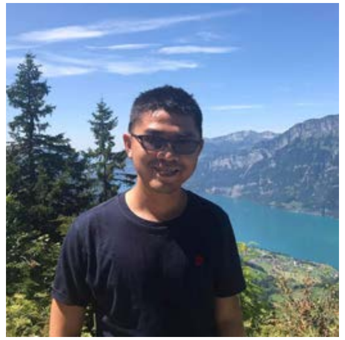


Life after CQT

Jayne Thompson
Principal Scientist,
Horizon Quantum Computing

After eight years as a Research Fellow at CQT, Jayne Thompson joined quantum tech start-up Horizon Quantum Computing in July 2020. "I became really interested in finding bottleneck problems in industry, which would make good use cases for quantum computing." says Jayne, who worked on quantum computing and algorithms as a theorist during her time at CQT.

Horizon Quantum Computing is compiling programmes written in classical programming languages such as C down to code that can be run directly on a quantum processor. As a Principal Scientist, Jayne's work involves understanding the quantum algorithms that can be harnessed to obtain a quantum speedup in executing these computations. While she now works on a broader scope of problems, the technical, communication and mentoring skills she honed as a researcher still apply. "There are a lot of transferable skills you gain as a researcher," says Jayne.



Nguyen Chi Huan
Quantum System Verification Engineer,
Zurich Instruments

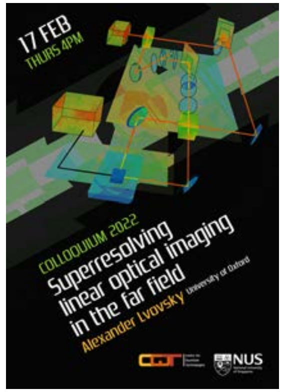
Nguyen Chi Huan trained as an atomic physicist in CQT's experimental labs, first as a PhD student in the group of Christian Kurtsiefer, and then as a Research Fellow in Dzmitry Matsukevich's group. Keen to build on the scientific expertise he acquired, Chi Huan sought out opportunities in the burgeoning quantum technologies industry, joining Zurich Instruments in 2022. Headquartered in Zurich, Switzerland, the company develops measurement instruments for advanced laboratories.

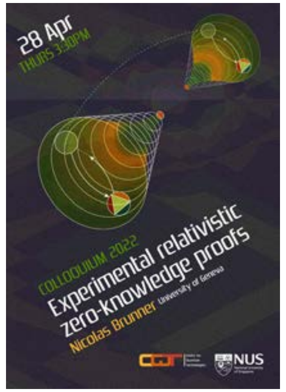
As Quantum System Verification Engineer, he is part of a team developing control software that coordinates various devices to manage large-scale quantum computing systems. His focus is on creating an automated regression testing framework that thoroughly assesses the software against specifications. Chi Huan says, "One of the greatest benefits of my job is the opportunity to collaborate with a highly skilled and diverse group of colleagues."

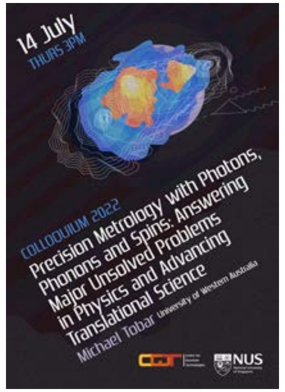
Events

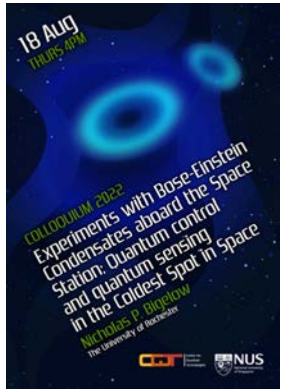
CQT hosts a busy programme of scientific talks helping researchers to keep up to date with the field, with a total of 58 events in the calendar during 2022. Those included nine colloquia by distinguished visiting scientists that inspired the posters presented here, plus two lunchtime seminars in a new series for CQTians to share their research findings.

