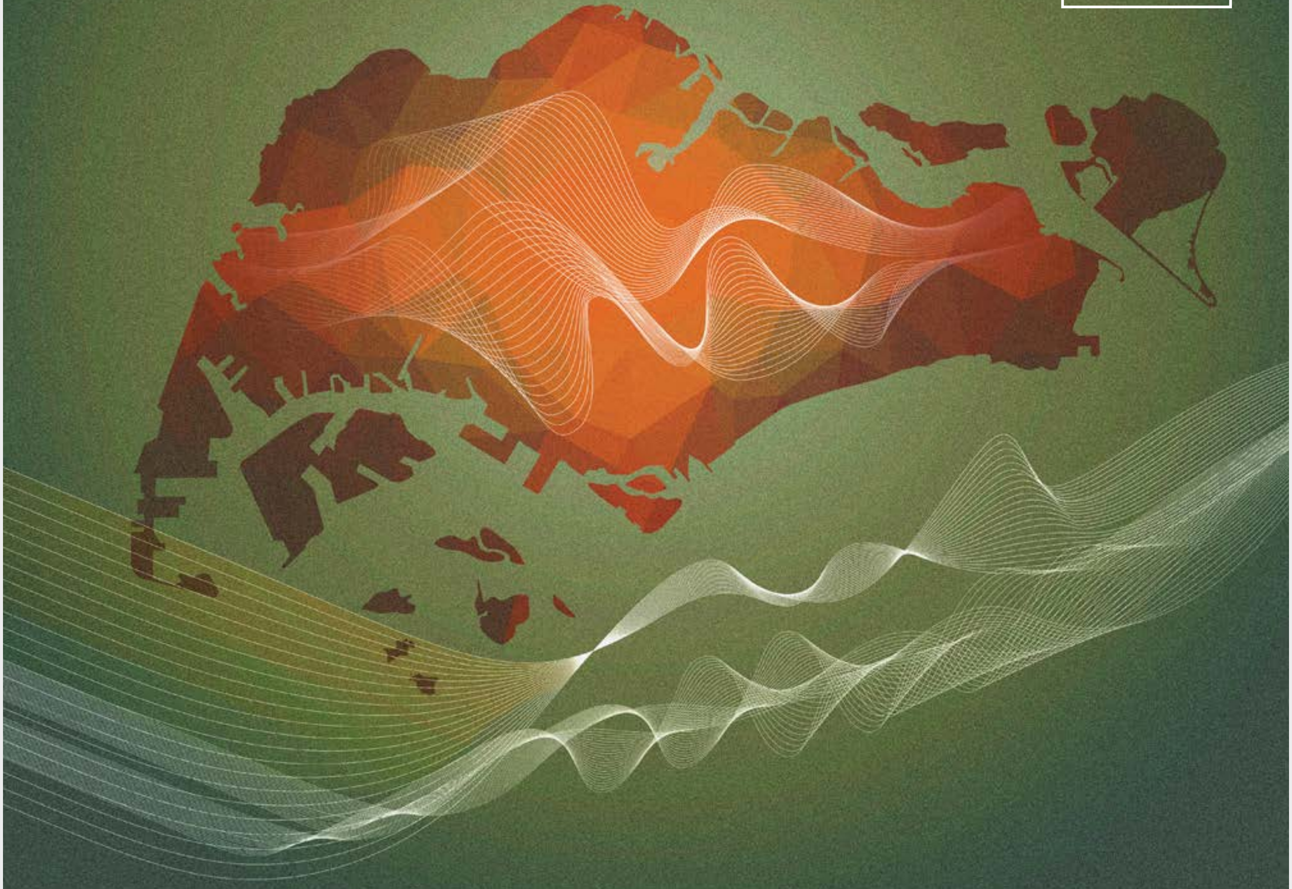
annual report 2019



Centre for Quantum Technologies

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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 (NUS) and also has staff at Nanyang Technological University (NTU).

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.

VIEW FROM THE DIRECTOR

The dinner conversation is in full swing. I tell a story of a sign in Munich that reads "Heisenberg might have slept here." Outburst of laughter. By the way, do you know Schrödinger's favourite Bond-movie? "Live and Let Die." Another good one, I thought...

Now, you may think I was dining with CQTians, my geeky colleagues. Not so. Most of my companions that night were bankers and politicians. I used to think that introducing myself as a quantum physicist was a conversation stopper. These days, courtesy of the media's obsession with quantum computers, we are perceived as cool. People may not know exactly what we do but still they find it fascinating. So here we are again with our CQT annual report to inform, educate and entertain.

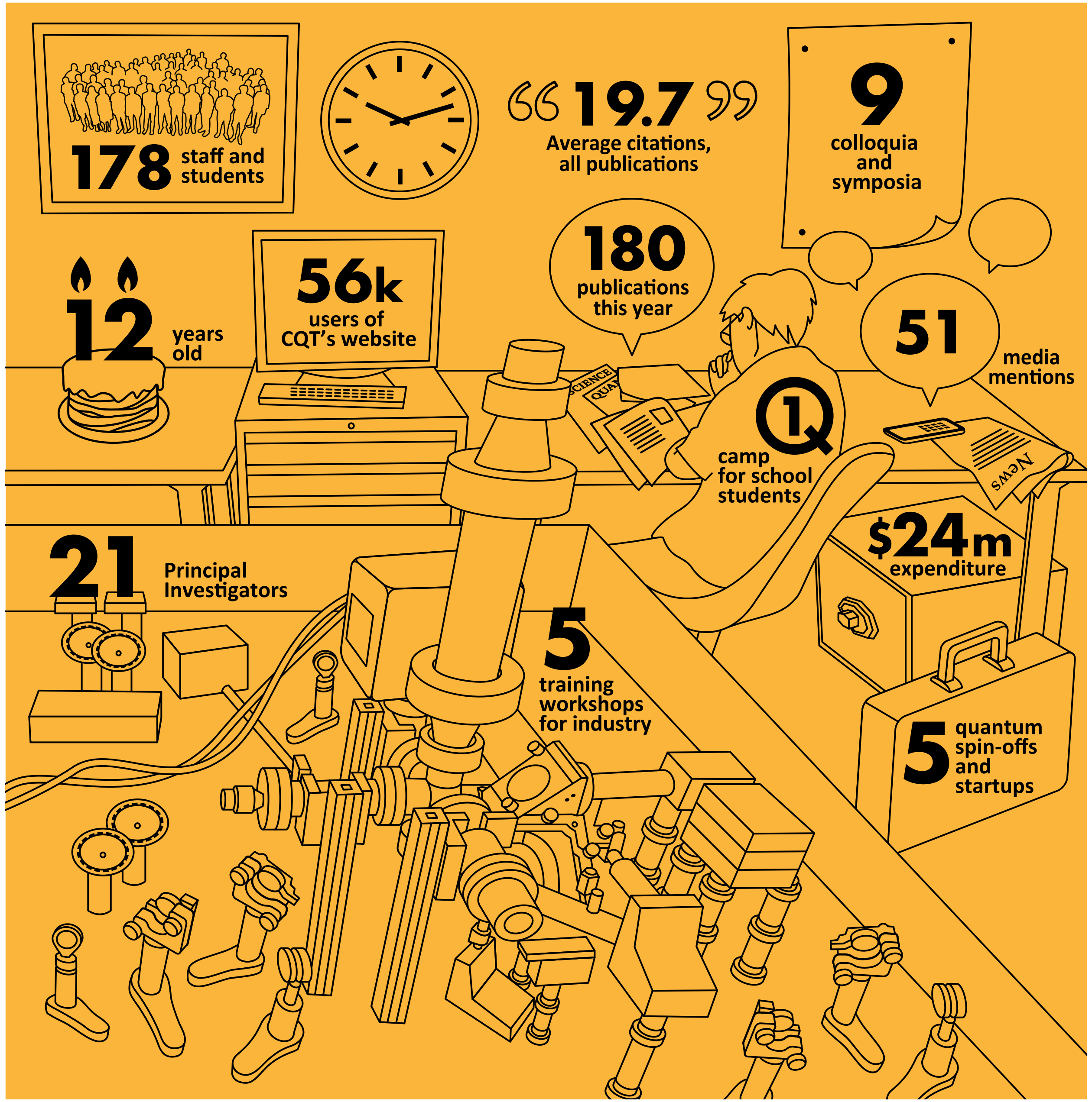
In some sense 2019 was like any other year; research went on, papers were published, laser beams were aligned. We welcomed David Wilkowski as our new Principal Investigator (see pp.17–18) and, in our efforts to support quantum startups, we joined forces with SGInnovate (see pp.21–23). We worked together with Science Centre Singapore to stage the exhibition QUANTUM (see pp.24–26). The exhibition traces the history of quantum theory and the development of quantum technologies worldwide, including contributions from Singapore.

We are also looking to the future. Singapore's quantum community is growing rapidly and, if we are to remain internationally competitive, we must work together to consolidate our research and engage with policymakers to contribute to the development of national strategy in quantum technologies. You can read more about our plans on pages 19–20.

Finally, if you want to know more about the basic components of quantum computers, learn from our feature on quantum logic with trapped ions (see pp.8–13). Building quantum computers will take time, but it will be time well spent, a truly joint effort of physicists, computer scientists and engineers.

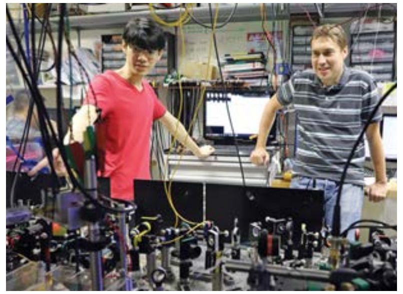
On the lighter side of science, I must mention the Nobel prize, well, OK, the Ig Nobel prize, awarded to Rainer Dumke and his team for their work on the magnetisation of cockroaches. Whenever scientists come up with new technology, that technology is likely to find applications we could never have predicted at the outset of the research. Using an atomic magnetometer to study the magnetic sense of cockroaches is an excellent example of an unexpected use case for a quantum device. The findings also fit the ambition of Ig Nobel prizes to honour achievements that make you laugh, then think (see p.32).

That's a story I can add to my after-dinner repertoire. We hope that readers of this report will also find stories they want to share. CQTians have worked hard for these results. Our annual report aims not only to give updates to our colleagues and collaborators, but also to inform those who may find themselves in conversation with, or even in business with, a quantum physicist. I wish you happy reading.



Exceptional research, projects and people

Highlights of CQT's work in quantum technologies in 2019



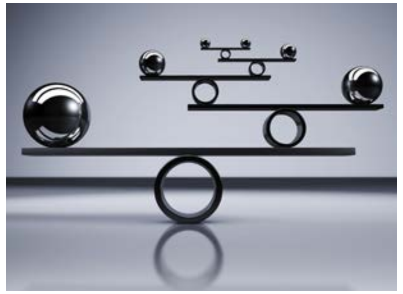
A three-atom fridge

CQT researchers have built a fridge just three atoms big, making it work as an absorption refrigerator where heat drives a cooling process.

Absorption refrigerators, first introduced in the 1850s, were widely used to make ice and chill food into the 20th Century. The 21st Century version created in the CQT lab of Dzmitry Matsukevich has three ytterbium ions and moves heat between the ions' different modes of motion.

The system provides a testbed for thermodynamics at the quantum scale. The researchers found against expectations that 'squeezing' the ions' quantum state did not enhance cooling. However, they found they could exceed the maximum cooling predicted by classical equilibrium thermodynamics using a method dubbed single shot. The team have since applied their exquisite control of ions to quantum computing (see pp.8–13).

Nature Communications **10,** 202 (2019)



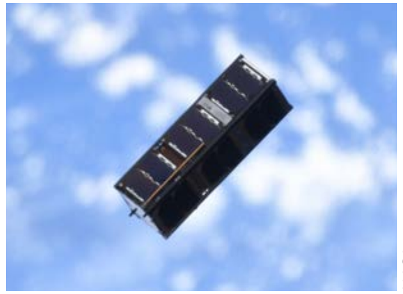
Knowledge is power

In thermodynamics, the capacity for a system to do work is closely connected to its capacity to store information. CQT's Mile Gu and colleagues developed a new way to characterise links between knowledge and power in quantum systems.

They defined a quantity called the 'thermal information capacity', which is the average number of bits a system could retain with no external energy source. Moreover, the researchers work out an explicit writing mechanism, in which a quantum system stores structured data while using no sources of energy other than what is contained within itself.

"The obvious application of this would be nano-engines that are able to extract work from structure at the quantum-scale," says Mile. The technique could find applications in sensors and computers operating in remote environments with limited energy.

Phys. Rev. Lett. **122,** 060601 (2019)



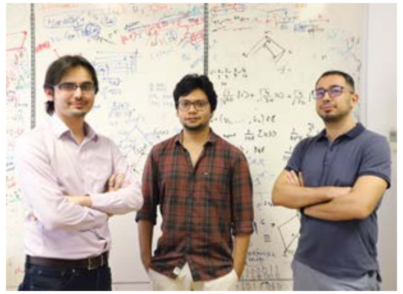
NASA

Quantum satellite launches

The SpooQy-1 nanosatellite built at CQT by Alexander Ling's team entered orbit in June 2019. The satellite is testing a source of entangled photon pairs with on-board measurements, validating technology that could enable long-distance secure quantum communication. The team expect to publish data from the satellite in 2020. As well as the scientific instrument, the satellite carries a quotation from a play (see p.39).

