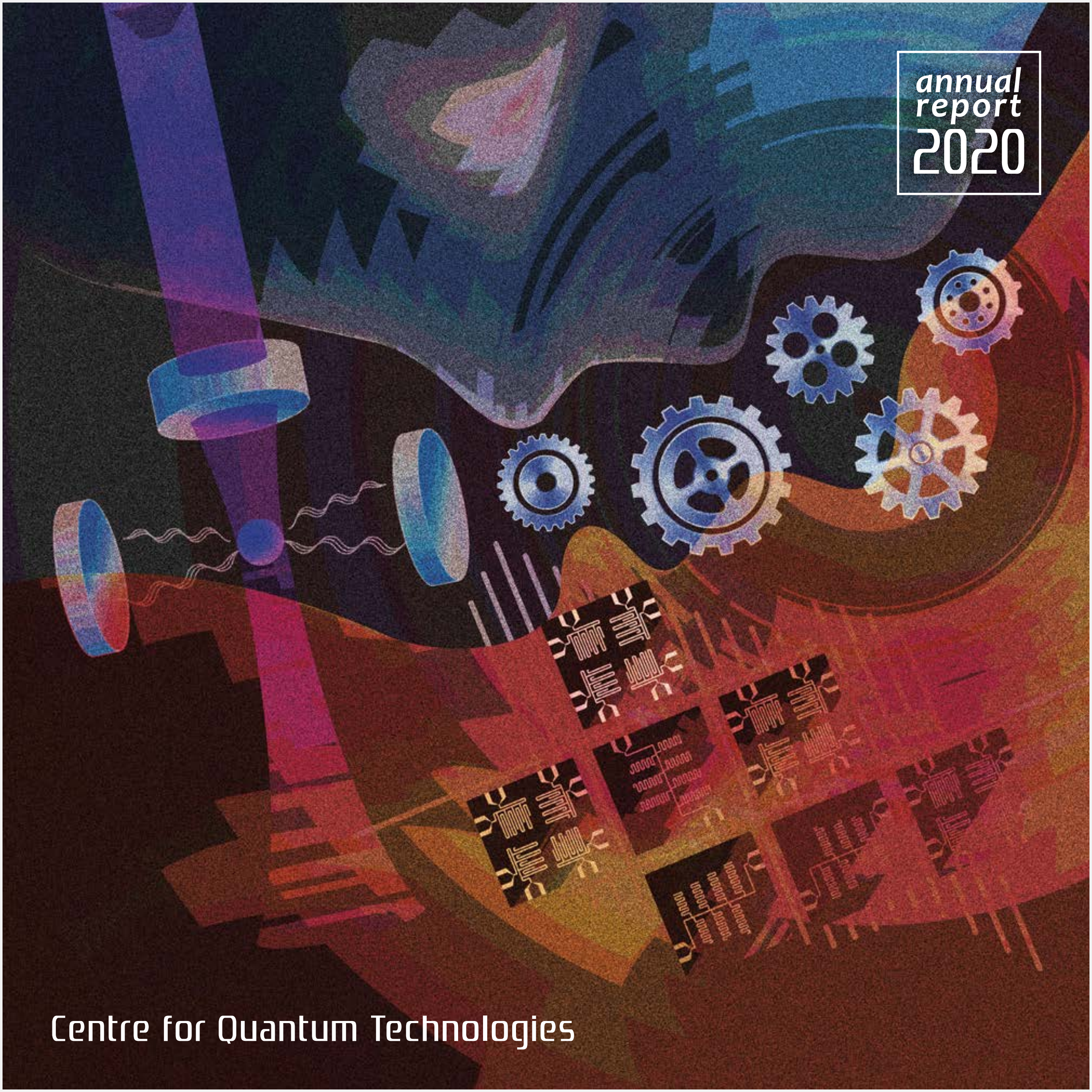

annual report 2020

Centre for Quantum Technologies

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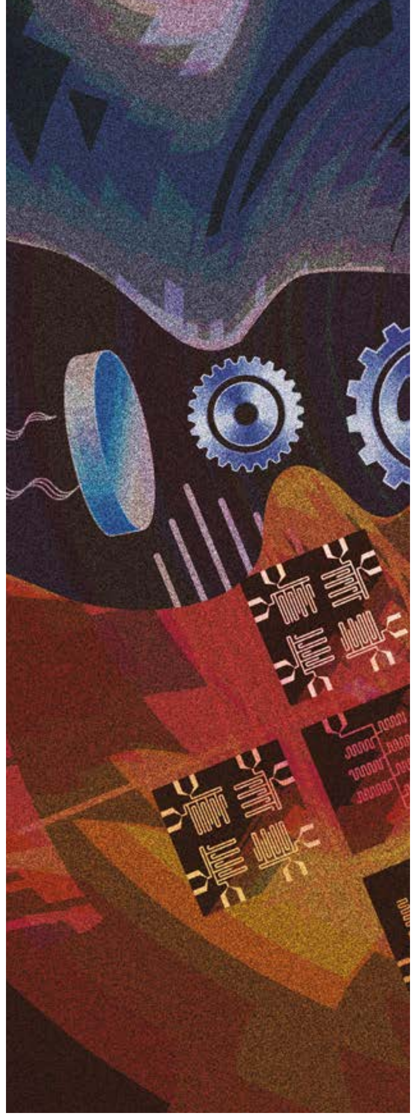
CQT AT A GLANCE



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

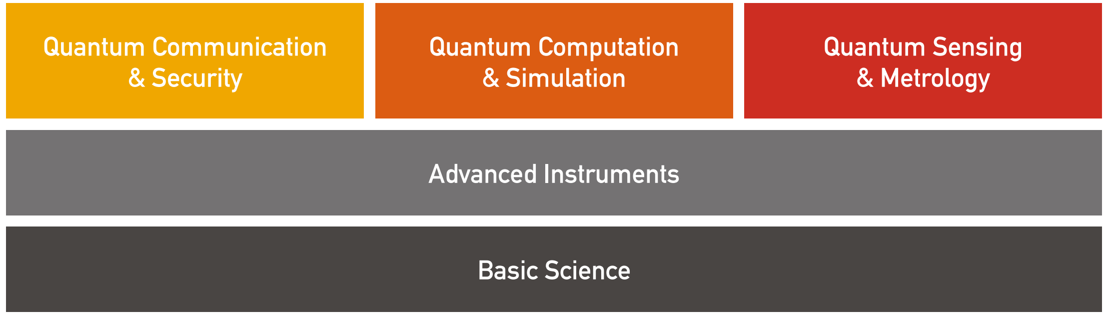
We pursue insight into the physics that describes light, matter, and information. We develop novel tools to study and control their interactions. Our research goals range from understanding the properties of materials to working out new encryption schemes.

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.



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 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

The year 2020 will not be forgotten easily. We all had to come to grips with Covid-19: a strand of around 30 kb of classical information able to massively replicate itself within human cells. For scientists, the safety measures of being deprived of freely working in a laboratory, or of not sharing blackboard discussions, raised the art of making good science to a higher level. The challenge may be better phrased by Goethe: “It is in self-limitation that a master first shows himself”.

I can only thank Artur Ekert, the founding Director of CQT, for his timely handover. More seriously, I have always admired his work and vision. Leading CQT is just an amazing challenge, crowded with lessons that I’ll have to learn.

One lesson we all know: science is truly unstoppable. The year of the pandemic has been a time of dramatic actions in quantum research. We went through a very difficult year, full of constraints and isolation, while interest for quantum technologies percolated in the minds of decision makers. Keep in mind the national programmes presented in e.g. Germany, France, Israel, or such news as IonQ going public. Quantum is on the rise.

Moreover, Singapore launched the second phase of the Quantum Engineering Programme, with new funding of $96.6 million, which is now developing fast under the direction of our colleague Alexander Ling. The Singapore government also announced its next five-year plan for research, innovation and enterprise, to see a $25 billion investment. CQT anticipates more funding to carry out research on quantum sensing, quantum communication and quantum computation and simulation. The near future for our research is definitely exciting.