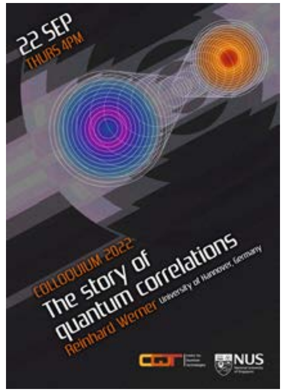
At a larger scale, CQT helped to organise in Singapore the **Quantum Technologies on Small Satellites QTX-6 Workshop** (26–27 October) and held a one-day conference for Singapore's quantum community during the visit of the Centre's Scientific Advisory Board. The Centre's four new PIs (see pp.14–16) gave inaugural talks at this **CQT SAB Conference Day** (4 August).





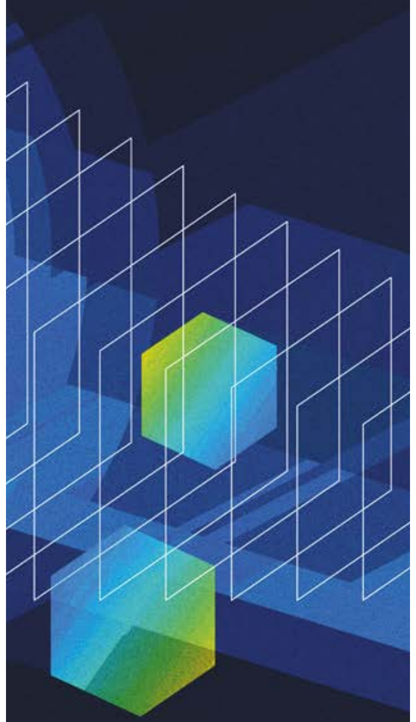






OUR IMPACT

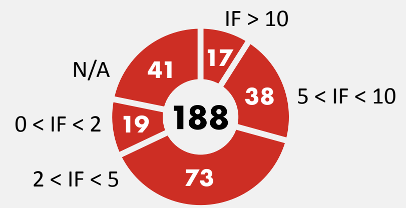
A look at CQT's outputs and spending in 2022



Peer-reviewed research papers are not the only measure of the Centre's research output – read the other sections of this report for more insight into the skills, collaborations and companies that are grown at CQT – but they are one measure of our scientific productivity. These data show the quantity and quality of our publications.

Data on publications in these pages is derived from CQT's records and Clarivate *Web of Science* searches*.

Publications



Publications during 2022 by journal impact factor (IF)

- 11 Physical Review Letters
- 3 npj Quantum Information
- 1 Physical Review X
- 2 Science Advances
- 1 Nature
- 2 Nano Letters
- 2 Reviews of Modern Physics
- 2 Nature Communications

Publications during 2022 in selected high impact journals

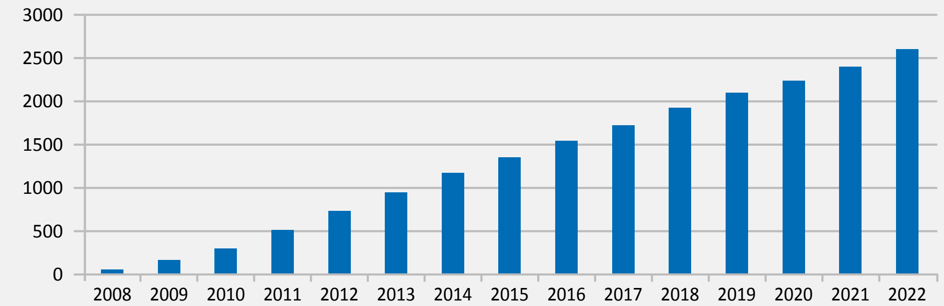
*Search by address field for (Natl Univ Singapore AND Ctr Quantum Technol) OR (Ctr Quantum Technol AND Singapore)

There are **2,596** publications in total from CQT's first 15 years.