The nanosatellite has a mass of just 2.6kg. This makes it substantially smaller and cheaper to launch than China's 635kg-Micius satellite that demonstrated space to ground entanglement distribution in 2017. CQT handed over operations of SpooQy-1 to spin-off company SpeQtral in December. The researchers are collaborating with RALSpace in the UK to launch a next satellite that will establish a quantum link with ground stations in Singapore and the UK.

More details: https://spooqylabs.quantumlah.org



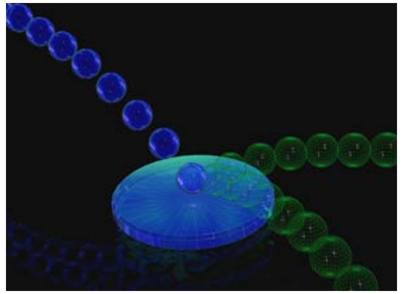
Scheme will certify solo quantum devices

Physicists and computer scientists at CQT collaborated to achieve a breakthrough in self-testing for quantum devices. Self-testing is an approach to certify a device's operation. The researchers showed that the phenomenon of contextuality can be a basis for self-testing, where previous schemes were based on quantum nonlocality.

"Entanglement is considered a costly resource for quantum information processing tasks," says CQT's Kishor Bharti, first author. "Thus, certifying a quantum device with less entanglement is always favourable."

The scheme has the advantage of being able to test single devices, not only pairs of quantum systems, with a few key assumptions: the quantum device has bounded memory, and the measurements going on inside the device follow some structure dictated by an 'odd cycle graph'.

Phys. Rev. Lett. **122,** 250403 (2019)



Quantum simulation explores all futures

CQT theorists Jayne Thompson and Mile Gu collaborated with experimentalists in Australia to realise a quantum simulation of a 'stochastic process' that explores all possible futures. Stochastic processes are those involving an element of chance, such as a coin toss, the diffusion of gases and stock market movements.

As a proof-of-principle, the team simulated with photons a perturbed coin over three tosses, recreating up to 16 possible futures simultaneously in quantum superposition. The algorithms could scale to larger systems, but even at this scale the researchers could demonstrate an application. They measured how quickly possible futures diverge depending on the bias of the coin by interfering the simulated superpositions. The team also want to explore how these simulation techniques could be useful in predictive models for machine learning.

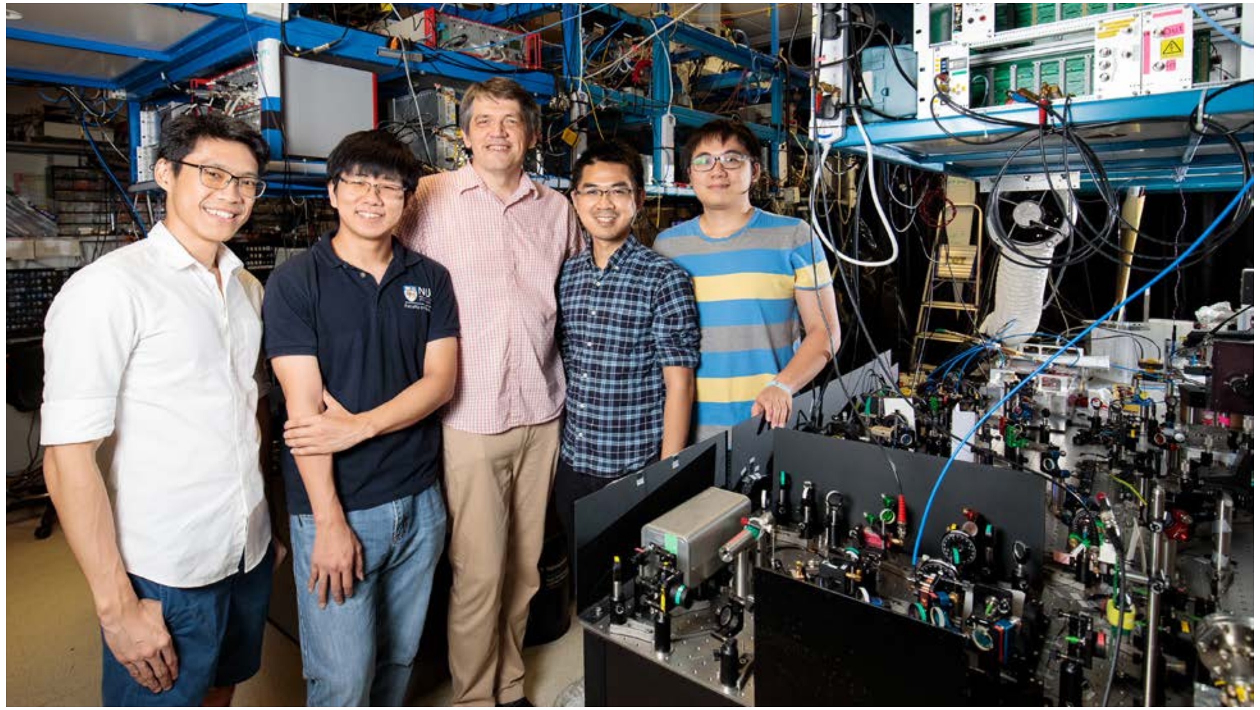
Nature Communications **10,** 1630 (2019)

A precise quantum thermometer

CQT's Valerio Scarani, Stella Seah and their collaborators have proposed a way to achieve quantum advantage in temperature measurements. The team's hypothetical quantum thermometer would use a single quantum bit to take the temperature of an environment by interacting briefly but repeatedly with an intermediary system.

The researchers calculate that this stream of qubit interactions can extract more information about the environment's temperature than could purely classical physics, which hits a limit known as the thermal Cramer-Rao bound. The quantum system gains precision in two ways: each qubit encodes information on the temperature not only in the populations of its energy levels, but also in the coherence between them, and entanglement is generated between successive qubits by their interaction with the probe.

Phys. Rev. Lett. **123,** 180602 (2019)



Information in motion

Research at CQT on quantum computing includes an approach to tackling bigger calculations with smaller machines

There is more than one way to build a quantum computer. Superconducting technology was behind some of last year's big news, but other technologies are still in the race.

At CQT, Dzmitry Matsukevich's lab is exploring a novel approach to computing with trapped ions: encoding information in how the ions move, as well as using ions' internal energy states. This could be a route to doing bigger calculations using fewer physical bits. In 2019, the researchers showed how to perform some logic gates in this system.

Qubits have the potential to exponentially increase our computational power because they can exist in superpositions of information states. Researchers have long known in theory that interfering such quantum states should make it possible to do some calculations more quickly than traditional computers can.

Photo: The group of Dzmitry Matsukevich at CQT is trialling trapped ions as a platform for quantum computing. Pictured from left to right are Jaren Gan, Kim Mu Young, Dzmitry, Nguyen Chi Huan and Tseng Ko-Wei. Jaren and Chi Huan are Research Fellows, Mu Young is a fourth-year NUS physics undergraduate and Ko-Wei is a CQT PhD student.

In 2019, in a milestone for the field, this was shown in practice by the quantum team at Google (see box **From supremacy to advantage**).

Google has focused on building superconducting qubits, likewise IBM. But Intel is working on spin qubits in silicon, and Microsoft on the notion of topological qubits. There are startups across a range of technologies too. Dzmitry previously worked with Christopher Monroe at the Joint Quantum Institute in the United States, co-founder of IonQ and a member of CQT's Scientific Advisory Board. IonQ is using trapped ions for quantum computing.

As in the commercial world, researchers at CQT are exploring a range of platforms (see box **Technology explorers**). There's still basic science to be done.

Consider the problem of scaling. The more complex a computation, the more qubits are needed. We expect to need thousands or even millions of qubits to have a universal quantum computer that offers an advantage for real-world problems. Current quantum machines have just tens of qubits.

To reduce the number of ions needed for complex computational problems, Dzmitry's group is looking at the motional modes of ions as an additional resource. "There has not been so much work in this direction, so I hope that we can do something that other people haven't thought about," says Dzmitry. The project is supported by CQT's core funding and is located at the National University of Singapore.

Confined in a trap, ions oscillate. Dzmitry's group has begun with a single ytterbium-171 ion trapped by electric fields inside a vacuum chamber. The pictures overleaf show details of the setup.

The ion wiggles about the holding point. This motion is a harmonic oscillation – analogous to a mass bouncing on a

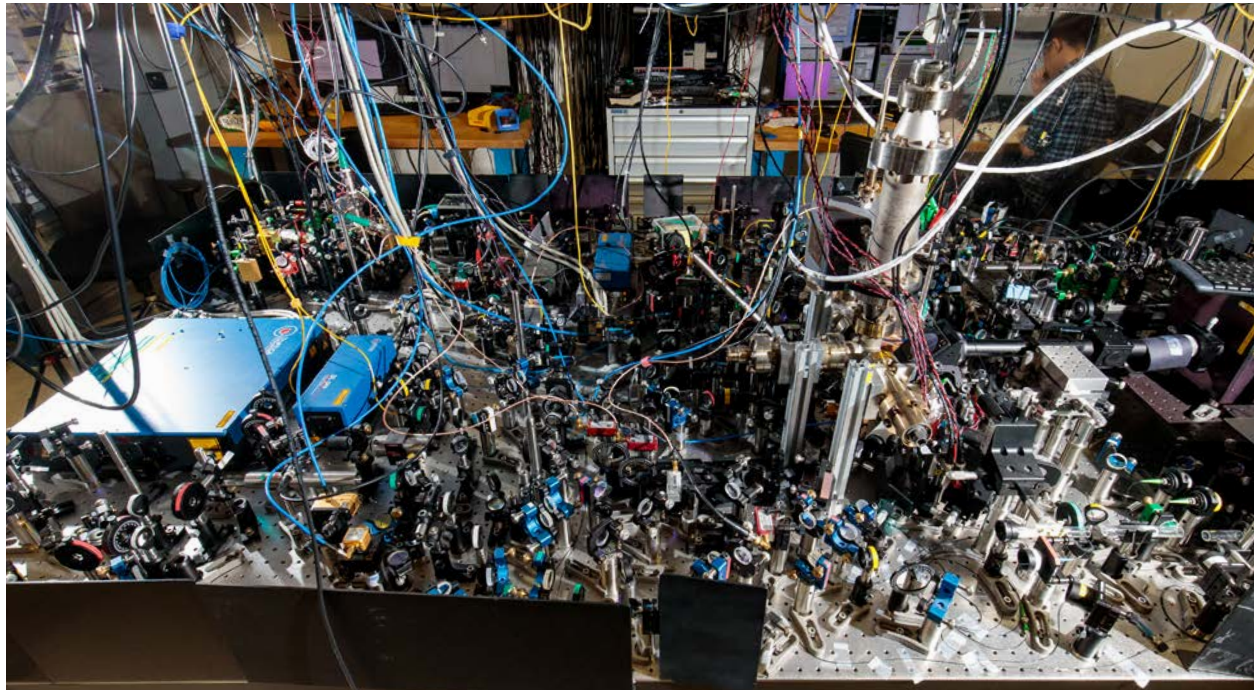
From supremacy to advantage

In October 2019, Google claimed to have achieved 'quantum supremacy', running in three minutes on a quantum computer a calculation they estimated would take the world's mightiest supercomputer 10,000 years. The details were reported in *Nature*. The quantum computer used 53 superconducting qubits. IBM countered that its Summit supercomputer could in fact do the calculation in 2.5 days – if it uses the computer's 250 petabytes of disk storage.

CQT Principal Investigator Dimitris Angelakis, a theorist who previously collaborated with Google's quantum team to simulate materials physics on a 9-qubit chip, wrote about the milestone result for Singapore newspaper *Today*. The sampling problem tackled by Google gave a proof of principle but has no practical application.

"What we're focused on now is turning the power of the soon-to-be-reached few hundred qubits devices into something useful," Dimitris wrote. "There's promise for even small quantum computers to help us design better materials, simulate the structure of molecules for drug discovery, or find more efficient ways to make chemicals with less of an impact on the environment."

Dimitris, along with other CQT researchers and some local start-ups, is exploring algorithms for quantum computers towards a practical quantum advantage. To build a wider community with skills in this field, CQT also hosted opportunities this year for local researchers to explore coding for quantum computers using Qiskit, a software development framework founded by IBM, and CirQ developed by Google (see p.38).



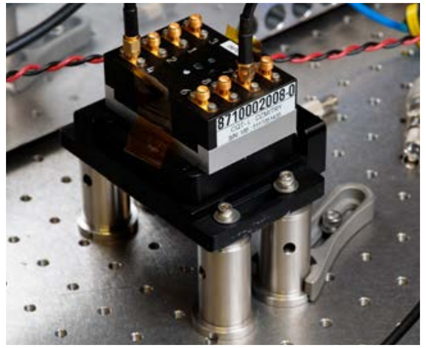
To perform experiments in continuous variable quantum computing, the group uses this entire setup. It occupies a table measuring 4m x 1.5m. In total, there are about 400 to 500 optical elements such as mirrors and lenses.

spring. The ideal harmonic oscillator has infinitely many energy levels. If the researchers can move an ion between its motional energy levels with good enough precision, a single ion could encode in its oscillation more information than even the largest set of qubits. This approach is known as continuous variable quantum computation.