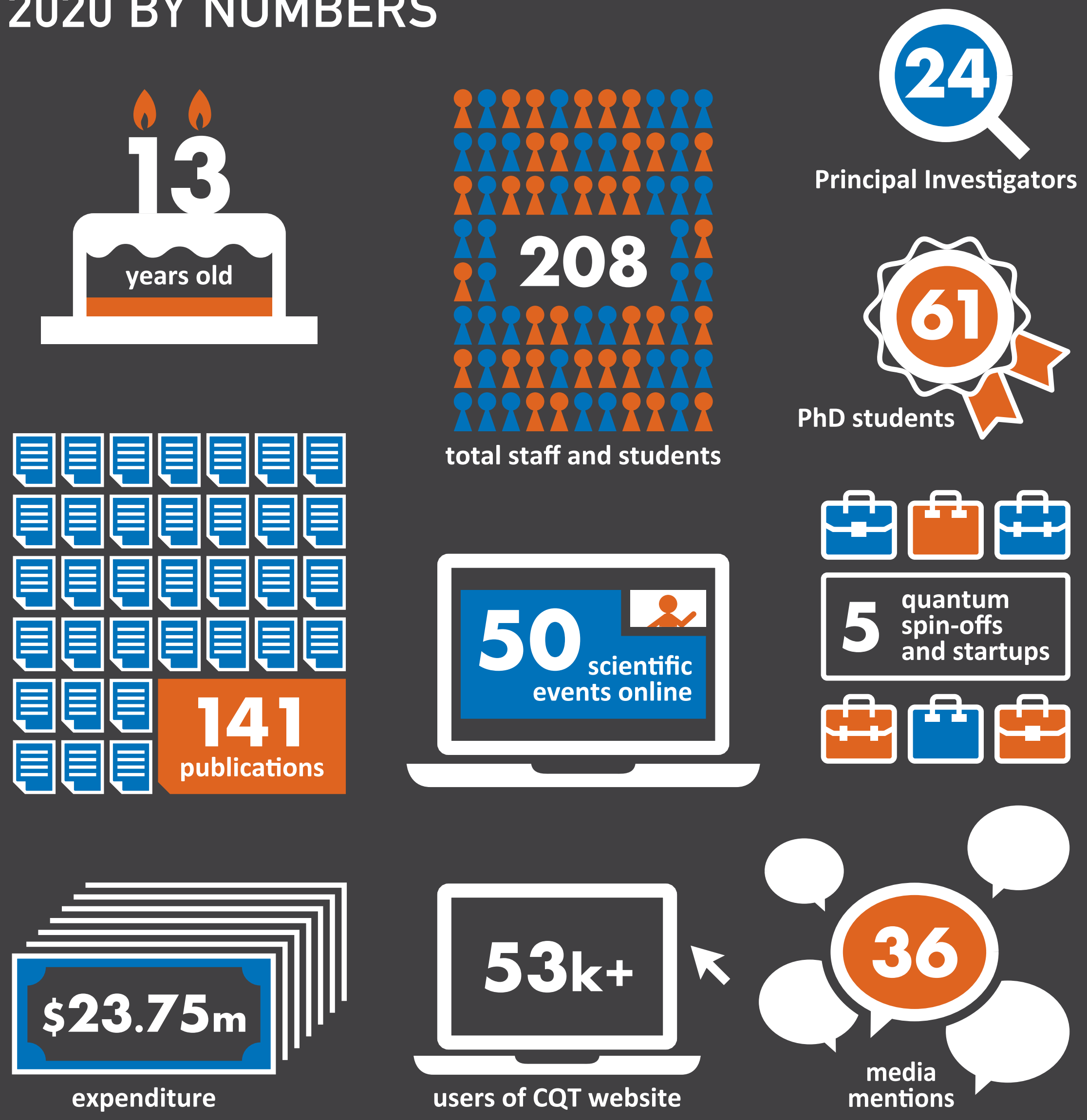
New quantum challenges and increasing funding require large coordination efforts. It is my strong opinion that it is time to collaborate, not to compete. I believe Singapore can stay relevant on the world stage by setting up national quantum facilities, working hard at educating talent, and coordinating basic and applied research. CQT can take the lead on such responsibilities. There are also new and tantalising opportunities for innovation, venture building and internationalisation. And we should never forget outreach: science is part of our culture. It is our duty at CQT to reach and interact with all parts of society.

Let us dream a little bit of the future. A nascent quantum ecosystem in Singapore will be made of universities and institutes that collaborate to create top level research, as well as companies that explore quantum technologies and startups that open deep tech markets and large bets. It is the combination of research, business and investors that can forge the future economy of Singapore.

All around the planet, corporations and universities are competing for quantum talent. The surprise for many is that a student cannot learn quantum physics at the same speed they develop coding skills in Python. Understanding quantum laws requires time, depth, reflection; those qualities are hard to find in our times, and that makes CQT even more valuable.

José Ignacio Latorre

2020 BY NUMBERS



OUR PROJECTS

Highlights of CQT's work in quantum technologies in 2020

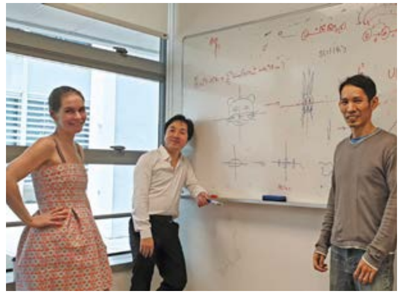
Dark matter evades detection

Scientists posit the existence of dark matter because our current theory of gravity cannot explain some astronomical observations, but searches for this missing matter have been inconclusive.

CQT's Manas Mukherjee and Tarun Dutta suggest a quantum probe might detect a particular dark matter candidate – light mass axion-like particles (ALP). They looked for the signal of ALPs coupling with an electron in a trapped ion. A feedback strategy applied to enhance the expected phase effect meant the probe beat the 'Heisenberg limit' on measurement precision.

The researchers' non-detection of ALPs bounds the hypothetical particle's coupling strength. Although astronomical observations have set tighter constraints, the method represents a direct test and could be made more sensitive using more atoms. Manas says "We try to bridge the gap between quantum information and particle physics".

npj Quantum Information **6,** 3 (2020)



More squeezing, less effort

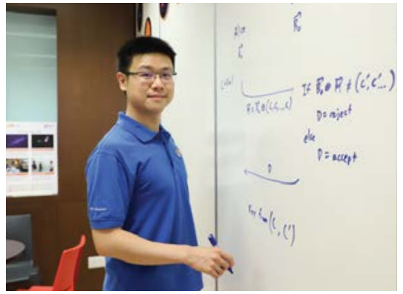
'Squeezing' the quantum state of light can be helpful for quantum sensing and quantum computing. Working with researchers in Australia and China, CQT theorists Mile Gu and Jayne Thompson found a way to do squeezing better.

The concept of squeezing has its roots in the quantum uncertainty principle, which holds that it is impossible to exactly fix certain pairs of properties. Squeezing reduces noise in one property of the light, such as phase, by moving it into another, such as amplitude.

"We were able to beat all previous limits in doing this protocol by sacrificing determinism," says Mile. The scheme is probabilistic. The apparatus will squeeze any incoming state, but how likely it is to work depends on how precise you need it to be. However, the setup signals when the squeezing gate has worked, making it useful for tasks such as building up cluster states for measurement based quantum computation.

Nature Photonics **14,** 306 (2020)

SCIENCE UPDATES

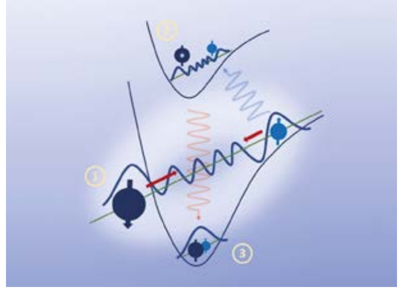


Alice and Bob versus Eve

Two-way communication can boost the noise tolerance of device-independent quantum key distribution (DIQKD), found an international team including CQT's Charles Lim and alumnus Ernest Tan. The goal of QKD is to give two parties, traditionally known as Alice and Bob, matching and private encryption keys. A scheme is 'device-independent' when its security can be vouched for without detailed knowledge of the devices involved, such as the photon source or detectors.

Existing security proofs for DIQKD have Alice and Bob communicate just once. In the new work, the researchers studied a repetition-code protocol in which Alice and Bob review their data in multiple rounds. This scheme is well studied for standard QKD. The team extended the security proof to DIQKD and found the extra communication brings an advantage: Alice and Bob can overcome more noise from eavesdropping or imperfect implementation.

Phys. Rev. Lett. **124,** 020502 (2020)

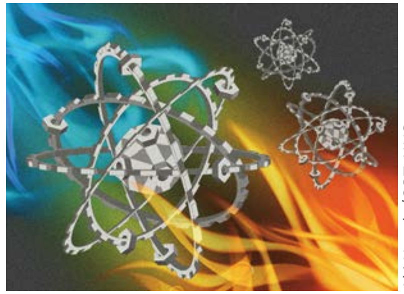


Simplified steps for ultracold molecules

CQT researchers found a simple and effective way to coax pairs of disparate atoms towards their coldest molecular state. The creation of such ultracold polar molecules is groundwork for experiments in quantum simulation and fundamental physics.

A typical path to the ground state involves both singlet states and triplet states of molecules, which differ in the orientation of the atoms' quantum spins. Kai Dieckmann and his team realised they could instead make all the steps between singlet states. "With the new pathway, we use molecular states that are easier to understand and model," Kai says. "What we're doing is control of the quantum world in a bottom up approach." The group's setup creates up to 10,000 lithium-potassium molecules at a time. The molecules have a large dipole moment, enriching options for experiments because the molecules interact strongly over long distances.

Phys. Rev. Lett. **124,** 133203 (2020)



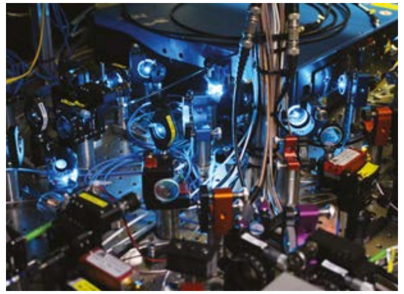
Aki Honda/CQT, NUS

A single-atom machine

A single barium (Ba) atom was made to function as an engine and a fridge by an international team including CQT researchers. "We want to understand how we can build thermodynamic devices with just a few atoms. The physics is not well understood so our work is important to know what is possible," says CQT's Manas Mukherjee, who led the experimental work. In the future, such devices might be engineered into computers or fuel cells to control energy flows.