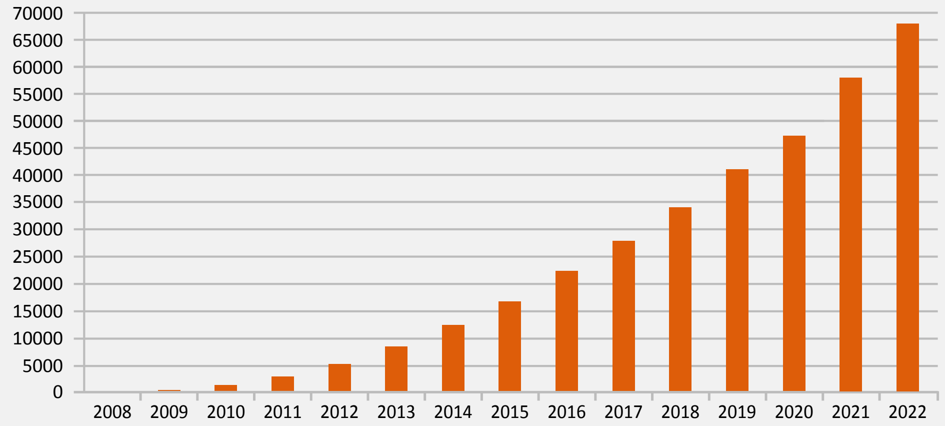
The body of work has accumulated **67,743** citations. That's an average of 26.1 citations per paper.

As a centre, our h-index is **105**.

Cumulative Publications 2008-2022



Cumulative Citations

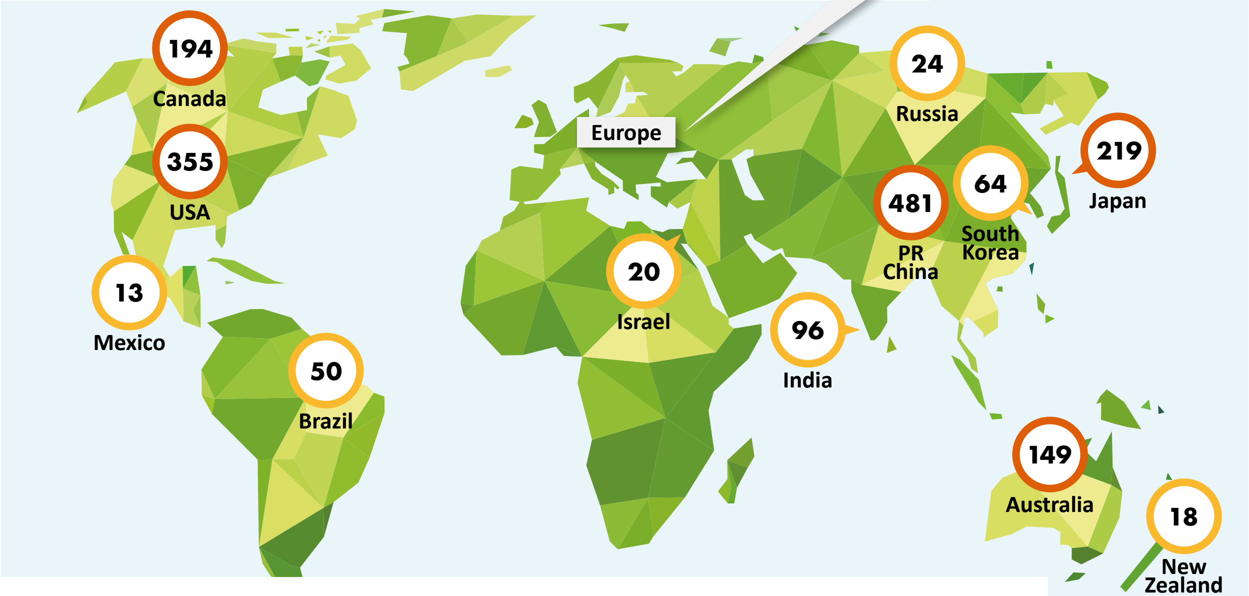


CQT has wide networks of collaborators at both the individual and institutional level.
The world map shows counts of co-authorships across all publications including CQT researchers.