Dzmitry concedes that this method for quantum computation, while promising, is challenging. "In practice, noise and imperfections of our experiments limit the number of harmonic oscillator states that we can control – in our experiment it is usually between five and ten," explains Dzmitry. "But even in this case the amount of information the oscillator can hold is equivalent to two or three qubits."

A further challenge is that the motional states are fragile. Information encoded in the ions' internal states can remain coherent for seconds or even minutes. In contrast, the researchers have observed that quantum states of motion decay in about 10 milliseconds.

The group has made headway with a hybrid approach to quantum computing with ions that uses both the ions' internal states and motion. They are the first to perform a conditional beam splitter (CBS) gate using ions' motional modes. "When

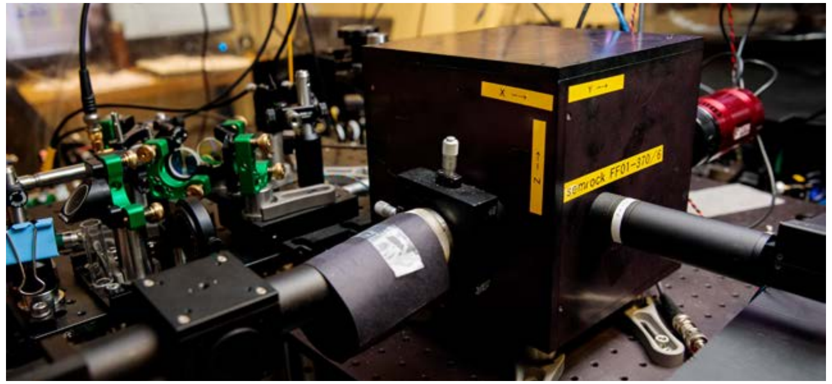


The group is making upgrades to their experiment, including adding an acousto-optical modulator with eight channels. This can direct eight laser beams, so the group will be able to control eight ions simultaneously. The team's old modulator only had a single channel.

For more control over the ions, the group is redesigning their trap. Whereas the old trap had four rods, two needles and only one electrode, the new trap will use four of the gold blades pictured, each of which has five electrodes. The blades will be arranged in X shapes in the white holder. The additional electrodes will allow the researchers to shape the trap which holds the ions, for example to equalise the spacing between ions when they trap a few in a line. This will improve the fidelity of their operations.

we found out that a conditional beam splitter gate could be experimentally realised, we were the only ones in the world who knew that it could be done," says Jaren Gan, who earned his PhD in 2019 with a thesis on this work. He continues in the group as a Research Fellow.

The CBS gate swaps two quantum states depending on some 'control' state. For the group's trapped ytterbium ion, if there was oscillation along one direction and none along another, for example, applying the CBS gate can exchange those states depending on whether the



These unassuming boxes act as eyes for the researchers. The ions are too tiny and dim for humans to see directly. Instead, a photomultiplier tube and camera catch light emitted from the ions to create a digital image.

ion's spin is in the excited or ground state. This swapping function is important for universal quantum computation. The CBS gate also allows the implementation of a 'swap test', a measurement that determines how identical two quantum states are, which has uses in quantum machine learning. This work is described in a preprint posted in August 2019[1].

The group has also performed a controlled SWAP (C-SWAP) gate. Like the CBS gate, the C-SWAP will swap two quantum states depending on a control state. The two gates have different uses because the CBS gate introduces a phase difference between the two swapped states while the C-SWAP gate does not. The team are working on improving their setup before publishing results on the C-SWAP gate.

A future goal of the group is to implement machine learning algorithms. With mastery over ions and their movement, the researchers are also doing experiments in quantum thermodynamics. Previously the group used three trapped ions to demonstrate an absorption refrigerator. This work was published in *Nature Communications* in January 2019 (see p.6).

For PhD student Tseng Ko-Wei, the experimental realisation of the C-SWAP gate was the most exciting part of the work so far. "We knew that it was possible in theory to perform the controlled SWAP gate from the CBS gate, but achieving it in our experiment was something really amazing," he says.

Technology explorers

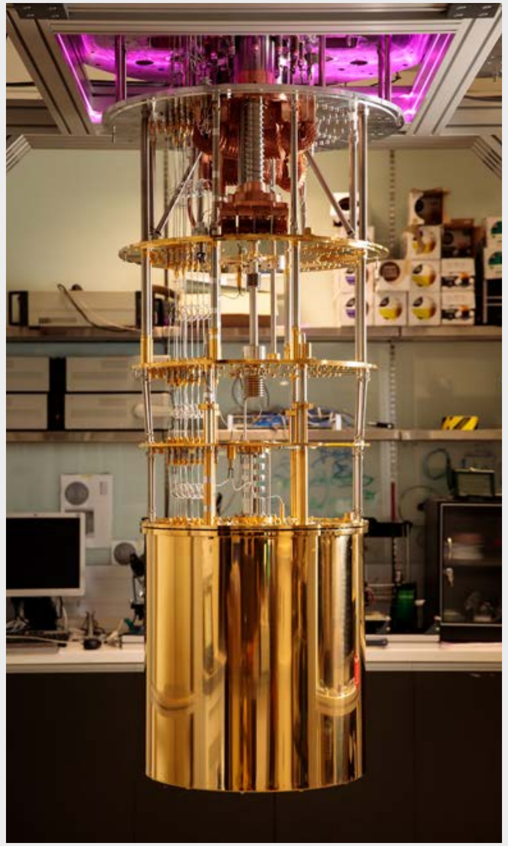
Today's computers are powered by the silicon transistor. Before silicon technology was perfected, computers used unwieldy vacuum tubes and filled whole rooms. The state of today's quantum computers is often compared to those early days of computing history. What quantum transistor might we find inside the quantum computers of the future?

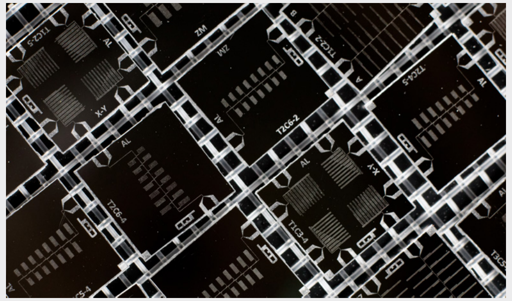
Photo: Superconducting quantum bits have to be chilled to temperatures near absolute zero to function. Here CQT's Rangga Perdana Budoyo (left), Alessandro Landra (right) and Christoph Hufnagel (centre back) work on the dilution refrigerator that will enclose and cool a superconducting chip.

[1] H. C. J. Gan, G. Maslennikov, K.-W. Tseng, C. Nguyen, D. Matsukevich, Hybrid quantum computation gate with trapped ion system, https://arxiv.org/abs/1908.10117

Superconducting qubits seem to have the lead for now. That technology, pursued by Google and IBM among others, is also worked on in Singapore. CQT Principal Investigator Rainer Dumke in 2019 installed a new dilution refrigerator (pictured) and manufacturing equipment in his laboratories at the Nanyang Technological University to make and test superconducting chips. They aim to match the state-of-the-art within five years. Singapore's National Research Foundation has also awarded a Fellowship to Yvonne Gao who has expertise in superconducting qubits to begin setting up her own research group in 2020.

Ions remain contenders, and at CQT it is not only Dzmitry Matsukevich (profiled in the main story) who is doing quantum computing with ions. CQT Principal Investigator Manas Mukherjee traps barium ions. His group specialises in optical qubits for information processing by global operations. He is also working on the miniaturisation of ion traps for scalable quantum computing.

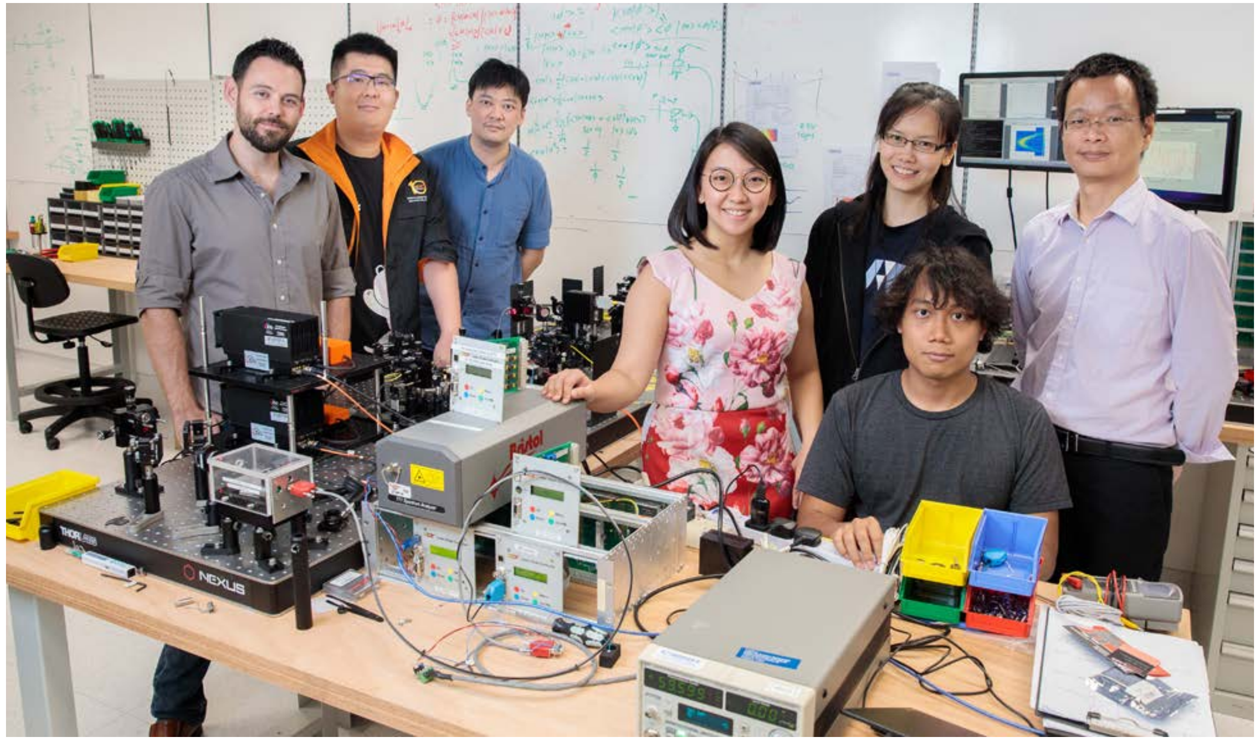




That's not to say it's a two-horse race. There are other technologies in consideration around the world. Researchers at CQT are working with some of them, such as Rydberg atoms and cold molecules. These research groups have other goals, such as the simulation of quantum systems, but they develop techniques and expertise that may support quantum computing too. Elsewhere in Singapore, researchers at the Agency for Science, Technology and Research are working on spin-valley qubits in 2D materials and photonic approaches to quantum computing.

"It makes sense to keep a broad base of expertise across different quantum technologies because we cannot predict that one will be the winner," says CQT Director Artur Ekert.

Photo: Facilities to operate and manufacture superconducting quantum chips were set up in a collaboration by Nanyang Technological University (NTU), DSO National Laboratories and the Centre for Quantum Technologies. Rainer Dumke's team at NTU has designed superconducting chips (bottom picture) which include resonators and several superconducting qubit architectures. The top picture shows the inner workings of the dilution refrigerator.



Commercial collaborations to advance QKD

Partnership with Singtel sees technique tested in deployed fibre

CQT researchers have demonstrated a technique that boosts expectations for quantum key distribution (QKD) over commercial fibre. The technique, tested over 10km of Singtel's fibre network, keeps entangled light particles in sync as they navigate the network.

The work results from years of close collaboration with Singtel, Asia's leading communications technology group, which partnered with the National University of Singapore in 2016 to form a corporate research laboratory.

QKD promises communication security resistant to progress in computing power and programming, making it a natural fit for the lab's focus on cyber security.

When the NUS-Singtel team published results in April 2019[1], Mr Bill Chang, CEO, Group Enterprise at Singtel said: "The breakthrough achieved by the NUS-Singtel Cyber Security R&D Lab not only strengthens our defences in a new cyber reality where threats are becoming more sophisticated, it also positions Singapore as a hub for global QKD research. We will continue developing and fine-tuning this technology with the aim of commercialising it through our global footprint of product engineering centres."

Photo: In the NUS–Singtel Cyber Security R&D lab, researchers from CQT work closely with scientists and engineers from Singtel to develop quantum communication technology.

RESEARCH IN FOCUS

The NUS-Singtel Cyber Security R&D Lab is a public-private partnership supported by the National Research Foundation (NRF), Prime Minister's Office, Singapore. NRF is also supporting a collaboration in QKD with a commercial partner for hardware development (see box **Making chips**).

Singtel is not the only big company in telecommunications giving QKD a close look. South Korea's SK Telecom made news in 2018 with a US$65 million investment in the company ID Quantique, among the first commercial providers of QKD technology. ID Quantique was originally established as a spin-off in 2001 by four scientists from the University of Geneva in Switzerland. Other companies working on deployment of QKD include Toshiba and BT.