For the experiments, the researchers trapped a single Ba+ ion, then used cycles of laser pulses to move one of the ion's electrons between two energy levels. This caused energy to be pushed into or removed from the atom's vibrations, with quantum effects appearing in correlations between the electronic states and vibrations. The team modelled the behaviour in terms of two thermodynamic quantities: ergotropy and entropy.

npj Quantum Information **6,** 37 (2020)

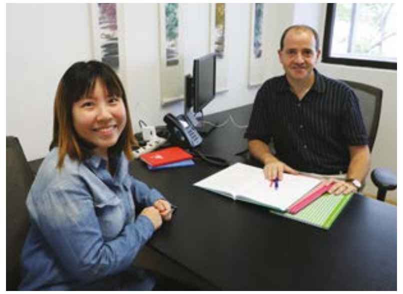


Rydberg atoms image ions

Highly excited atoms revealed the whereabouts of ions in a new imaging technique demonstrated by Wenhui Li and her team. The approach could track the dynamics of ions in quantum matter experiments or monitor ions not amenable to other methods of imaging.

The highly exited states, known as Rydberg states, were coupled with laser light to realise 'electromagnetically induced transparency' (EIT). This allows a probe light, resonant to an atomic transition, to pass right through a cloud of such atoms. When ions were introduced into the atomic cloud, however, they interacted strongly with nearby Rydberg atoms, destroying the EIT condition. The probe light was then absorbed in the vicinity of the ions, such that the ions' position showed as shadows in a camera image. The researchers used the technique to observe avalanche ionisation – ions multiplying as collisions with atoms trigger more ionisation.

Phys. Rev. Lett. **124,** 053401 (2020)



Engine employs Maxwell's lesser demon

CQT's Stella Seah, Valerio Scarani and alumnus Stefan Nimmrichter proposed a new model for a quantum heat engine that offers performance advantages.

Maxwell's demon plays a role in quantum engines to acquire information about the system and perform the appropriate action – that is, taking out energy when the working medium is in an excited state. Previous quantum engine models used a qubit as a measurement pointer to indicate the internal state. The new idea is to use a macroscopic pointer instead, which the researchers found would be more stable to temperature fluctuations in the environment. The measurement can also proceed without having to sync to the pattern of engine strokes. "Everything can run continuously," says Stella. The researchers describe the demon as 'lesser' because it interacts only with the macroscopic pointer, rather than the entire system.

Phys. Rev. Lett. **124,** 100603 (2020)

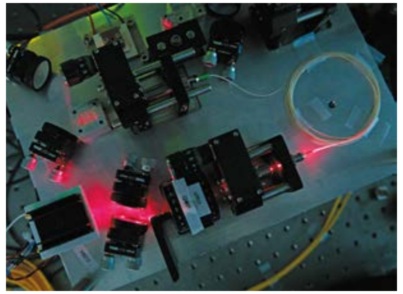
Quardia/Shutterstock.com

Quantum advantage survives noise

CQT's Marco Tomamichel worked with researchers in Canada, the US and Germany to identify the first known separation in computational power between noisy quantum computers and classical computers that does not rely on assumptions about the classical hardness of the underlying problem.

The team considered a variant of the 'quantum magic square game' embedded in circuits of qubits. The researchers showed that a noisy intermediate-scale quantum (NISQ) device could win the game using a constant circuit depth, whatever the number of players. Depth refers to how many rounds of gates the quantum device needs to implement. In contrast, any classical circuit would need a depth that grows at least logarithmically in the problem size. "Some of the new techniques we had to develop to make the circuit noise-resistant are useful to better understand the power of NISQ algorithms in general," Marco says.

Nature Physics **16,** 1040 (2020)

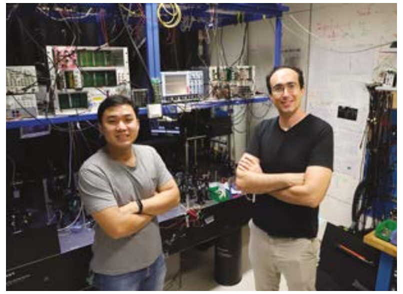


QKD on commercial fibre

Quantum key distribution (QKD) is under trial worldwide as governments and companies seek to strengthen their cyber security. In the NUS–Singtel Cyber Security Research & Development Laboratory, CQT researchers achieved entanglement-based QKD at 109 bits/s over 10 km of deployed fibre in Singapore. At this rate, the team say, the system could directly encrypt low bandwidth communication such as command and control of industrial systems or be used as input for fast encryption schemes such as AES-256. There is also a clear path to boosting the key rate.

The team designed their entangled photon source to operate at a shorter wavelength than standard telecoms. That opens an interesting possibility. Shi Yicheng, first author and a CQT PhD student, explains: "We would be able to run QKD and classical internet data traffic on the same fibre – QKD at 1316 nm, and internet at 1550 nm."

Appl. Phys. Lett. **117,** 124002 (2020)



Photons made to suit atoms

CQT researchers demonstrated a novel technique to compress the frequency spread of single photons, aiming for more efficient light-matter interactions for applications such as quantum networks.

The team led by Christian Kurtsiefer reported compression of narrowband photons created in cold rubidium from a width of 20.6 MHz to less than 8 MHz. Like a block fitting into a child's shape-sorting toy, the photon is now a better match to the atom's absorption preferences. Rubidium's absorption profile is about 6 MHz.

"Conventionally, spectral compression has been done using optical fibres for photons of larger bandwidths. But the amount of optical fibres we would need to compress the spectrum of the photons we are dealing with would span from here to Mars," says co-author Yeo Xi Jie. This scheme instead uses a resonant cavity and a time-lens.

Phys. Rev. Lett. **125,** 183603 (2020)

Sergey Tarasov/Shutterstock.com

Hybrid algorithm helps sensor

An international team including CQT's Mile Gu and Jayne Thompson demonstrated a hybrid quantum-classical algorithm that helps engineer a quantum sensor.

Mile and Jayne found a 'quantum efficacy estimator' algorithm that provides feedback on the sensitivity of a quantum probe. The best probe states for sensing are often hard to calculate in principle and limited in practice by what the setup can make.

At the University of Science and Technology of China in Hefei, researchers incorporated the quantum algorithm into a classical machine learning system already in place in their lab. The quantum-classical algorithm ran on a three-qubit nuclear magnetic resonance computer, converging on a probe state that achieved near-optimal limits. The goal was to engineer the best qubit probe for sensing the direction of a magnetic field.

npj Quantum Information **6,** 62 (2020)

Meet the Director

José Ignacio Latorre, appointed Director of CQT in July 2020, answers questions on his past, passions and vision

How would you describe the current state of quantum?
The evolution of quantum technologies started with understanding. Then, we built the first instruments and applications. Now, we use these instruments to generate ever more powerful instruments. In a way, quantum mechanics is leaving infancy and entering adolescence, which is a really crazy phase full of possibilities. It is a very exciting time to be working in this field.

What is your vision for CQT?
Internationally, being in Singapore is a strategic advantage. We are a natural partner for new projects, and companies would like to work with us. To stay relevant, I think CQT should be a little bit bigger, well funded, and that it should maintain the double spirit of basic curiosity-driven research and applied mission-driven research (see box **Engaging industry**).

When I look back at what it means to be a scientist, I always divide my life into three parts. One is generating knowledge, the second is passing it to new generations – this can be by teaching and outreach – and the third is making the first steps to translation. These are for me the three pillars of being a scientist and I think it is the same for CQT.

What are your three favourite things about Singapore?
I have a great admiration for Singapore, that's one reason why I came to CQT. The first thing I like is that common problems in many countries have been solved in original ways here. Another is the meritocracy. A third is the respect the country has for science.

What role do you think CQT should play in Singapore's quantum ecosystem?
CQT can be a flagship centre of the country, a hub for quantum research in the island. CQT is a place where we generate knowledge, and where we translate knowledge to society. We educate dozens of students a year and inject PhDs into the system. Very few institutions can do basic and applied research, education, and translation all at a high level.

What's in the works?
In 2021, we will have more PhD students. The group size, per Principal Investigator, is increasing. The next thing I would like to see is one more experimental line and probably another theoretical line. These are the scientific policy goals.

In the longer term, in my opinion, we should have more scientific research lines because that brings scientific muscle. It is very important to have critical mass. Moreover, the teams embedded in CQT should not compete but collaborate. It is clear to me that we are at the stage where we need collaboration to achieve higher goals.

Do you have any concerns about the state of the field?
News nowadays, not only scientific news, is often biased by some interests or driven by hype. On top of that, 'quantum' is a magical word that people adore and use for anything. It is catchy. Something that happens in the lab can get magnified and taken out of context in the media, with the excuse that this is the only way to make people interested. This is a bad situation. Many of my colleagues are afraid of a 'quantum winter', as a reaction to hype.

I am also concerned about ethics in science, whether research is free or not free, whether it is public or not public, open source or not open source. Are we doing science in a way that benefits all humans? The quantum computer can be such an unbelievable and powerful machine that more and more research is done by corporations, which would mean that whatever can be done is property of the company. I think the public sector has a moral responsibility to ensure such top knowledge can be shared.

What do you enjoy outside of physics?
I'm a humanist. I love literature, dancing, paintings, sculpture and music. One of my sons composes music, and he is a source of inspiration. He sends me things and tells me to listen to them.