650 UK	271 France	240 Germany	194 Italy	130 Poland	133 Spain
127 Switzerland	75 Greece	73 Austria	47 Netherlands	39 Sweden	38 Scotland

159 Rest of Europe: **31**: Hungary, **30**: Belgium, **26**: Denmark, **23**: Czech Republic, **13**: Ireland, **10**: Finland, **6**: Latvia, Slovenia, **5**: Portugal, **2**: Bulgaria, Croatia, Malta, Slovakia, **1**: Estonia

129 Rest of world: **29**: United Arab Emirates, **16**: Taiwan, **8**: South Africa, Turkey, **7**: Argentina, Iceland, **6**: Chile, Saudi Arabia, Serbia, Qatar, **5**: Malaysia, Norway, **4**: Armenia, **3**: Iran, **2**: Colombia, Indonesia, Thailand, **1**: Belarus, Botswana, Egypt, Kuwait, Luxembourg, Nigeria, Uruguay



Source: Clarivate *Web of Science.* Data captured for publications 2008-2022.

In 2022, CQT through NUS was part of agreements with institutions including:

- UMI Majulab agreement with the Nanyang Technological University, the French National Centre for Scientific Research (CNRS), the Université Côte d'Azur and the Sorbonne University, France
- Partner Organisation Agreement with the ARC Centre of Excellence for Quantum Computation and Communication Technology (CQC2T) at the University of New South Wales, Australia
- Memorandum of Understanding with each of TCG Centres for Research and Education in Science and Technology and the Physical Research Laboratory, India; Tel Aviv University, Israel; University of Catania, Italy; University of Otago, New Zealand; National Institute of Metrology, Thailand; University of Strathclyde, United Kingdom; and the University of Applied Sciences Northwestern Switzerland

CQT creates knowledge and trains skilled people. Here are some of the ways these outputs translate into tangible benefits for the economy and society.

Spin-offs and startups

The commercial promise of quantum technologies is driving activity in companies big and small around the world. There are six young companies in quantum technologies in Singapore with strong links to CQT and NUS. S-Fifteen Instruments and SpeQtral are spin-offs that have licensed technology. AngelQ, Atomionics, Entropica Labs and Horizon Quantum Computing are startups founded by CQT staff and alumni. Find introductions and links to all of them at www.quantumlah.org/startups

Quantum Engineering Programme

A funding initiative launched in Singapore in 2018, the Quantum Engineering Programme (QEP) supports translational research and activities for quantum science to solve real-world problems. CQT plays a leading role in three national platforms launched in 2022 with support from QEP that are building public-private collaborations (see pp.19–25). CQT researchers also received QEP grants in 2022 for projects including work on quantum processor hardware and applications of quantum computing in chemistry, route optimisation and finance.

Industry engagement

CQT's engagement with industry spans from exploratory meetings to collaborative research projects. Recognising that the spark for collaborations can start at events, CQT coordinated sessions in 2022 including a webinar for the Singapore Semiconductor Industry Association that highlighted enabling technologies, a quantum computing track for the Supercomputing Asia conference and events on quantum-safe communication (pictured) co-organised with the government-backed deep tech supporter SGInnovate and partners. The Centre can also organise specialised training sessions on request.