Most QKD schemes require that the sender and receiver exchange individual photons directly or trust the source of their keys. CQT Principal Investigator Alexander Ling leads development in the NUS-Singtel lab of an alternative technology that uses pairs of entangled photons instead. With this approach, it is possible to check the security of a key provided by a third-party supplier.

The idea is that the supplier creates pairs of photons, splitting them up to send one to each of the two parties. Those two parties then have a way to communicate securely. Detecting the photons allows the two parties to generate a matching key that can be used to lock and unlock a message. The parties rule out eavesdroppers or untrustworthy operators by openly comparing a set of their measurements to check the correlation between paired photons.

A challenge is that each photon encounters a different obstacle course of spliced fibre segments and junction boxes. The photons also suffer dispersion, where they effectively spread out. This affects the operators' ability to track the photons.

To cancel out this effect, CQT researchers carefully designed a photon source to create pairs of light particles with colours either side of a known feature of optical fibre called the 'zero-dispersion wavelength'. In optical fibres, bluer light would normally arrive faster than redder light, spreading out the photons' arrival times. Working around the zero-dispersion point makes it possible to match the speeds through the photons' time-energy entanglement. Then the timing is preserved.

Known as nonlocal dispersion compensation, the technique had been tested before in labs but not across real networks. Alexander said, "Before these results, it was not known if the multi-segment nature of deployed fibre would enable high precision dispersion cancellation, because the segments don't generally have identical zero dispersion wavelengths."

Photo: Quantum signals generated in CQT's labs were routed through a section of Singtel's fibre network. Here CQT Research Fellow Poh Hou Shun checks the connections.

[1] J. A. Grieve, Y. Shi, H. S. Poh, C. Kurtsiefer, A. Ling, Characterizing nonlocal dispersion compensation in deployed telecommunications fiber, *Applied Physics Letters* **114,** 131106 (2019)

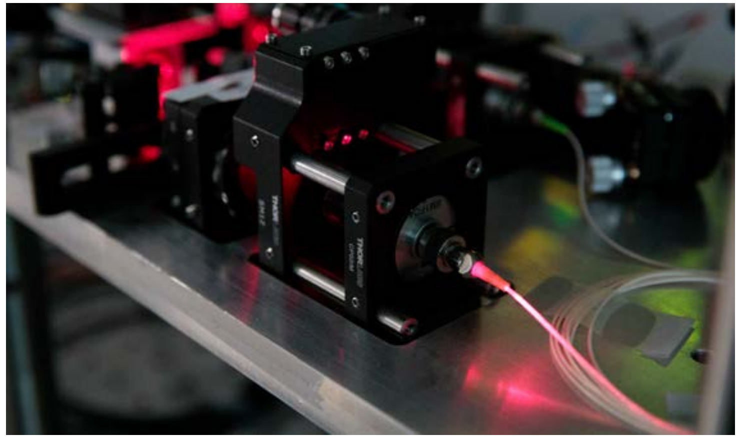


Photo: The team designed and built a quantum light source that creates entangled particles of light at wavelengths well suited to commercial optical fibre. They have wavelengths around 1316 nm, falling within the telecoms O-band.

The fact it works is good news for QKD. "Timing information is what allows us to link pairs of detection events together. Preserving this correlation will help us to create encryption keys faster," says James Grieve, a CQT Senior Research Fellow. He and Alexander co-authored the paper along with CQT's Shi Yicheng, Poh Hou Shun and Christian Kurtsiefer.

Such well-timed entangled photons could find applications even beyond key distribution. For example, the photons in each pair are created within femtoseconds of each other. Their coordinated arrival times might synchronise clocks for time-critical operations such as financial trading.

Making chips

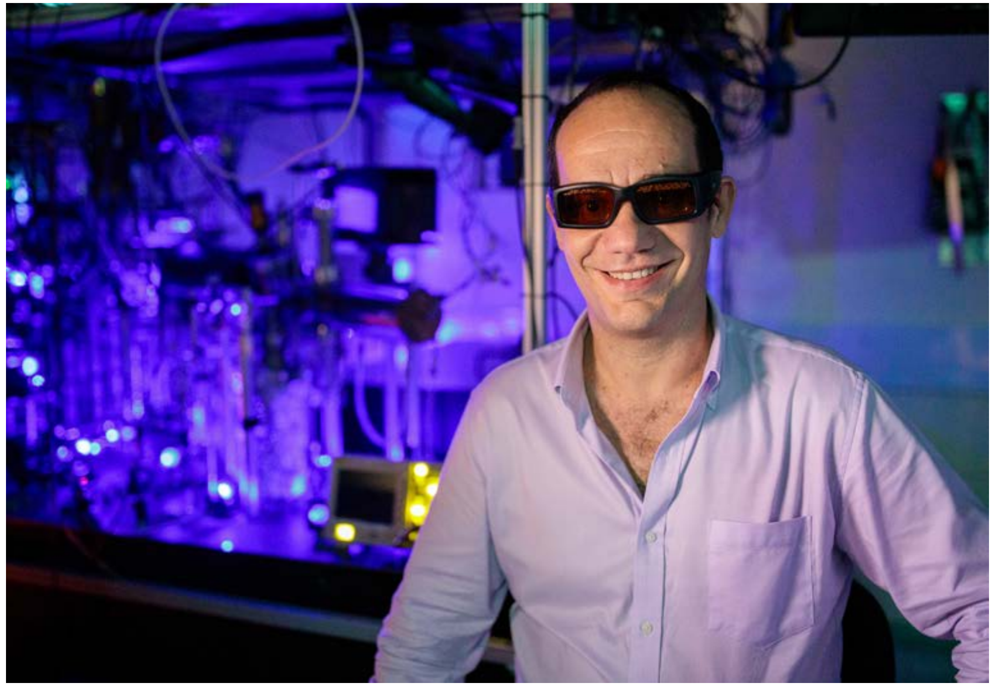
In a separate project, CQT Fellow Charles Lim will be working with imec, known for its work in nanoelectronics and digital technologies, on developing QKD chips. imec is an international company headquartered in Belgium.

When NUS and imec signed a Research Collaboration Agreement in September 2019, both sides explained their goals.

"Our approach consists of developing and integrating all QKD key components in a single silicon-photonics based chip, which ensures a cost-effective solution," said Joris Van Campenhout, R&D Program director at imec. "As a first deliverable, we will jointly develop an ultrafast quantum random number generation (QRNG) chip, a key component for generating the secret keys. Secondly, we will work on a compact, fully-integrated photonic quantum transmitter prototype chip. In these efforts, we will strongly leverage imec's deep expertise in silicon photonics technology, originally developed for conventional datacom and telecom applications."

Charles said "Our team at NUS will bring in expertise on the theory, protocol design, and proof-of-concept experiments of the quantum random number generator and QKD systems. We're very excited to collaborate with imec, as their expertise will allow us to translate these solutions into real silicon-photonics based chips – by using imec's process design kits and re-usable IP blocks."

The collaboration is supported under Singapore's Quantum Engineering Programme.



A new spin on cold strontium atoms

CQT welcomes David Wilkowski as Principal Investigator

Bringing decades of experience in cold atoms research, experimentalist David Wilkowski in 2019 became a Principal Investigator at CQT. This followed him accepting a position as Associate Professor at the School of Physical and Mathematical Sciences of the Nanyang Technological University (NTU) the previous year.

But David is hardly a newcomer to the CQT family – he first joined CQT in 2009 as a Visiting Associate Professor through a collaboration with the French National Centre for Scientific Research (CNRS) (see box **Transcontinental ties**). "To work in a rapidly growing field like quantum technologies, it's important to know what's going on and have the right information at the right time. So, since the beginning, the CQT has been a very important affiliation to me," he says.

In this time, David has enjoyed building his research projects at NTU from scratch. His group now has a total of three cold atom setups, two with strontium and one with caesium atoms. "In experimental science," he says, "we are attached to our equipment and we have to ask ourselves: what can we do with this machine and can we choose the right element to work with? Cold atom experiments may take several years to set up."

Cold atoms are promising for condensed matter physics, since they offer a controllable platform for the simulation of particles' actions. Commonly, experiments aim to simulate electron systems, which have symmetry SU(2) corresponding to the electron's half-integer quantum spin.

In his most established setup with strontium, David envisions going to

Photo: The laser used to control strontium atoms in experiments run by David Wilkowski, who was appointed a CQT Principal Investigator in 2019, bathes his laboratory in a purple glow.

higher spins to study more complex systems. "We can go up to spin-9/2, and I think it's very exciting to see what these higher symmetries can bring," he says. Such work may address unsolved questions in material science or lead to new quantum error-correction protocols.

David is using strontium atoms to simulate and study the artificial gauge fields they can create. The experiments involve watching the evolution of the atoms' spin degrees of freedom. The team in 2018 observed non-Abelian geometric transformations in stationary atoms that experienced different temporal loop patterns of the laser phase. Instead of keeping the atoms' positions fixed, David now wants to let them move. "We expect to see the equivalent of a spin Hall effect: the gauge field will separate the two spin components. While the gauge field remains constant and homogenous, the atoms will make their own little loop," he says.

The second strontium setup is under construction and aims at precision measurement, exploiting an optical clock transition to measure gravitational effects. This experiment may soon find practical applications, but David sees it as a stepping stone to more revealing results. "It's important to have intermediate goals, to reach some results in between. I believe that fundamental studies are still crucial for the development of quantum technologies," says David.

The group's third project is hosted by NTU's Centre for Disruptive Photonic Technologies. The aims are to trap, manipulate and image caesium atoms beyond the diffraction limit, using nanophotonic technology.

To ensure everything runs smoothly, David is proactive in his collaborations and strives to help his group members develop into independent researchers by mentoring them with respect and kindness.

His former doctoral student Kwong Chang Chi, whose dissertation earned him a medal from the Materials Research Society of Singapore in 2017, appreciates this guidance. "That's why I stayed as a postdoc," Chang Chi says, "I can go home to my family every day and feel good about the work I do."

"I work with my PhD students a lot," David says, "they have a well-defined project on a well-defined experiment. When the student has difficulties, you need to know enough to help them debug, but you don't have to micromanage. At the end of their project, I hope that my students are better than me at their experiment — they should be the experts and I should learn from them."

Going into 2020, David's group comprised only three doctoral students and three postdoctoral researchers. He plans to grow his team in the year ahead and will be listing opportunities on his group website.

Transcontinental ties

Having begun his research career in France, David has put down roots in Singapore while maintaining international collaborations. He obtained his doctorate from the University of Lille in France in 1997, then went to a postdoc position in Pisa, Italy. He was subsequently awarded an associate professorship at the University of Nice in France, moving to Singapore in 2009 with a visiting position. "Being in Singapore gave me access to a research environment that is difficult to find in France," he says. He is one of a few CQT researchers to have strong French connections.

The MajuLab, an international joint research unit established by CNRS in 2014, supports collaboration between a set of French and Singaporean research organisations. David acts as Associate Director for MajuLab.

The Quantum SG initiative

Singapore's quantum community engages with policymakers to plan for the future

With an eye on advances in quantum technologies and investments in other countries, Singapore's quantum researchers are putting their heads together to contribute to the development of national strategy. These ground-up efforts aim to complement the top-down views of government agencies as Singapore plans its next five years of research funding.

The Quantum SG initiative began in 2018 as a series of meetings for researchers in Singapore in quantum science and technology. Initiated by a group of CQT Principal Investigators, the goal was to create a forum to network, discuss research and share visions on the scientific future of the field with a special focus on the contributions Singapore can make.

There are over 40 quantum research groups in Singapore (see infographic, next page). After just four meetings, this community has built itself an online home at quantumsg.org, issued a report on Singapore's quantum ecosystem that presents 15 actionable recommendations, and prepared research reviews as inputs for strategic planning.

The report "Quantum Technologies in Singapore – preparing for the future" released in October 2019 was prepared by a team of seven editors in consultation with the community. It surveys the local quantum landscape, looking at activities in quantum computation and simulation, quantum communications, quantum sensing and metrology, and upstream research.

The report makes the case that Singapore has the potential to be an international hub in quantum technologies thanks to its far-sighted investment in research.

To quote from the executive summary: "There are already early signs of research contributing to the local economy, through engagement with industry partners and the creation of spin-off companies. Considering the country's active startup culture and excellent industrial base, we think Singapore could find an international role as a test-bed for deploying quantum applications."

Recommendations include increasing the number of PhD positions in quantum science and technology, providing more small grants for upstream research and seizing opportunities to join international research efforts.