I have written three books in Spanish. One was about nothingness, the other about quantum, and the third about ethics for machines, which has brought me to amazing places to meet people. I also love travelling. I've been to 63 countries now, and I think I've given talks in more than 200 universities.

Another passion I have is winemaking. For the last 16 years, I've been producing with friends a wine called 'h-bar'. We've had it before at centre meetings and parties.

How did you know that you wanted to become a scientist?
I'm an only child from a very humble family. Nobody in my family had ever finished high school. I'm from Spain, where there was a civil war. My father said the only thing he could do for me was to give me a good education. He used the money he was making in his two jobs to pay for a good school. I had good teachers and was exposed to a high level

"CQT should maintain the double spirit of basic curiosity-driven research and applied mission-driven research."

of thought, from science to philosophy and art. I was educated in the spirit of discovery and thinking for yourself.

At some point, I had to decide what I wanted to do. I had many options and doubts. I didn't understand the difference between science and technology, to decide whether to study physics or engineering or something else. I went to talk to my teacher of Latin and Greek, a woman who knew nothing about science. She said, "You learn the basics, and then you can decide in the future." It seems so irrefutable, so obvious. And that's how I learnt physics (see box **A path through physics**).

What advice do you have for students looking to pursue quantum research?
To young people, I would say that each one of us must make decisions. Who am I to change whatever you decide? However, definitely, to make meaning out of life, be passionate about something. I think that science is one of the most beautiful ways of spending our lives.

A path through physics

José Ignacio, who joins the National University of Singapore as Director of CQT and Provost's Chair Professor in the Department of Physics, has explored many paths during his research career.

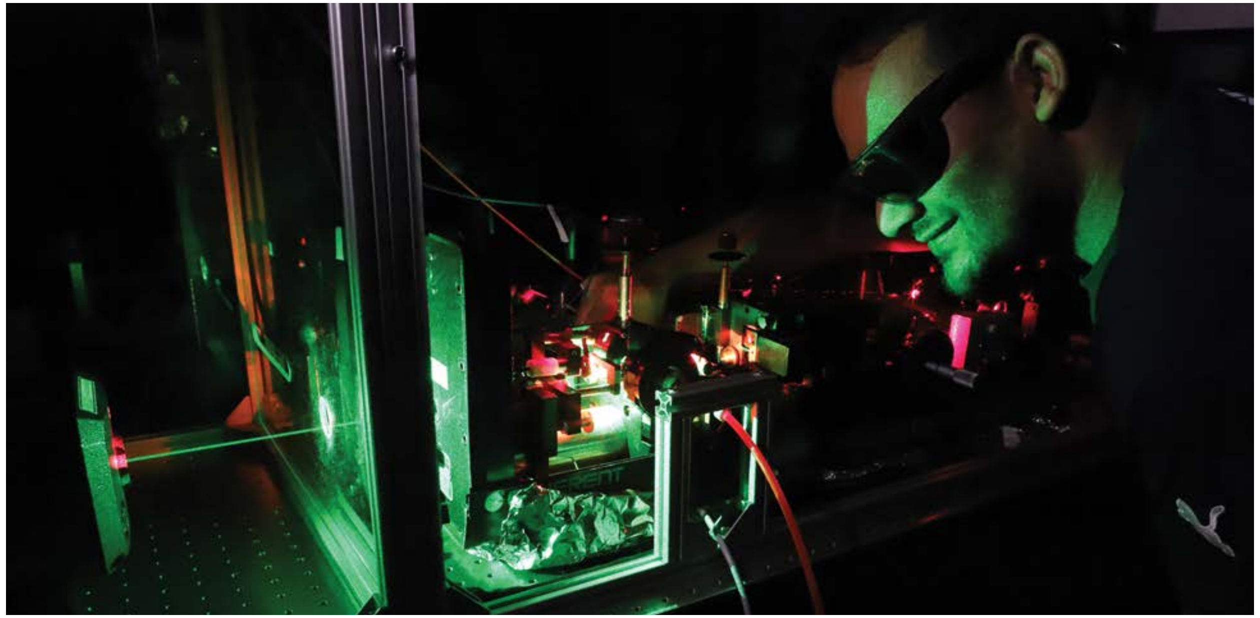
Early on, he was a theoretical high energy physicist, working on renormalisation in quantum field theory and string theory. In 1992, he learnt about neural networks and wrote his first paper on the topic. "For some years I was working in neural networks as a dilettante, as a guy who is visiting the field, as a tourist," he said. Later, he worked on a neural network approach to analysing data at CERN, the European particle physics facility, relating to the parton distribution function.

Then, he learnt about quantum information. Little by little, he learnt more. He was the founder and Director of the Centro de Ciencias de Benasque Pedro Pascual, a Spanish scientific facility that became well known in the quantum information community for hosting workshops and conferences. He and his colleagues applied the ideas of quantum information to condensed matter, discovering the scaling of entropy in condensed matter. He decided to go full steam into theoretical quantum computation and work directly on projects on quantum computing. Before moving to Singapore, he was heading a research group at the Barcelona Supercomputing Center to build the first quantum processor in Spain. He is also Chief Researcher at the Quantum Research Centre in the Technology Innovation Institute in the United Arab Emirates.

José Ignacio says, "Now, I see that my knowledge in different fields has collaborated. When faced with a new problem, the fact that you know a wide variety of things is very useful and produces new insights."

Engaging industry

It takes a diversity of skills to turn a discovery from the lab into a piece of the economy. José Ignacio brings with him commercial experience from being the creator of three start-ups, and is currently the Chief Science Officer of Qilimanjaro, a startup designing coherent quantum annealers. He highlights that the translation of deep tech is neither easy nor, in particular, fast. "There is this enormous desert, as many people say, from idea to business." He explains that scientists have to travel the first kilometres alone, bringing their ideas out of the lab and talking to people to find natural friends for crossing the desert. He aims for CQT researchers to collaborate closely in Singapore's Quantum Engineering Programme, which has a remit to engage industry and fund projects solving industry challenges (see pp.24–27).



Tools to power science

CQT researchers build advanced instruments to help push the boundaries of knowledge and develop new technologies

Enter the office of CQT Principal Investigator Christian Kurtsiefer and you could mistake it for a workshop. Desk and shelves are filled with devices and printed circuit boards, cables mixed in and tools alongside.

Christian's group works on quantum communication and atom-light interactions. To support their experiments, he and his team are also expert instrument-builders. The researchers make power meters for lasers, detectors for single photons, time-taggers that register signals within nanoseconds, and more tools for their projects. In 2017, Christian and some CQT colleagues spun-off a company to commercialise some of these devices, with a primary market being other research groups (see box **Making a business of instruments**).

In other CQT labs, the development of advanced instruments remains a key part of research. The Centre has both mechanical and electrical workshops for building equipment, supported by a dedicated team of support staff.

Laser focus

One speciality of CQT's experimental scientists is lasers. Lasers in quantum labs have a multitude of purposes: providing photons for communication experiments, for example, or acting on atoms, ions or molecules to cool them, move them or change the particles' internal energy states.

Photo: CQT researchers modernised a dye laser from the 1980s to search for the energy levels of an ultracold molecule. This photo shows the laser in action: a green pump laser beam hits the dye jet to produce lots of red light.

Groups often build their own lasers to exacting specifications. CQT PhD student Oon Fong En, for example, built lasers to give a gravimeter high sensitivity (see pp.21–23). In 2020, the group of Travis Nicholson even proposed an entirely new laser design (see box **Ultrastable and superradiant**).

Researchers also find inventive ways to use existing technology. A breakthrough for the group of Kai Dieckmann in 2020 came thanks, in part, to a vintage laser. The group has built a complex setup to perform quantum simulations with ultracold polar molecules. The researchers used the laser to look for the molecule's energy states.

"Doing spectroscopy can be very time-consuming. It is a bit like fishing in the dark. Although we calculated the energies of the ground states with existing literature, the uncertainties were much larger than the linewidths, making the states hard to find," explains group member and CQT PhD student Yang Anbang.

The team purchased a refurbished dye laser originally manufactured in the 1980s to help. Dye lasers are no longer common because they are bulky and fiddly to operate compared to modern diode lasers, but they have the advantage of offering high-power light over a vast range of tuneable frequencies. The group added modern components to obtain stable operation – and identified all the energy levels they needed (see p.7).

Control centre

CQT labs also need control electronics: quantum experiments need many parts to work together and operate with some degree of automation. CQT groups may have electrical engineers working on tasks such as designing custom printed circuit boards and programming microcontrollers.

Control systems can also be essential components of quantum technologies. Consider the work of CQT Principal Investigator Rainer Dumke and his group in quantum computing. They are making superconducting qubits, similar to the building blocks of IBM's and Google's quantum computers.

To store and process information in superconducting qubits takes carefully timed and shaped pulses of microwave radiation. Rainer's team is designing a device to create these pulses based on a field-programmable gate array (FPGA). It has 16 inputs and outputs, more than the current standard and enough that a single device could control between five and eight qubits at once. Controlling more qubits from one device lessens the problem of synchronising signals from multiple FPGAs.

"The FPGA is a central piece of the control system for our quantum computer. The exciting part of this work is that we are realising a simplified, compact, scalable qubit control system, comparable to the significant miniaturisation we have witnessed for classical computing," explain Park Kun Hee and Yap Yung Szen, researchers working on the project. Park is a CQT PhD student and Yap a visiting researcher from Universiti Teknologi Malaysia.