Photo: "What Cybersecurity Needs To Get Quantum-Safe" was the topic of an event on 28 September 2022, organised by CQT in collaboration with SGInnovate and The Embassy of Switzerland in Singapore. Pictured from left are Haw Jing Yan and Michael Kasper from the National Quantum-Safe Network, Lim Soon Chia, Director, Cyber Security Engineering Centre, Head, Certification Body of Cyber Security Agency of Singapore and Christoph Wildfeuer, Professor, University of Applied Sciences and Arts Northwestern, Switzerland.

CQT's outreach activities engage students and the wider public to explore quantum technologies

Educational outreach

CQT reached its youngest audiences yet when the author of Quantum Physics for Babies, Chris Ferrie, visited from Australia in 2022. We arranged two readings at libraries attended by parents with infants and toddlers.

Older students also got opportunities. In collaboration with the NUS School of Continuing and Lifelong Education and Department of Physics, CQT PIs Yvonne Gao and Berge Englert ran three, two-day workshops on quantum computing (pictured). This was part of the "Temasek Foundation-NUS Youths for SG: Building a Shared Future" programme for secondary schools and polytechnics.

For pre-university students, CQT offered QCamp, a week-long workshop organised by a committee of PhD students. The camp featured lectures, hands-on activities, lab visits and discussion circles. Among the 36 participants, one deemed the camp "was astronomical for a topic that speaks about qubits".

Students in higher education could choose from the NUS "Specialisation in Quantum Technologies" for physics undergraduates and the "Master of Science in Physics for Technology", both featuring teaching by CQT researchers. Postgraduates could apply for CQT's own PhD programme (see p.30).

Science in culture

Quantum technologies often get mentioned in the media. CQT's work cropped up in some 30 stories in 2022, including a cover feature on quantum computing that ran in Singapore's Business Times newspaper in December. CQT also featured in the documentary series "Innovating for the future" developed by the National University of Singapore in partnership with Channel News Asia.

Creative interpretations of the field frequently appear in pop culture. CQT supports projects that combine art and science to reach those audiences. This year, the Centre's long-running Quantum Shorts contests for fiction and film reached a tenth edition (see pp.26–27) and CQT hosted two artists-in-residence under a collaboration with NUS Museum.

Find us online

For the latest news from CQT, join the 90,000 users who visited the Centre's website in 2022, or be among the more than 22,000 combined follows across our social media channels. We post regular updates on LinkedIn, Twitter, Facebook and Instagram. We also share scientific talks and other videos on YouTube.

Expenditure in 2022

	Manpower	Equipment	Other	Total
Core Funding	8.97	1.9	11.11	21.98
Competitive Grants	3.61	0.92	1.27	5.8
Total	12.58	2.82	12.38	27.78

All figures in million SGD.

Stakeholder support

CQT was established in 2007 as a national Research Centre of Excellence with core funding from the National Research Foundation (NRF), Singapore, and the Singapore Ministry of Education. The total core funding allocated for the period 2017–2022 was $100 million. The Centre graduated from the RCE scheme on 7 December, with core support now coming from a two-year, $25 million Bridging Grant from NRF (see pp.8–11). CQT also receives substantial core support from its host institution, the National University of Singapore (NUS), where the majority of its staff and students are based. This includes some salary costs and building space. CQT researchers at the Nanyang Technological University, Singapore (NTU Singapore) receive additional support from NTU.

Competitive grants

CQT researchers also compete for grant funding. CQT PIs received funding through seven new external grants awarded in 2022: six under the Quantum Engineering Programme supported by NRF and one MOE Tier 2 grant. These amount at CQT to about $10 M. Other active grants in 2022 include awards from NRF, MOE and DSO National Laboratories, all in Singapore. Some CQT research is funded through NUS competitive funds. International grants come from sources including the USA Air Force Office of Scientific Research.