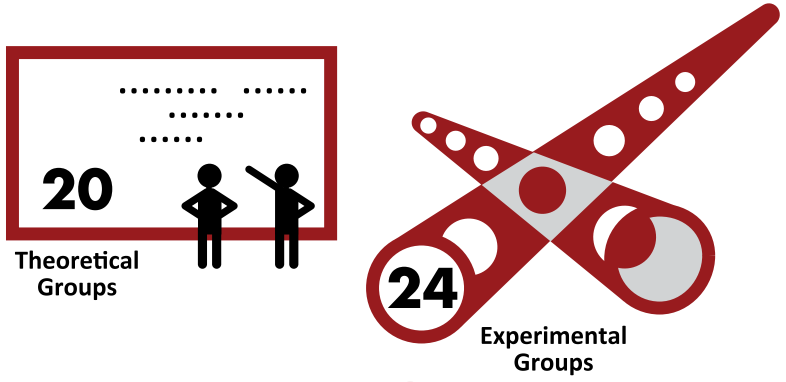
The summary notes "It is a critical time to review Singapore's strategy in quantum technologies because of the launch of other national and international initiatives in the field. In the face of increased global funding for quantum technology research, the fledgling quantum ecosystem in Singapore is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

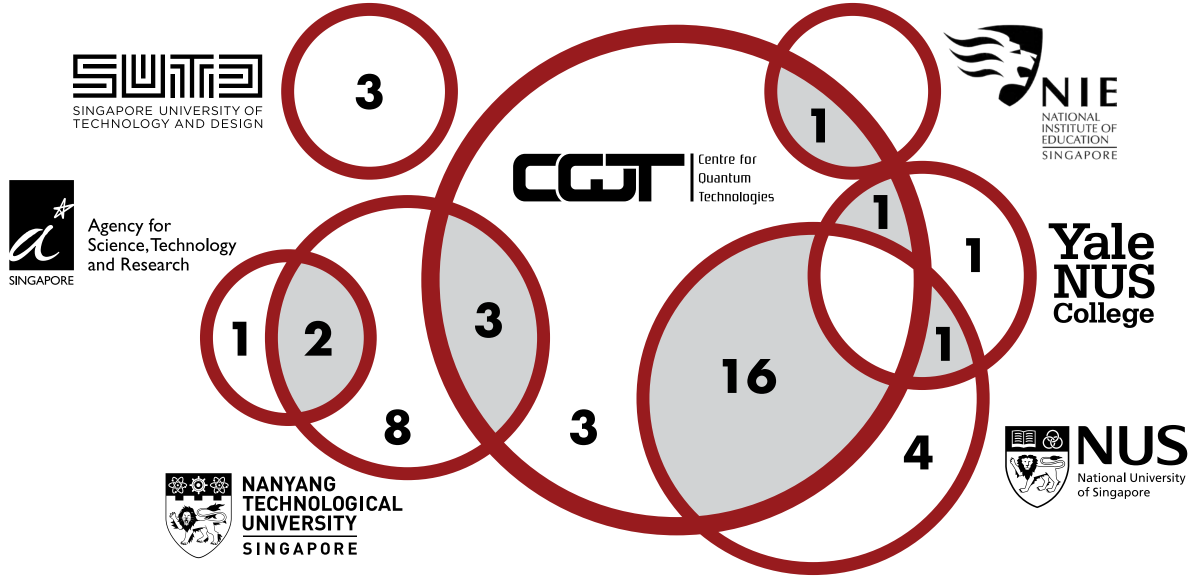
The full report is available to download at quantumsg.org. The editors were Dimitris Angelakis, Rainer Dumke, Christian Kurtsiefer, Charles Lim, Alexander Ling, Loh Huanqian and Manas Muhkerjee.

Now the community is rallying to contribute ideas on research directions for Singapore's future for the next five years, ten years and beyond. Scientists have selected a range of potential focus topics, preparing summaries that will be fed up to an expert committee. This ground-up view of what Singapore can achieve as a quantum island will be input for policy-makers putting together Singapore's Research, Innnovation and Enterprise (RIE) Plan 2025.

Singapore has planned its research spending in five-year tranches since 1991, with the budget rising to a $19 billion commitment for the RIE 2020 plan. This is about 1% of GDP.

Singapore Prime Minister Lee Hsien Loong, speaking at a press conference following a meeting of the Research, Innovation and Enterprise Council in March 2019, said "The RIE efforts we do must be balanced across a range – from basic research in focus areas, to promoting development in the application of new ideas, to promoting entrepreneurship and companies which can exploit these ideas, in order to ultimately reap economic dividends from our investments. We must and we will continue to invest in science, technology and innovation in the long term."





In 2019, Singapore's quantum community launched the quantumsg.org website, inviting groups doing research in this field from all institutes to list themselves. By the end of the year, 44 groups had joined. The infographic shows the interconnected relationships that Singapore's research entities have established in hosting these groups. The website shows in one place the breadth of the local research community and facilitates collaboration by linking directly to each group's homepage.

SGInnovate

Partnership supports quantum 'deep tech'

CQT is collaborating with SGInnovate to build commercial awareness and successful businesses in quantum technologies

As an academic research centre, CQT develops technical skills and generates ideas. To bolster the commercial know-how and networks of scientists who want to turn their innovations into products with real-world impact, CQT has formed a strong partnership with local organisation SGInnovate.

"The mission of the SGInnovate team is to work with entrepreneurial scientists to build deep tech startups. One of the most complex and exciting areas for our work is the field of quantum technologies. Through our partnership with the Centre for Quantum Technologies, we are going straight to the source of remarkable quantum research conducted in Singapore. We want to help entrepreneurial scientists working with quantum technologies to build commercially successful startups," said Steve Leonard, Founding CEO, SGInnovate.

In June 2019, CQT and SGInnovate signed a Memorandum of Intent (MOI) to promote quantum technologies and facilitate the commercialisation of quantum innovations in Singapore.

Through the two-year collaboration, the two organisations will help local researchers working on quantum technologies to commercialise their research in the field, translating quantum science into scalable industry solutions. CQT and SGInnovate will also partner to organise events that raise market awareness and connect people with ideas to opportunities.

SGInnovate, a private-limited company owned by the Singapore Government, is focused on adding value to Singapore's deep-tech startup ecosystem by development of talent and through investment.

CQT has already seen a handful of startups established in quantum technologies

Photo: Shaking hands on a Memorandum of Intent: Steve Leonard (left) from SGInnovate and Artur Ekert (right) from CQT agreed a partnership between the two organisations that will support events, training and businesses in quantum technologies.

by its alumni, some licensing IP from the University. Three of these startups have already received investment from SGInnovate (see box **Funded startups**). The individual sums are not disclosed, but the companies join a portfolio that has been successful in attracting further funding. SGInnovate told newspaper *The Straits Times* in October 2019 that it had invested $40 million in some 70 local and foreign deep tech startups in just under three years – and that those companies went on to attract $450 million of funding from the market.

For CQT scientists deciding whether to follow an entrepreneur's route, Tong Hsien-Hui, Head of Venture Investing at SGInnovate, gave a talk at CQT in September 2019 about what it takes to build a deep tech startup. One tip: start from the problem you can solve, not the technology you have.

For those aspiring entrepreneurial scientists, SGInnovate would serve as a commercial advisor, providing coaching and active support at all stages of forming, launching and scaling their startups. The support from SGInnovate also includes the raising of investment funds from the VC community.

Beyond investment, startups can also benefit from SGInnovate's Summation Programme, which recruits and co-funds students for apprenticeships of three to six months. Prospective apprentices, from both Singapore and abroad, already have the option to choose projects in quantum startups.

In the second strand of the collaboration, SGInnovate and CQT are hosting frequent quantum-focused events, especially among potential industry partners and investors. A total of eight events were held in 2019 (see box **Growing community**). Such events will help to build a strong and entrepreneurial quantum ecosystem in Singapore. A first joint training workshop giving a two-day introduction to quantum technologies is planned for March 2020.

Summing up the two sides' goals when the MOI was announced, CQT Director Artur Ekert said "Together, we aim to catalyse the translation of our scientific advances into technologies that will benefit the economy and society."

Growing community

CQT and SGInnovate are partnering to organise workshops, thought-leadership and community events, pooling expertise and networks to select speakers and invite attendees. Over 1000 people registered for the eight joint events held in 2019, which featured speakers from organisations including Google, Baidu and Alibaba as well as local experts. Video recordings of many of these events are available on YouTube.

- Securing communications with quantum networks, 21 November 2019
- Quantum: The Exhibition – industry networking evening, 14 October 2019
- Building quantum computers: current state of the art, use cases, and challenges and opportunities ahead, 19 September 2019
- Building useful quantum computers with atoms, 16 August 2019
- Quantum computing meets AI: concepts and use cases, 6 August 2019
- Towards a future quantum economy, 7 June 2019
- Getting ahead in the quantum economy: a deep dive into the hardware, 8 May 2019
- Quantum computers: how they work and what they'll mean for big data and business, 17 January 2019

Funded startups

Three startups with connections to CQT have received funding from SGInnovate as of the end of 2019.

HORIZON
QUANTUM COMPUTING

The first company to join SGInnovate's portfolio was Horizon Quantum Computing in 2018. Singapore's first quantum computing startup, the company is led by former CQT Principal Investigator Joseph Fitzsimons. It is designing software development tools to simplify and expedite the process of developing quantum-enhanced applications, without the need for prior experience in the area. SGInnovate led the seed funding round.

SPEQTRAL

SpeQtral, which has licensed CQT-generated IP and know-how to develop compact quantum light sources, announced its USD 1.9 million seed round in April 2019. The round was led by the US-based Space Capital with SGInnovate among the investors. SpeQtral is using the funds to kick off a commercially-focused space-to-ground cubesat quantum communication demonstration mission, expand its team, open offices in Singapore and the United States, and develop further advances in quantum communication technology. The company CEO, Lum Chune Yang was formerly CQT Head of Strategic Development, Industry Relations, and continues to advise the Centre. SpeQtral has also recruited from the Centre's alumni (see p.33).

Photo: SpeQtral has quickly grown a team. Here members of the company including US-based colleagues are pictured in SpeQtral's new office space at Singapore's Science Park, just a few minutes away from the National University of Singapore campus.

ATOMIONICS

The most recent company to receive funding is Atomionics, co-founded by CQT alumnus Ravi Kumar. Details of the funding have not been made public. Atomionics intends to build atom-interferometry based sensing systems for navigation and exploration that will work reliably and accurately everywhere – including underwater, underground and other GPS-denied areas.

QUANTUM: The Exhibition

Public exhibition supported by CQT and partners opens to more than 150,000 visitors

Visitors to Science Centre Singapore have had the opportunity to learn about quantum technologies, thanks to a project initiated by CQT to bring QUANTUM: The Exhibition to its galleries.

The world's first travelling exhibition focussing on quantum science and technology, QUANTUM: The Exhibition was developed by the Institute for Quantum Computing (IQC) at the University of Waterloo in Canada. The installation in Singapore includes new exhibits on local research designed to complement the original exhibition.

The exhibition was officially launched on 19 August with Singapore's Minister for Education, Mr Ong Ye Kung as guest-of-honour. Originally scheduled to run until 2 January, it has been extended to stay open into March 2020. The exhibition toured seven science centres across Canada from 2016 before it came to Singapore in 2019 to make its international debut.

CQT is one of the sponsors of the exhibition and a contributor to the new exhibits. The other organisations sponsoring the Singapore exhibition are the Agency for Science, Technology and Research, Nanyang Technological University, National Research Foundation

Photo: QUANTUM: The Exhibition at Science Centre Singapore combines a travelling exhibition developed in Canada with new exhibits about research in quantum technologies in Singapore. One addition seen here features the stories of inspiring young scientists working in quantum technologies in Singapore today.

Singapore, and National Supercomputing Centre Singapore. Some 100 invited guests of the sponsors attended the official opening.

"The exhibition presented a wonderful opportunity for the different research organisations working in quantum technologies in Singapore to come together to show the breadth of activity and expertise in the country," says Jenny Hogan, Associate Director for Outreach and Media Relations at CQT. CQT's outreach team worked with Science Centre Singapore and other local partners to develop the local exhibition materials.

Altogether, the interactive exhibition occupies around 4,000 square feet across five different zones (see box **What's in the exhibition**). It brings scientific concepts to life through a mix of creative story-telling and gamified experiences. A visitor begins with quantum concepts, dips into the history of computing, and then dives deep into the potential of quantum technologies.

From the opening until the end of 2019, Science Centre Singapore received over 150,000 visitors who would have opportunity to enter the exhibition under their general admission ticket.

One goal of the exhibition is to introduce Singapore's young students to a cutting-edge field that will need more talent.

"We are proud to present QUANTUM: The Exhibition alongside our co-sponsors and research collaborators. We hope that Singapore's young people will visit, be excited and be thoughtful about how they will experience quantum technologies in their lifetime. Scientists of my generation are providing the tools to build quantum technologies. It is up to the next generation to discover everything that we can do with them," said Artur Ekert, CQT Director.

After the exhibition opened, CQT Principal Valerio Scarani wrote an opinion piece for Singapore newspaper *The Straits Times* explaining why the reader should care about quantum physics. As well as highlighting the exhibition, he noted that the National University of Singapore has begun offering a specialisation in quantum technologies to physics undergraduates. "To build a 'quantum-ready' workforce here in Singapore that understands these exciting new opportunities, we need to offer the right technical training," he wrote.

Associate Professor Lim Tit Meng, Chief Executive of Science Centre Singapore, said: "Quantum physics is arguably the greatest intellectual triumph in the history of human civilisation, but its reputation is often one that is mysterious and difficult. With QUANTUM: The Exhibition, we hope to make this discipline of science less remote and more relevant, for people of all ages and backgrounds to discover. It has always been our goal to create opportunities for our guests to be inspired by the marvels of science and ultimately push the frontiers of possibilities."

Photo: Interactive exhibits give a hands-on experience of quantum science and technology. They include a projected cat silhouette in a superposition of dead and alive, a double slit experiment and the game pictured, in which visitors control the path of a laser beam.

What's in the exhibition?

QUANTUM: The Exhibition has five distinct zones that bring visitors on a learning journey about quantum technologies. Over 30 local experts contributed to developing displays on research happening in Singapore, which are integrated throughout the original travelling exhibition.