The skills researchers develop working on projects like these can also launch careers. A PhD graduate from Rainer's group who had been working on cold atoms and superconducting qubits later worked at S-Fifteen Instruments, shifting focus to quantum communication. Lim Chin Chean joined the company after a short stint in a space startup – and is leaving with ambitions to build his own quantum startup.

Photo: CQT researchers are programming this compact device containing an FPGA to control superconducting qubits.

Chin Chean joined the Entrepreneur First programme in Singapore in February 2021 to develop his business idea. He is keen to work on health-tech, intending to explore the potential market for quantum sensors, especially to measure small magnetic signals in the brain or body. "The good thing about being an experimental physicist is that you are quite flexible about technical capabilities," he says.

Making a business of instruments

S-Fifteen Instruments is a spin-off from CQT, founded to commercialise instruments developed in-house for quantum experiments and devices for quantum key distribution and random number generation.

History suggests that companies can make a successful business of selling instruments to researchers. "My vision is to become the Thorlabs of Asia," says Brenda Chng, Managing Director of S-Fifteen Instruments since 2019. Thorlabs was founded in the US in 1989 by an employee of Bell Labs to make components for laser and optics researchers. Today, it's a global manufacturer offering thousands of photonics products to both academia and industry. (Many CQT labs are customers.)

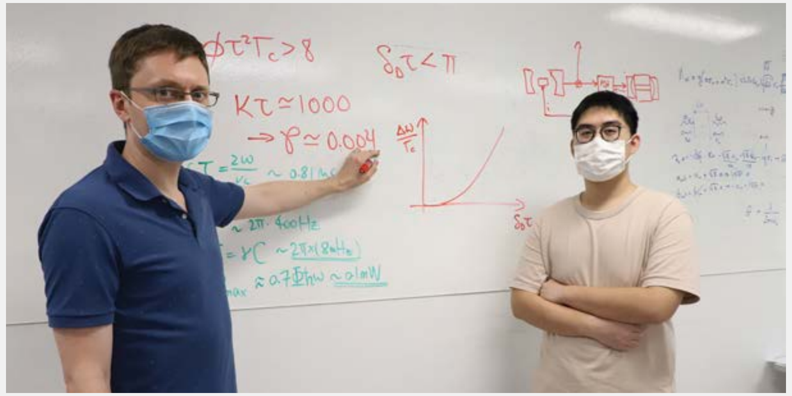
Before joining S-Fifteen Instruments, Brenda worked at CQT for more than a decade with Christian Kurtsiefer's group on projects in quantum optics. She views her current role as an expansion of her previous one – facilitating the interface between tools and users. "Instead of serving the CQT community, we are now supporting customers around the world," she says.

Entering 2021, S-Fifteen Instruments is advertising some ten control and measurement products. So far, the company has customers in the United States, Europe and Asia-Pacific region, starting with orders from CQT alumni and their contacts. Brenda explains the plan is to bootstrap from sales using local turnkey solution providers for manufacturing.

A second line of products from S-Fifteen Instruments are packaged quantum technologies, including a quantum random number generator for which the company has exclusively licensed a patent from NUS. The company was kickstarted by a grant from the Singapore-based Temasek Foundation Ecosperity to develop quantum-safe encryption devices, on which it has been collaborating with local partners.

Brenda works with other staff and consultants on the quantum encryption systems. Two CQT PhD graduates, Mathias Seidler and Lee Jianwei, were hired to full-time positions in 2019. Before them, another CQT alumnus, Lim Chin Chean, headed this line of work (see main story). The company also offers consulting and educational workshops.

Ultrastable and superradiant



A new design for lasers could bring top-performing devices to the masses, empowering research labs and fuelling development of precision clocks and other sensors. That's the hope of CQT researchers Travis Nicholson, Yu Xianquan (pictured) and Steven Touzard and their collaborators at JILA, a joint institute of the University of Colorado, Boulder, and the US National Institute of Standards and Technology.

The most stable lasers on Earth are currently used in the world's most precise atomic clocks, where they achieve frequencies stable to 18 decimal places. However, these lasers are custom machines that require ample resources, specialised maintenance and must be kept in carefully controlled environments. Their stability depends partly on precision engineering of their internal components, especially the optical cavity.

A cheaper, more robust way of building stable lasers could advance atomic clocks and be a boon for tests of fundamental physics. For example, such lasers could help search for dark matter, detect gravitational waves and look for changes in fundamental constants. A design that works outside lab environments might also be built into satellites to improve GPS, added to spacecraft for deep-space navigation, or used to measure gravity with high precision for earth science applications.

The team's proposal combines two old ideas – the phenomenon of superradiance and hot atomic beams – in a new way. In superradiant lasers, stability is determined by the properties of a superradiant material inside the cavity, namely densely packed atoms primed to emit light.

The first superradiant laser was reported in 2012 and used ultracold atoms, which are complicated to manage. The new work suggests that hot atomic beams, which are easier to make, could not only work but also perform better – offering continuous stable output with up to eight orders of magnitude more power. For instance, the researchers estimate a laser using a hot beam of calcium could deliver 0.1 mW at a linewidth of 40 mHz. This would be competitive with silicon-cavity-based stable lasers.

Travis recalls early discussions for this project with his co-author Murray Holland, who proposed the original superradiant laser. Travis and Murray were previously colleagues at JILA. "We weren't sitting there going, how do we make the world's most stable laser? We were thinking, how do we make a stable laser everyone can use?" says Travis. It has taken years of work, but he thinks they've got there: "What we've eventually come to is a design that appears to make superradiant lasers practical."

Satellites progress towards global quantum internet

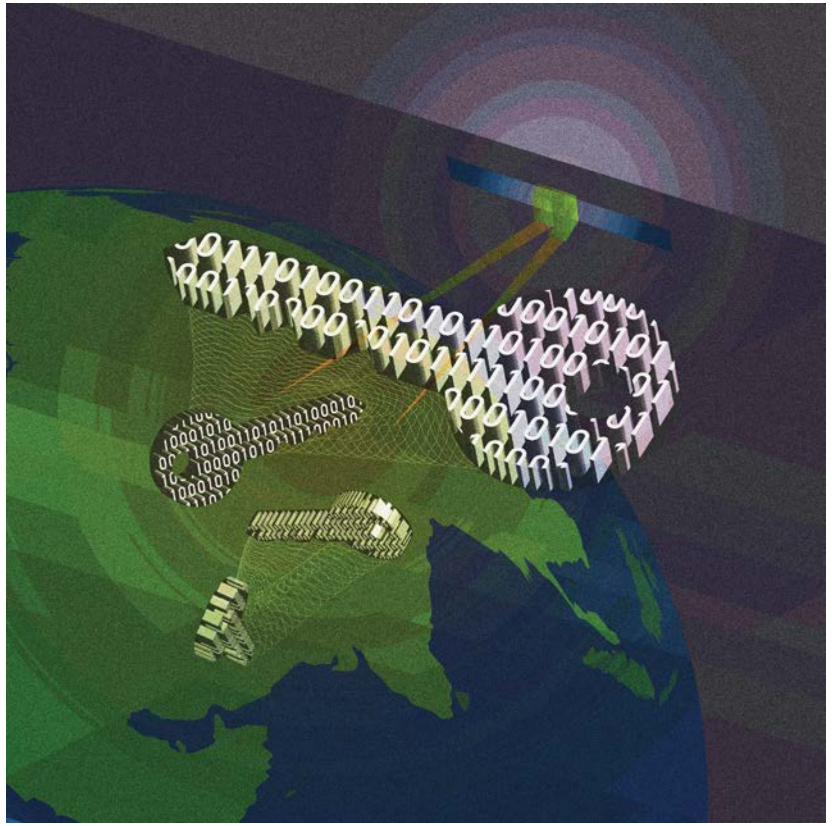
Scientific results from CQT's SpooQy-1 nanosatellite and China's Micius satellite show promise of entanglement technology in orbit

June 2020 was a big month for quantum spookiness in space: the scientific teams behind the world's first two quantum satellites both published results showing the promise of their technology for future communication networks.

In Singapore, the researchers who designed, built, and launched SpooQy-1 celebrated data confirming entanglement onboard their shoebox-sized, 2.6 kg nanosatellite. That team is led by CQT Principal Investigator Alexander Ling. The results appeared in the journal *Optica*[1] on 25 June.

In China, researchers working on the Micius satellite announced they had made an encryption key from entanglement shared between two ground stations 1,120 km apart. These results were published in *Nature*[2] on 15 June.

Artur Ekert, former CQT Director and the first to propose in the 1990s that entangled signals could secure communication, worked on some theoretical aspects of the Micius paper.



Aki Honda/CQT, NUS

Image: Entangled light particles sent from satellites to Earth could make encryption keys and connect quantum devices in a global quantum internet.