Thanks to our supporters

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Upcoming events:

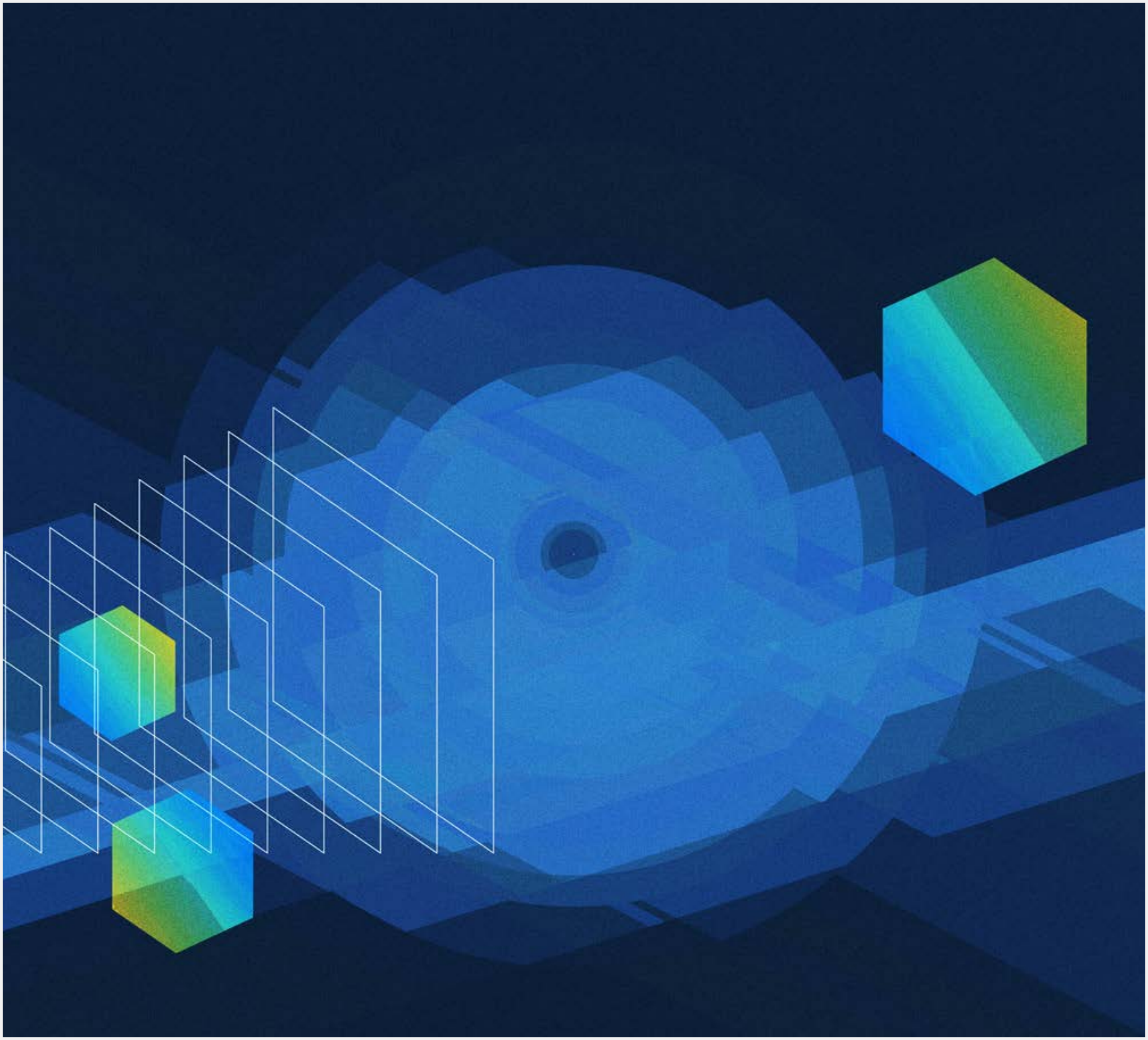
https://www.quantumlah.org/events/upcomingevents.php

Jobs:

https://www.quantumlah.org/about/joinus.php

Contact us:

cqtsec@nus.edu.sg



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