Introduction

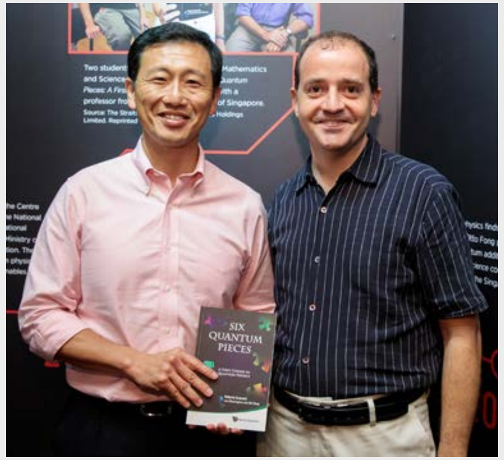
A video of local quantum scientists invites visitors to explore the quantum world. Entry is through a tunnel with lighting effects that evoke the feeling of entering the realm of quantum waves and particles.

Quantum mechanics '101'

In the first scientific zone, visitors meet the core concepts of quantum mechanics such as entanglement and wave–particle duality. Singapore additions include a device built at CQT that visitors can operate to make quantum-entangled light particles and an animation about the role of atomic clocks in Singapore, featuring work by A*STAR's National Metrology Centre and CQT researchers.

The evolution of information technology

This section provides a brief reminder of the history of information technology. What is a computer and how does it work? Interactives get visitors to explore the concepts of binary code and secret messaging. There's also an introduction to Singapore's supercomputer which has petascale processing power.



Quantum information science and technology

Armed with knowledge of quantum mechanics and information technology, visitors then explore what happens when we combine the two: more powerful computers, more secure communication and more precise sensing.

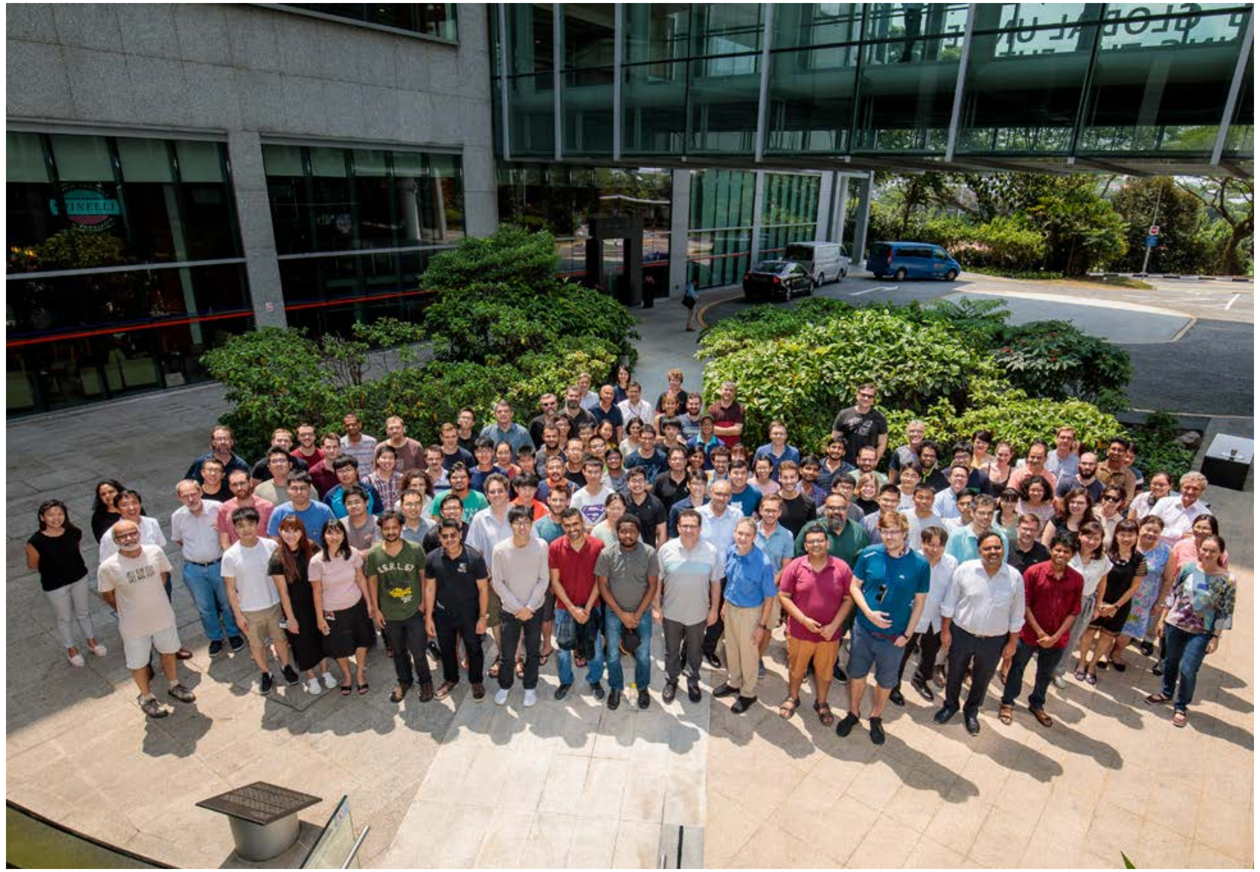
Local highlights include a collection of experimental quantum computing devices developed by various groups, a satellite loaned by the company GomSpace that carries a quantum light source built in Singapore, and Quantum, a laser artwork inspired by the concepts of quantum computing and entanglement. The artwork by Jun Ong was co-commissioned in 2018 by CQT and the ArtScience Museum at Marina Bay Sands.

This section also includes a series of profiles of six local scientists, including CQT's Manas Mukherjee, Ng Hui Khoon and Charles Lim. Their video interviews can be watched at https://bit.ly/quantum-scientists-sg.

The future

The last zone invites visitor feedback and closes with a timeline of events in Singapore's quantum history, showcasing the story of the local quantum community's growth from the 1990s to the present day.

Photo: Singapore's Minister for Education Mr Ong Ye Kung attended the exhibition opening in August. As a token of appreciation, CQT Principal Investigator Valerio Scarani presented to him an introductory textbook called Six Quantum Pieces. Valerio co-authored the book with two students from NUS High School.



Nurturing a community of quantum expertise

We bring together top physicists, computer scientists and engineers

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Artur Ekert
Director
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Lee Kong Chian Centennial Professor
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Professor of Quantum Physics
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Institute of Standards and Technology

CQT welcomed a new member to its Governing Board in 2019 with a change in representative from the Ministry of Education. We welcome Teo Kien Boon and thank Vincent Wu for his service. CQT also thanks Lui Pao Chuen, Advisor to the National Research Foundation, Singapore, who stepped down from the board in 2019 having provided guidance and oversight for the Centre since it was founded.

Principal Investigators

EXPERIMENTAL PHYSICS

Murray Barrett
Kai Dieckmann
Rainer Dumke
Christian Kurtsiefer
Wenhui Li
Alexander Ling
Loh Huanqian
Dzmitry Matsukevich
Manas Mukherjee
Travis Nicholson
David Wilkowski

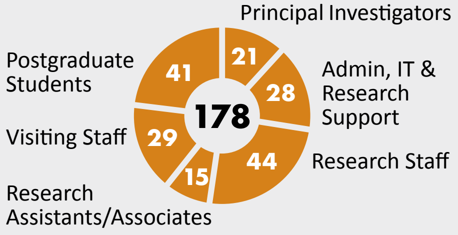
THEORETICAL PHYSICS

Dimitris G. Angelakis
Berge Englert
Dagomir Kaszlikowski
Kwek Leong Chuan
Valerio Scarani
Vlatko Vedral

COMPUTER SCIENCE

Divesh Aggarwal
Rahul Jain
Hartmut Klauck
Miklos Santha

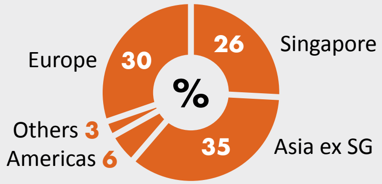
Headcount



Count of CQT staff and students
as of 31 December 2019

CQT also hosted in 2019 a total of
91 visitors and 39 interns

Nationalities



Nationalities of CQT staff and students
as of 31 December 2019

https://www.quantumlah.org/people

Students at CQT

41
CQT PhD students as of 31 December

11
CQT PhD graduates in 2019

75
CQT PhD graduates since CQT founded

PhD programme

CQT offers high-quality education and supports graduate students in making original contributions to research. We accept applications through the year from motivated students who want to work in the dynamic field of quantum technologies, offering a generous scholarship plus allowances for students of all nationalities. Doctoral degrees are awarded by the National University of Singapore, consistently ranked among the leading universities in the world. CQT Principal Investigators (PIs) also accept students funded by other sources.

Photo: Graduates who attended the the NUS commencement ceremony in 2019 were, from left, Len Yink Loong, Suen Whei Yeap, Goh Koon Tong, Jirawat Tangpanitanon and Ye Luyao. Four moved into research positions in Singapore and one took a postdoc role in Poland.

Internships

39
CQT Interns in 2019

CQT supports internships for students near the end of an undergraduate degree or during masters studies. Applications should be made directly to the PI with whom the student would like to work. Successful interns may be invited to join the CQT PhD programme.

"CQT is an excellent institution for PhD candidates to explore and develop scientific ideas. It has a very conducive and motivating learning environment, which encourages many inter-group collaborations. It is the ideal place for bringing research in quantum technology to the next exciting level."

Debbie Lim Huey Chih
PhD student in computer science

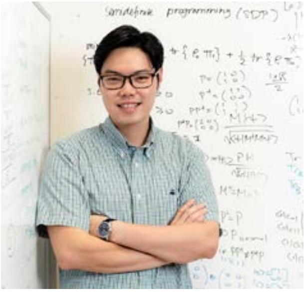
"The PhD experience at CQT is not just about being part of a renowned international research centre, it is also about building bonds with the other students through weekly and monthly activities such as board games, dinners and much more!"

Adam Florentin Thierry
PhD student in experimental physics

Recognition

CQT's achievements are a collective effort of its excellent scientists, students and support staff, but individual successes also merit celebration. Cheers to the CQT staff who won awards in 2019!

"For his research on quantum cryptography that paves the way to practical quantum-safe networks", **Charles Lim**, a CQT Fellow, won the **Singapore Young Scientist Award 2019**. The national award is presented to scientists aged 35 and below who have shown potential to be world-class researchers in their field of expertise. Charles received the prize at the President's Science and Technology Awards ceremony in October. Charles first learnt about quantum cryptography as an NUS undergraduate working with CQT researchers. He went on to earn a PhD in quantum information science in Switzerland and complete a postdoc in the United States. He returned to Singapore to take up a faculty position in the NUS Department of Electrical and Computer Engineering, holding a joint appointment with CQT. Charles also received a **National Research Foundation Fellowship** (Class of 2019).



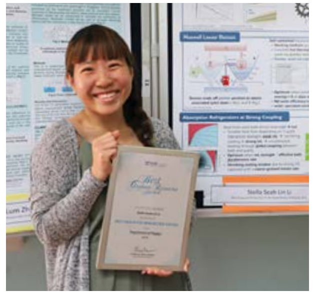
A*STAR

Charles Lim

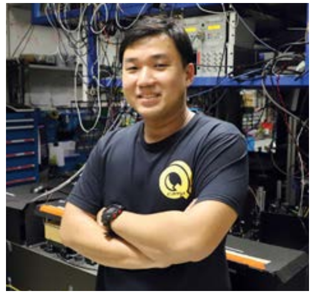
CQT's Director **Artur Ekert** collected more accolades in 2019. In April, he was named among the inaugural winners of the **Micius Quantum Prize**. The Micius Quantum Foundation, named for the Chinese ancient philosopher and scientist 墨子, was established in China with support from private entrepreneurs. Artur received the award "for his invention of entanglement-based quantum key distribution, entanglement swapping, and entanglement purification". He was one of six winners of the 2019 prize. In September, Artur was declared a **Citation Laureate** by the Web of Science Group, which handles research information and publications. He was one of only 19 scientists world-wide selected for the title in 2019. The choice is based on citations of the scientists' work, receipt of prizes and other factors that analysts decide makes the scientists 'Nobel Class'.

Artur Ekert

Two PhD students doing their research at CQT received university prizes in 2019. **Stella Seah**, supervised by CQT's Valerio Scarani, received the **Best Graduate Researcher Award** from the NUS Department of Physics for 2019. She does research on the theory of quantum thermodynamics. **Yeo Xi Jie**, who joined CQT's PhD programme in August, received the **NUS Outstanding Undergraduate Researcher Prize**. He received the prize for research done on single photon sources with Christian Kurtsiefer's group and will continue in this group for his PhD.