In an opinion article co-authored for Singapore newspaper *The Straits Times*, Alexander and Artur wrote: "In years to come, satellites such as the Singaporean

[1] A. Villar, A. Lohrmann, X. Bai, T. Vergoossen, R. Bedington, C. Perumangatt, H. Y. Lim, T. Islam, A. Reezwana, Z. Tang, R. Chandrasekara, S. Sachidananda, K. Durak, C. F. Wildfeuer, D. Griffin, D. K. L. Oi, and A. Ling, Entanglement demonstration on board a nano-satellite, *Optica* **7,** 734 (2020)
[2] J. Yin *et al*, Entanglement-based secure quantum cryptography over 1,120 kilometres, *Nature* **582,** 501 (2020)

SpooQy-1, or the Chinese Micius, will become part of a global network supporting quantum communication between any two points on Earth. Call it a quantum Internet."

Why orbit

Entanglement, once dismissed as 'spooky action at a distance' by Einstein, is a correlation in the properties of particles that can bring gains in privacy and computing power. Both SpooQy-1 and Micius carry quantum devices that create pairs of entangled light particles, called photons. Today's internet already uses photons to carry data through optical fibres. The challenge in building a quantum internet is that optical losses in fibre limit quantum signals to distances of a few tens of kilometres. Signals sent from satellites could reach further.

A country the size of Singapore could have a fibre-based quantum network, but innovation is needed to go global. "We are seeing a surge of interest in building quantum networks around the world. Satellites are a solution to making long range networks, creating connections across country borders and between continents," said Alexander.

SpooQy-1 was supported by the National Research Foundation's (NRF) Competitive Research Programme (CRP) funding scheme, which fosters use-inspired research projects. NRF Executive Director (Academic Research) Dr Lim Khiang Wee, said, "We are pleased that the NRF's CRP award enabled the team to develop the science needed to deploy quantum technologies in space through nanosatellites. The research findings can potentially be used for data encryption, offering the superior level of security that the technology is known for. As Singapore is a highly digital society, this development could help build a resilient and reliable quantum network that ensures digital privacy is more secure than ever."

The CQT team had collaborators at FHNW University of Applied Science and Arts Northwestern, Switzerland, the University of New South Wales Canberra, Australia and University of Strathclyde, UK.

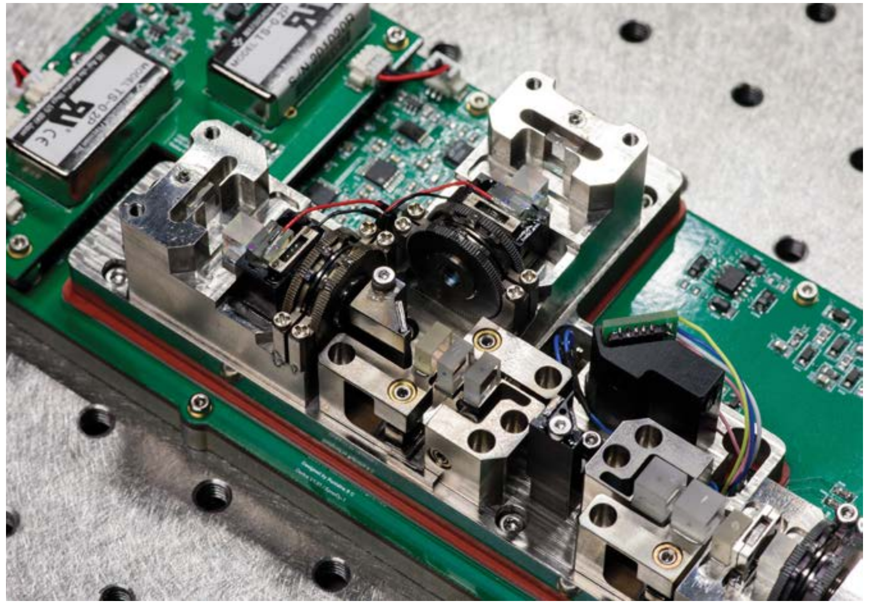
NASA

A smaller satellite

Nanosatellites like SpooQy-1 are cost-effective because they follow industry standards for CubeSats and have a small size. SpooQy-1 weighs just 2.6 kg. Micius weighs 630 kg in total, including a quantum light source weighing 23.8 kg.

A constellation of small satellites might work together to provide regional or global coverage, like the constellation of satellites SpaceX is launching to provide broadband internet.

Photo: SpooQy-1 was snapped as it was shot out from the International Space Station. Data from the 2.6 kg satellite, in orbit 400 km above the Earth, have since confirmed that it creates entangled quantum signals in a compact instrument onboard.



SpooQy-1 launched first to the International Space Station from the United States in April 2019, and then into orbit with help from the station's astronauts. CQT made these arrangements for space travel with the Singapore Space and Technology Association and the Japan Aerospace Exploration Agency.

Before the satellite left Earth, much of the team's work went into miniaturising the quantum light source to fit into SpooQy-1's tiny frame. "At each stage of development, we were actively conscious of the budgets for mass, size and power," said Aitor Villar, who worked on the quantum source for SpooQy-1 during his PhD at CQT. "By iterating the design through rapid prototyping and testing, we arrived at a robust, small-form factor package for all the off-shelf components needed for an entangled photon-pair source."

Photo: ▲ The quantum light source onboard SpooQy-1 is optimised to work with minimal power and rugged enough to survive a rocket launch and conditions in space. It consists of a blue laser diode that shines on nonlinear crystals to create pairs of entangled photons. In orbit, the instrument operated over temperatures ranging from 16 °C to 21.5 °C. ◀ Researchers and engineers at CQT tracked and communicated with the nanosatellite from a control centre established in the lab where SpooQy-1 was put together.

Trials of earlier prototype instruments were carried out by flying equipment on a weather balloon to the edge of the atmosphere and in another NUS-built nanosatellite called Galassia.

Up next

What Micius has achieved highlights the challenges ahead. The Chinese satellite first reported entanglement distribution to ground stations in 2017, but so few photons were detected on Earth that it was not practical for communication. The team upgraded the ground stations to increase detection efficiency and improved the signal processing. The CQT team is looking at an alternative to this double downlink model. A satellite can also create keys by doing quantum communication with one ground station at a time, then sending some classical signals.

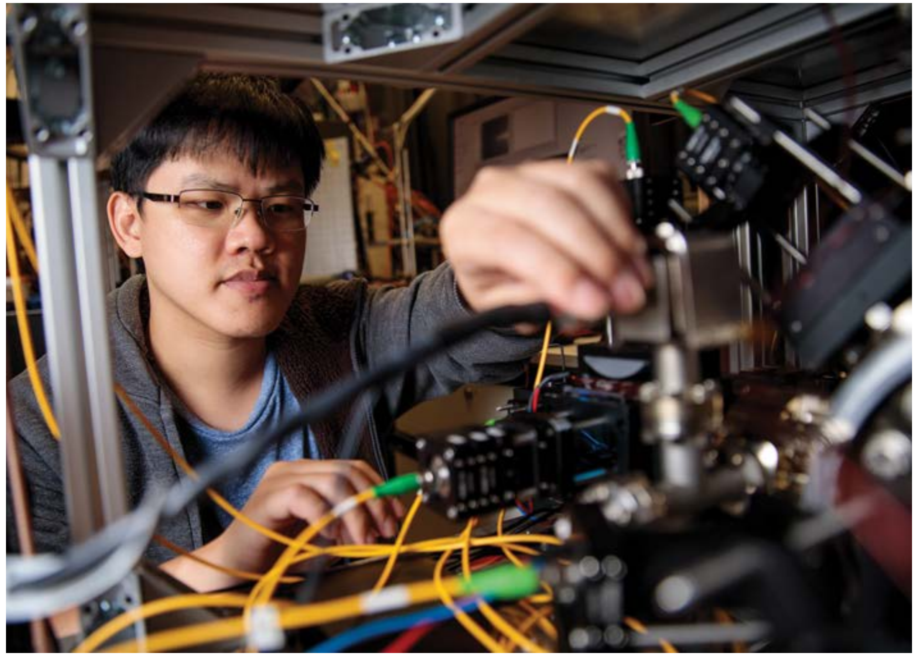
SpooQy-1 is controlled from ground stations in Singapore and Switzerland, but it hasn't attempted to send its quantum signals to Earth. The CQT team is collaborating with RAL Space in the UK on a design study for a quantum nanosatellite with these capabilities. With funding from DSO National Laboratories, the team also plans to build an optical ground receiver in Singapore.

Meanwhile, SpooQy-1 has completed thousands of orbits around Earth, its instrument still operational. SpeQtral, a venture-funded company, was spun-off from the Centre to offer commercial satellite-based quantum communication systems. The CQT and SpeQtral teams are collaborating to gather ongoing performance data. The researchers are interested, for example, in how radiation in the space environment affects its components.

SpooQy-1's story, however, is almost over. The nanosatellite is expected to meet a fiery end in 2021 as its orbit naturally decays. The nanosatellite will avoid becoming space debris by burning up in Earth's atmosphere.

Mission: outreach

In addition to its scientific life in orbit, SpooQy-1 has taken a role in culture, contributing to outreach by CQT. The satellite flew with two engraved plaques (pictured): one carries the name of all the team members that worked on it, the other a quotation from *The Golden Record 2.0* — a play written for the NUS Arts Festival in 2018, for which CQT was a partner. The play was inspired by the Voyager spacecraft launched by NASA in the 1970s carrying golden records engraved with messages about Earth and humanity. A replica of the satellite featured in a sequel performance. The SpooQy-1 replica was also shown in two museum exhibitions about quantum physics, at the Centre de Cultura Contemporània de Barcelona in Spain, April – September 2019, and at the Science Centre Singapore August 2019 – March 2020. *Quantum:The Exhibition* in Singapore was sponsored by CQT and other local partners.