Stella Seah



Yeo Xi Jie

Last but not least, the application of quantum technology to cockroaches won an international team of researchers including CQT's **Rainer Dumke** an **Ig Nobel Prize** in 2019. In research published in 2018[i], the team reported observations of magnetism in American cockroaches aimed at understanding the insects' ability to sense magnetic fields. The measurements were performed using an atomic magnetometer built at CQT, with potential applications in searching for mineral deposits, detecting buried objects and biological imaging. Applied to cockroaches, the measurements allowed modelling of a putative magnetoreception mechanism. The team won the Ig Nobel – a satirical prize for science that makes you laugh, then think – specifically for "discovering that dead magnetized cockroaches behave differently than living magnetized cockroaches". Rainer collected the award in person at the prize ceremony in September 2019. Animal magnetism has won the award before: the 2000 physics prize was awarded for the magnetic levitation of a frog. Physicist Andre Geim who shared that prize went on to win the Nobel Prize in physics for unrelated work in 2010.

NTU Singapore

Rainer Dumke (right) and Tomasz Paterek (left)

[i] L.-J. Kong, H. Crepaz, A. Górecka, A. Urbanek, R. Dumke, T. Paterek, In-vivo biomagnetic characterisation of the American cockroach, *Scientific Reports* **8**, 5140 (2018)

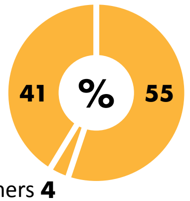
CQT presents its own prizes to staff who contribute to the CQT community in ways that go beyond their job description. Congratulations to the winners of the CQTian Awards in 2019:

- **Angelina Frank** - for contributing with optimism to so many activities at CQT, from Q Camp to board games nights to townhall meetings
- **Aki Honda** - for her initiative, care and positive attitude in finding ways to communicate science through figures and pictures
- **Alex Ling** - for launching and coordinating the Quantum SG community and its report on Singapore's quantum research landscape
- **Tseng Ko-Wei** - for enhancing the happiness of CQT graduate students by organising regular student dinners

Alumni

On leaving CQT, scientists who worked here and students who trained here take their skills into a wide range of new roles. Some find new positions in the growing international job market in quantum technologies, fuelled by government and commercial investment. A majority continue in academic research, but CQT alumni can also be found in other technical industries. We share some stories of recent graduates below. The chart summarises job types for the 29 staff and student who left in 2019 and shared details of their next career move. Of these alumni, around 70% remained in Singapore.

Job types for 2019 alumni



Life after CQT

See Tian Feng
Senior Engineer, Micron

CQT PhD graduate See Tian Feng was recruited by Micron in Singapore after meeting a hiring manager at a university careers fair. "They did an interview on the same day, and then I got the job offer," she says. She joined the multinational memory and storage company in June 2019. Micron has some 37,000 employees across 18 countries.

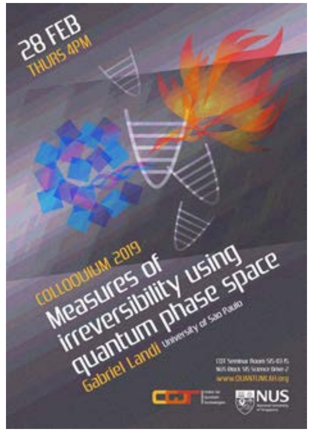
For her PhD in theoretical quantum physics, Tian Feng worked on "Few-Photon Transport In Strongly Interacting Light-Matter Systems: A Scattering Approach" in the group of Dimitris Angelakis. These days she is involved in the manufacturing of memory chips. Her current role is to analyse data from tests of NAND flash memory at intermediate production stages, checking performance before the product goes to the next step. The practice she got during her PhD in how to learn new stuff is coming in useful. She observes that having a PhD helps in other ways, too: "People expect you to do more challenging tasks. From the onset, you are given the chance to do more interesting work because you hold the degree," says Tian Feng.

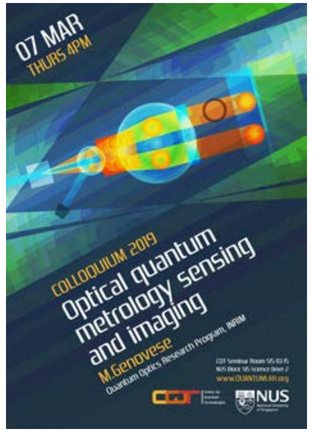
Aitor Villar Zafra
Quantum Engineer, SpeQtral

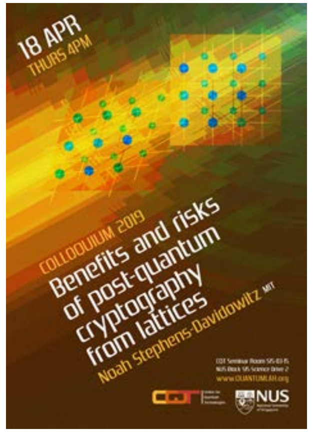
Originally from Spain, Aitor Villar Zafra moved to Singapore in 2014 for an internship at CQT, then joined the Centre's PhD programme the following year. Aitor earned his undergraduate and master's degree in telecommunications engineering, converting his skills to quantum communication during his research project in the group of Alexander Ling. He earned his PhD for "Building Entangled Photon Pair Sources for Quantum Key Distribution with Nano-Satellites".

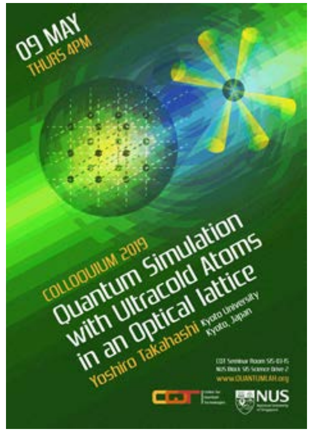
Aitor now continues this work as a Quantum Engineer for the CQT spin-off company SpeQtral. The company is developing space-based quantum networks for global delivery of secure encryption keys. "I have always been interested in building technology instruments, and to do it from a more commercial perspective was an extra motivation factor," he says. Aitor was the fifth full-time employee at SpeQtral when he joined in October 2019, and one of six staff hired to the company from CQT in the year. He chose to stay in Singapore, seeking the work-life balance the country offers: "here I can focus on my career without neglecting family plans in the future".

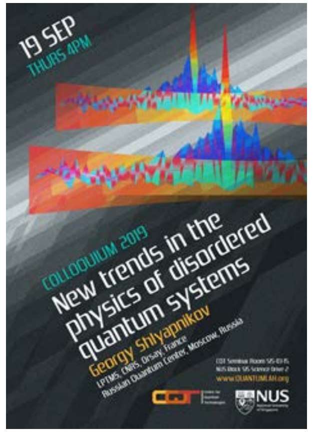
Scientific events

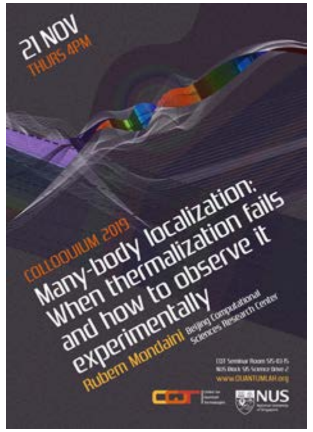




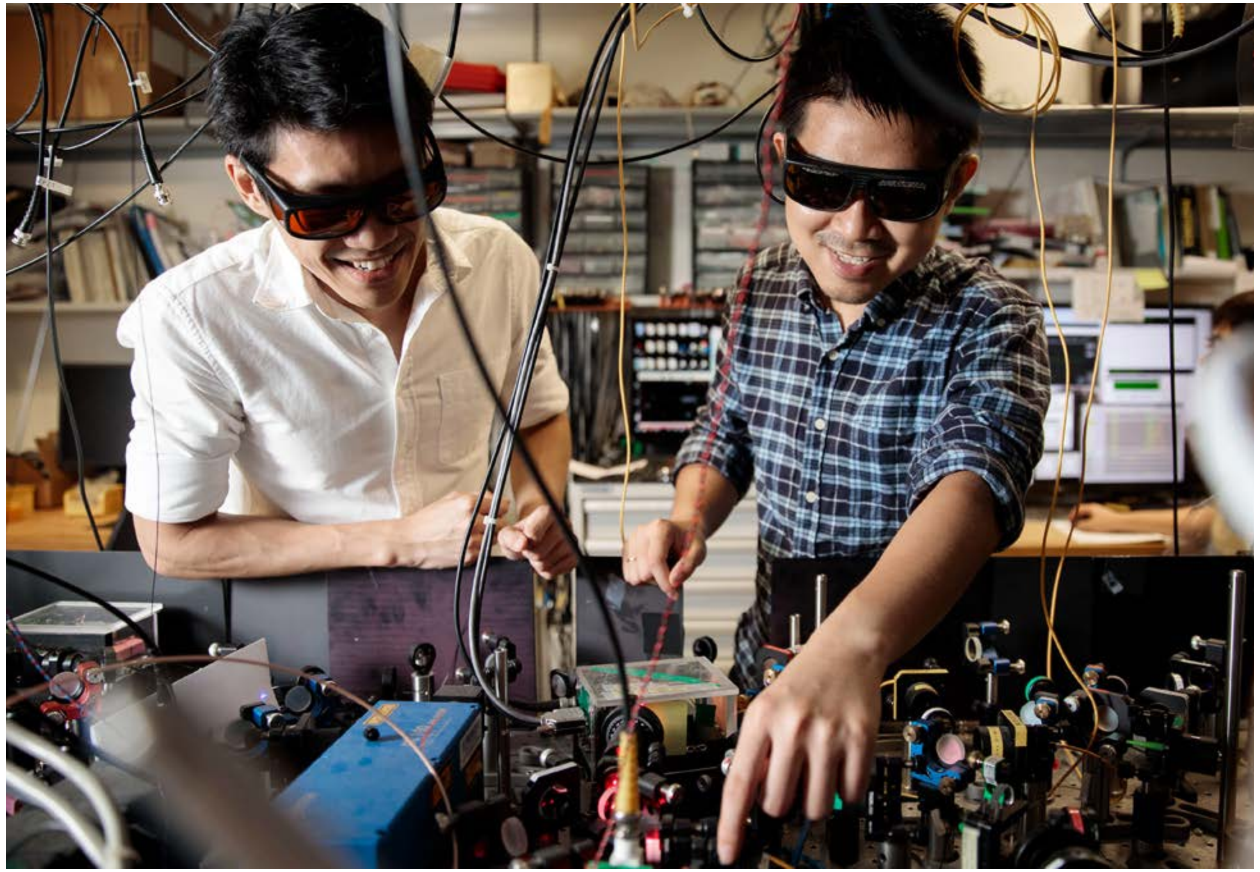








CQT hosted eight colloquia by distinguished visiting speakers in 2019. These talks help researchers at CQT stay up to speed with exciting scientific developments and can foster collaborations. CQT also held a one-day symposium in January 2019 to mark the Centre's eleventh anniversary, with eight talks on the theme of quantum computing and algorithms by local and international experts. Videos of many of these expert talks are available to watch on CQT's YouTube channel.

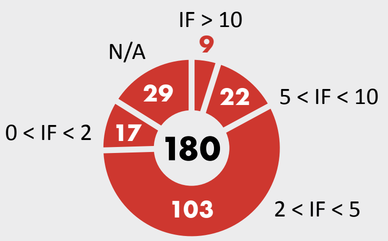


Measuring CQT's achievements and impact

A look at CQT's outputs and spending in 2019

Publications

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.



Publications during 2019 by journal impact factor (IF)

- **14** Physical Review Letters
- **6** Nature Communications
- **4** npj Quantum Information
- **1** Nature Photonics
- **1** Optica
- **1** Physical Review X
- **1** Science

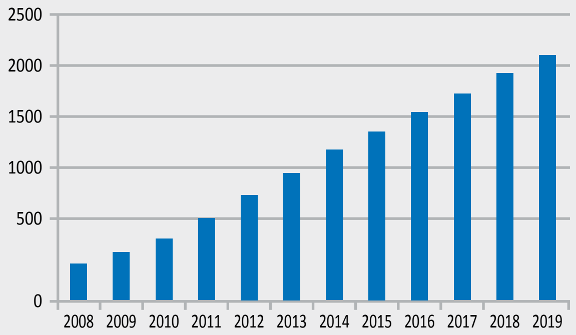
Publications during 2019 in high impact journals

There are **2,133** papers in total from CQT's first 12 years.

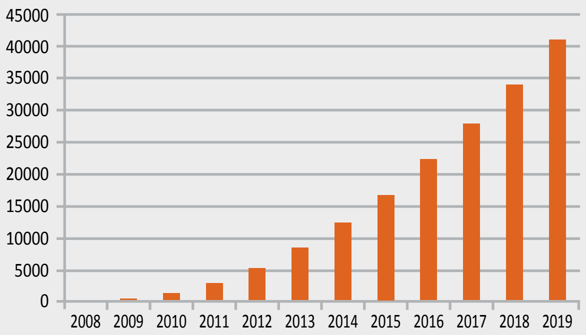
The body of work has accumulated **41,199** citations*. That's an average of 19.68 citations per paper.

As a centre, our h-index is **78**.