Atoms feel Earth's pull

CQT researchers plan to take their portable gravimeter into the field

For his PhD, Oon Fong En has followed in the footsteps of Galileo. The renaissance scientist Galileo Galilei is famously said to have studied gravitational acceleration by dropping items from the Leaning Tower of Pisa over 400 years ago. In the past five years, Fong En has built an apparatus to make incredibly precise measurements of local gravity by dropping clouds of cold atoms.

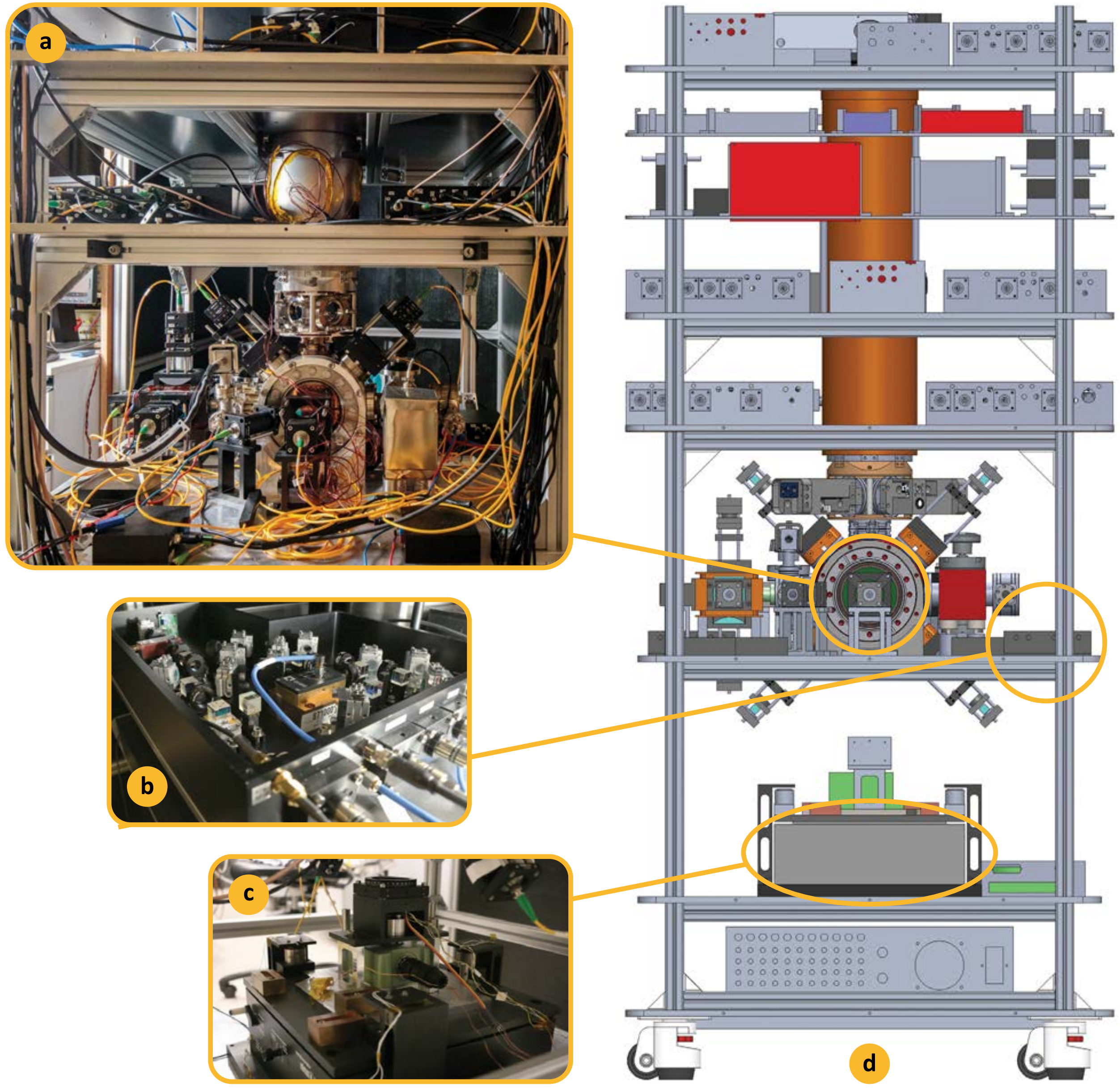
Absolute measurements of Earth's pull at specific locations can reveal underground structures or movement, both manmade and geological. That makes the tool interesting for applications ranging from defence to earth science. We learn at school that acceleration due to gravity at Earth's surface, denoted by g, is about 9.8 m/s². The gravimeter built by Fong En should be able to measure g to nine decimal places, known as μ-*Gal* sensitivity. Volcanic eruptions, for example, might change local g by a few hundred μ-*Gal*, and mining activities by tens or more.

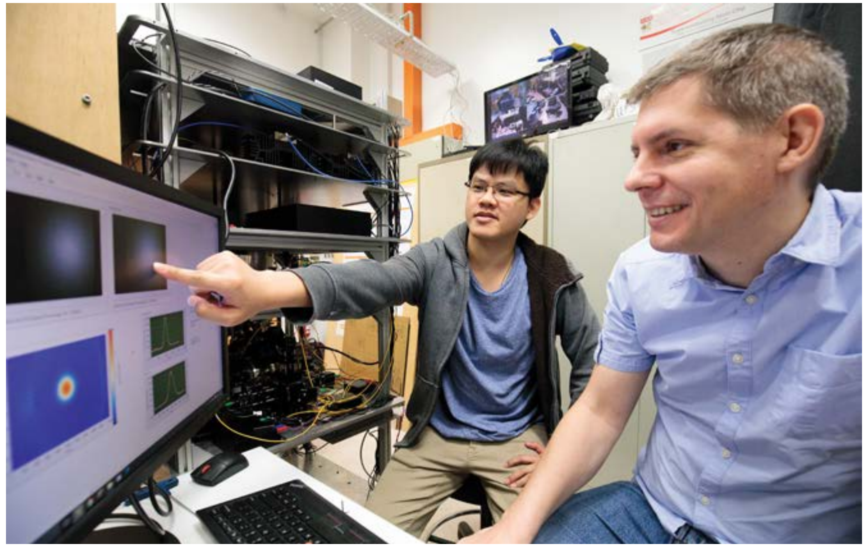
The project has support from Singapore's DSO National Laboratories. The team is also exploring opportunities to collaborate with the Earth Observatory of Singapore for field tests. Beyond sensing gravity, the atomic interferometer in their device could be adapted for use in navigation.

Measurements completed in late 2020, just before Fong En submitted his thesis, show the instrument is on track to reach their sensitivity target. He has identified a source of noise that needs to be addressed to reach optimal performance, arising from the gravimeter's laser systems, and is extending his time in the group to work on this. His PhD is supervised by CQT Principal Investigator Rainer Dumke at Nanyang Technological University.

"I have done everything for the gravimeter from the drawing to the construction – working on the computer control, optics, electronics, vacuum system and so on. To start from a design to making something that can actually be helpful to the world, it makes you feel satisfied," says Fong En. Read on to learn more about the gravimeter he has built.

Photo: CQT PhD student Oon Fong En has designed and built from scratch an atomic gravimeter.





a The atomic gravimeter uses the wave-like properties of matter. In the chambers pictured, a cloud containing hundreds of millions of atoms are readied, launched and interrogated by lasers. The cloud is prepared in a magneto-optical trap, then transferred into the main chamber (the central circular object). From there, the atom cloud is launched upwards into a 60 cm tube. The tube is emptied of air by a vacuum system so the atoms can move unhindered by collisions with air molecules. The tube (shown orange in schematic d) is made of mu-metal, which shields the atoms from magnetic fields that affect their energy levels. As the atoms rise and fall, three short laser pulses of 16, 32 and then 16 microseconds long and spaced by 180 millisecond pauses, move them in and out of a superposition of energy-momentum states. The laser interactions effectively create and then recombine two different paths for the atoms to follow. In this way, the setup acts as a Mach-Zehnder interferometer: the matter waves on the two paths interfere, affecting how many atoms end up in each energy state.

b The interaction of the lasers pulses with the atoms is affected by gravity, since the acceleration of the atoms causes them to see the frequency of the laser light shifting. This is a Doppler shift like the rising and falling pitch of a passing siren. The measurements of *g* are deduced by how quickly the laser frequency must be adjusted – the laser frequency chirping rate – to compensate for the Doppler shift. The rate is matched to the gravitational acceleration by observing the interference. Shown is an electro-optical modulator that helps to create the different laser frequencies.

c Sitting near the base of the gravimeter is an active vibration cancellation system. It prevents acceleration of a mirror reflecting the laser beams – caused by vibrations in the environment from contaminating the measurement of the acceleration of the atoms. It combines a spring-mass isolation stage with an accelerometer and tilt sensors that provides feedback to three voice coil actuators. These push on the stage to cancel vertical movement and tilt.

d The components of the gravimeter fit compactly in a metal rack about the size of a household fridge. The 1.8 m tall structure, estimated to weigh some 300 kg, is on castor wheels. It is portable in the sense that a small van could bring it to outdoor locations. It can also be controlled remotely.