Cumulative Publications 2008-2019



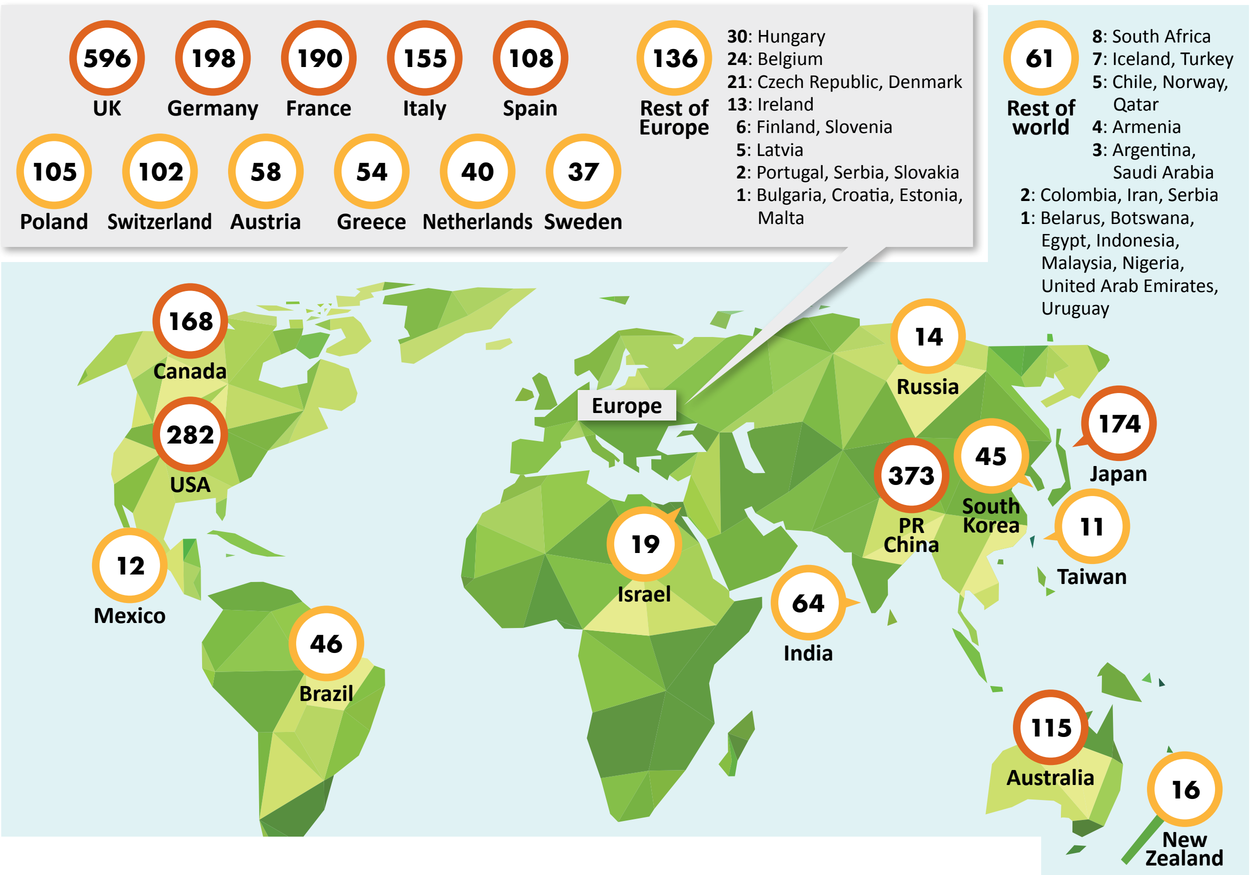
Cumulative Citations



*Citations: Thomson Reuters' Web of Science on 31 Dec 2019.

https://www.quantumlah.org/research/publications.php

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



In 2019, 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 University of Nice Sophia Antipolis 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 the Graduate School of Information Science and Graduate School of Mathematics, Nagoya University, Japan
- Memorandum of Understanding with the National Institute of Metrology, Thailand

Source: Thomson Reuters' Web of Science on 6 Jan 2020. Data captured from 1 Jan 2008 to 31 Dec 2019.

CQT's strategy to translate discoveries in quantum technologies into tangible benefits for the economy and society has three prongs: to inform, to engage and to create. Here's an overview of what we did in 2019.

5 collaborative projects

We work with partners with complementary expertise where we need to drive our research towards commercial goals. We negotiated five new agreements in 2019, including a research collaboration agreement to develop capabilities in manufacturing superconducting qubits (see pp.12–13). Other projects are in the fields of industry engagement, quantum algorithms and quantum communication.

5 spin-offs and startups

As of the end of 2019, there are five active quantum technology startups in Singapore that have connections to CQT through licensed IP or being founded by alumni. Many of these companies are hiring.

2 trade exhibitions

Responding to industry interest, CQT exhibited at two conferences in Singapore in 2019. We were at the Global Space and Technology Convention in February and at the Supercomputing Asia Conference in March, which featured a quantum track.

8 events

CQT partnered with local deep-tech supporter SGInnovate in 2019 to organise seven events at SGInnovate's premises (see pp.21–22). We also organised an industry networking evening at QUANTUM: The Exhibition at Science Centre Singapore.

5 training workshops

To grow deeper knowledge for organisations working in or monitoring quantum technologies, CQT offers training workshops. We delivered five such events in 2019, including two with Singapore's Infocomm Media Development Authority following the Memorandum of Intent signed between us in 2018.

40+ visits

CQT is a point of contact for both local and international organisations seeking information or collaboration in quantum technologies.

2 quantum programming sessions

In October, CQT hosted a Qiskit hackathon (pictured), giving some 40 attendees experience with the open source quantum computing software development framework founded by IBM. Initiated by a CQT alumnus and NUS PhD student, it was the first community-organised hackathon with support from the Qiskit team. In November, we hosted trainers from Google for a workshop on their Cirq software for quantum computing.

CQT does outreach to public and school audiences to share the outcomes of our publicly funded research, engage in dialogue and promote scientific careers. These are highlights of our work in 2019.

330 student visitors

CQT hosted some 30 pre-university students for Q Camp, an intensive, week-long experience of quantum technologies in June. CQT also supports camps organised by the NUS Department of Physics, such as offering short workshops for 160 participants in the NUS Physics Enrichment Camp.

2 public exhibitions

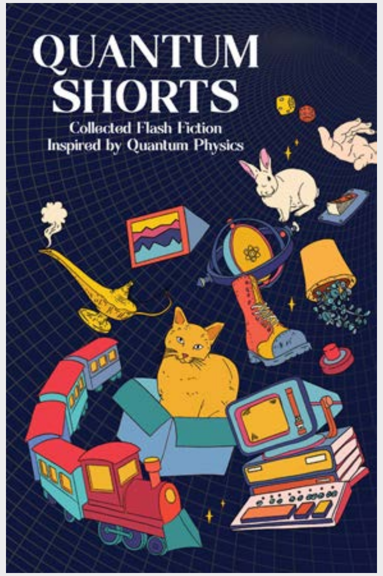
We made quantum research accessible to the public at Science Centre Singapore in 2019 with the opening in August of QUANTUM: The Exhibition (see pp.24–26). CQT was also a partner of the exhibition All Possible Paths: Richard Feynman's Curious Life at the ArtScience Museum at Marina Bay Sands which ran until 3 March 2019.

10 Quantum Shorts films

CQT organises the annual Quantum Shorts competitions for quantum-inspired creative works, alternating between international calls for short films and flash fiction. This initiative is support by media partners *Nature* and *Scientific American* and scientific partners. The last film round concluded in 2019 with 11 screenings of the ten shortlisted films across six countries.

1 Quantum Shorts book

When Quantum Shorts returned in December with a new call for flash fiction, we released an ebook collecting some of the best entries to previous competition rounds. The anthology of 37 shorts stories by 32 writers has a foreword by CQT's Director. It is available as a free download at the Quantum Shorts website and from online bookstores.



1 project in space

The SpooQy-1 satellite carried into space not only a quantum light source (see p.6) but also a quotation from choreographer and Cultural Medallion Recipient Santha Bhaskar. An engraved aluminium panel on the exterior of the satellite carries the message: "We are all different nationals, we are entangled together with all the races." This caps a collaboration between CQT and NUS Centre For the Arts. Back on Earth, a SpooQy model and CQT researchers starred in a companion play in October.

51 media mentions

Highlights of media coverage in 2019 include a feature in *Bloomberg BusinessWeek* on Murray Barrett's atomic clock project and opinion pieces by Dimitris Angelakis and Valerio Scarani in local papers *Today* and *The Straits Times*.

56k website visitors

CQT's website had over 56,000 users and almost 270,000 page views in 2019. We also post on YouTube, Facebook, Twitter and LinkedIn, with a combined following across these channels exceeding 12,000.

Expenditure in 2019

	Manpower	Equipment	Other	Total
Core Funding	10.23	1.04	8.34	19.61
Competitive Grants	1.98	0.66	1.79	4.43
Total	12.21	1.70	10.13	24.04

All figures in million SGD.

Stakeholder support

CQT was established in 2007 as a Research Centre of Excellence with core funding from the National Research Foundation, Prime Minister's Office, Singapore, and the Singapore Ministry of Education. The total core funding allocated for the period 2017–2022 is $100 million. The Centre 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 Singapore's Nanyang Technological University (NTU) receive additional support from NTU.

Competitive grants

CQT researchers also compete for grant funding. In 2019, the Centre won over $6 million in new grants. Active grants in 2019 include awards from the Ministry of Education, the National Research Foundation and Agency for Science, Technology and Research, all in Singapore. Some CQT research is funded through the NUS–Singtel Cyber Security R&D Lab, a corporate research laboratory, and NUS competitive funds. International grants come from sources including the USA Air Force Office of Scientific Research and companies.

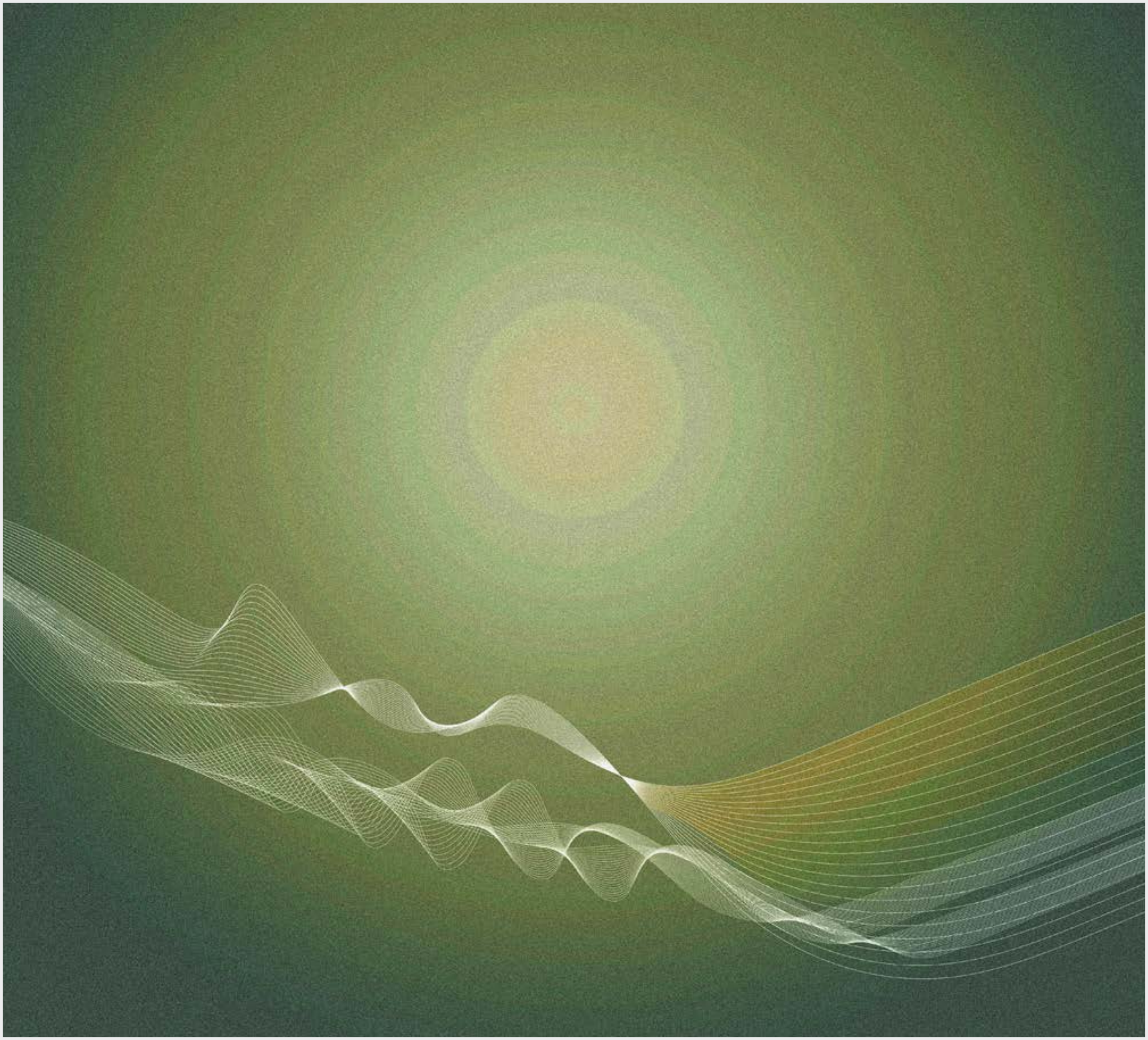
Thanks to our supporters

Ministry of Education SINGAPORE
National Research Foundation Prime Minister's Office Singapore
Nanyang Technological University Singapore
NUS National University of Singapore
MajuLab
CNRS
NSCC Singapore National Supercomputing Centre

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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