Photo: Fong En (left) first got interested in cold atoms when he did an undergraduate research project with Rainer (right). He then worked for a few years as a Research Assistant before starting a PhD to create the gravimeter. In the photo, the two scientists are looking at images of a cold atom cloud in the gravimeter during testing. The setup uses clouds of the element rubidium-87 cooled to just above absolute zero.

Quantum Engineering Programme gears up

National initiative will support translational work across four pillars

Singapore's national Quantum Engineering Programme (QEP) received a second wave of funding in 2020, kickstarting new plans.

The programme also took new leadership, with CQT Principal Investigator Alexander Ling appointed Director of the programme in September 2020 (see box **People of QEP**).

QEP's goal is to develop quantum science and technology into solutions for real-world problems. Launched by Singapore's National Research Foundation (NRF) in 2018 with a $25 million investment, QEP was in 2020 allocated an additional $96.6 million over five years.

"Our quantum community has a good base of technical knowledge on which we can build new capabilities to solve national challenges and ensure value-capture for Singapore," said Alexander.

CQT Director José Ignacio Latorre, who serves as a member of the QEP steering committee, said, "We welcome the role of the Quantum Engineering Programme in Singapore in turning discoveries from the edge of knowledge into technologies that can improve human lives."

R&D projects

QEP is hosted at the National University of Singapore, but it funds projects led from any of Singapore's research organisations. In 2021, the programme office will move into offices in the same building as CQT.

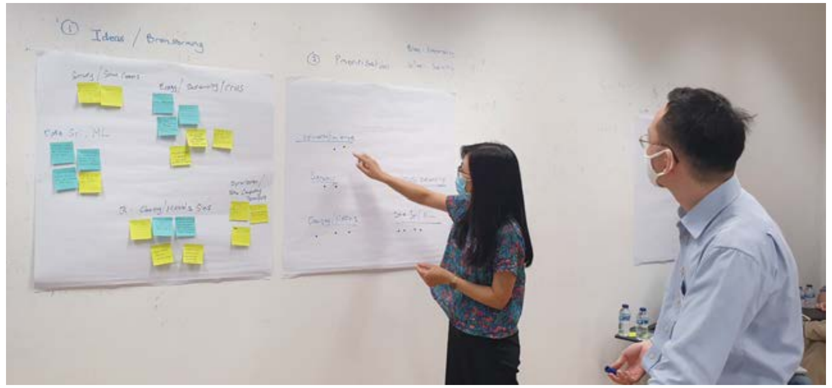
Supported by the first phase of QEP funding, seven research projects are already underway. These include efforts to develop chip-based quantum key distribution technology (pictured right), improve single photon detectors, build a quantum memory and miniaturise atomic clock components. QEP also partnered with IBM to provide researchers in Singapore access to the company's quantum computers on the cloud.

The new funding will support research across four pillars: quantum communication and security, quantum computing, quantum sensors and a quantum foundry. There is also support for ecosystem building.

A major project under the quantum communication and security pillar will be the establishment of a National Quantum-Safe Network to trial quantum key distribution concepts and architectures.

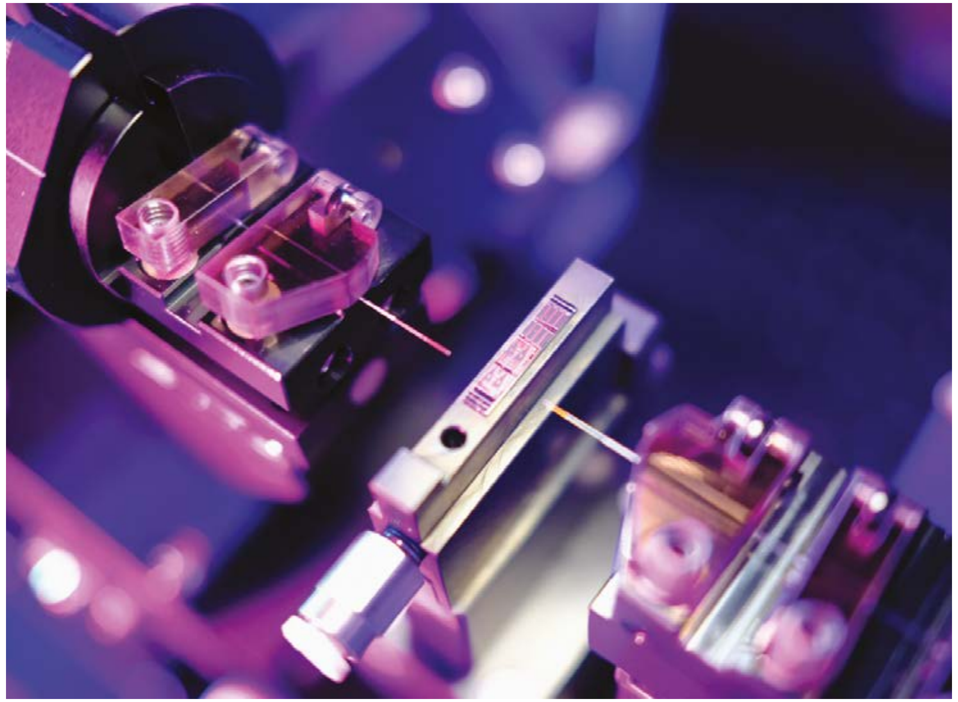
Industry challenges

To focus research funding, the QEP office is holding workshops with researchers and potential end-users from target industries. The workshop discussions inform the creation of challenge statements, which will then drive calls for proposals.



The first QEP workshop in September 2020 was on Quantum Sensors for Environment and Navigation, with participation by the Earth Observatory of Singapore and the Singapore Ministry of Defence. The resulting call, open to proposals until April 2021, presents seven challenges, including satellite-free inertial navigation and magnetic field sensing to detect hidden objects.

Workshops held in November 2020 on Quantum Computing for Supply Chain Management and Finance (see box **A hub for finance and logistics**) will inform a call opening in 2021. More workshops and calls will follow: Quantum Computing for Chemistry and Materials, Quantum Processors and the Quantum Internet are next on the agenda, creating new opportunities for applied research in Singapore. Check for the latest news at **qepsg.org**.



Gong Xiao/ECE, NUS

Photo:
◀ QEP has held design thinking workshops with small groups of participants from target industries to identify challenges the programme might adopt as research goals.

▲ With funding under QEP's first phase, CQT Principal Investigator Charles Lim is working on quantum key distribution (QKD). Charles has a joint appointment in the NUS Department of Electrical and Computer Engineering. He has two industrial partners in the project: imec to make chip-based devices and ST Engineering to advance technology using measurement-device independent protocols. When the latter was announced in May 2020, Goh Eng Choon, President of Cybersecurity Systems Group at ST Engineering, said, "This research into quantum cryptography and the co-development of the industry's first solution will allow us to explore the potential of this technology, further strengthen our arsenal of advanced cybersecurity solutions and gain a foothold in the QKD market."

People of QEP

Behind the scenes at QEP is a hard-working team. Many of the people supporting the programme's operations are drawn from CQT's pool of experts.

QEP Director Alexander Ling is both a CQT Principal Investigator and an Associate Professor in the NUS Department of Physics. He brings experience of translational research: his group has trialled quantum devices on Singapore's urban fibre network, in collaboration with Singtel (see p.9), and in nanosatellites in space (see pp.17–20). He is also a co-founder of two quantum spin-off companies, S-Fifteen Instruments and SpeQtral. Evon Tan, a founding member of CQT's administrative team, serves as QEP's Deputy Director (Operations).

Volunteer coordinators for the programme's pillars bring expertise in other domains. These include CQT researchers Christian Kurtsiefer and Marco Tomamichel working on quantum communication and security, Miklos Santha and Patrick Rebentrost on quantum computing and Manas Mukherjee and Rainer Dumke on the quantum foundry. The coordinator for the quantum sensors pillar is Gao Weibo from Nanyang Technological University.

Two further coordinators support other dimensions of the programme. CQT's Charles Lim and Michael Kasper from Fraunhofer Singapore are working on the National Quantum-Safe Network and CQT's Dimitris Angelakis is coordinating cloud access to commercial quantum processors.

The QEP office reports to a steering committee with 12 senior representatives of Singapore's institutes of higher learning and agencies. The steering committee is co-chaired by the Chief Executive Officer of NRF, Low Teck Seng, and Singapore's Chief Defence Scientist, Quek Gim Pew, who is also Chair of CQT's Governing Board.

A hub for logistics and finance

The skyscrapers of the central business district and the container ships that circle Singapore's shores are visible signs of two important sectors in Singapore's economy: logistics and finance. These industries are also potential adopters of quantum computing, since they use high-performance computing to tackle complex problems such as supply chain optimisation, forecasting and the pricing of derivatives. That has put them on the QEP agenda.

Working with Singapore's Economic Development Board and IBM, the QEP team planned a pair of workshops on Quantum Computing for Supply Chain Management and for Finance. Held in November 2020, the workshops had speakers from DHL and IBM, from financial companies TradeTeq and EastSpring Investments, from local quantum startups and research experts. After each set of public online talks, IBM facilitated a private 'design thinking' workshop with selected participants to home in on challenge statements.

CQT's Patrick Rebentrost, a Senior Research Fellow, was one of the coordinators for these workshops. He has worked on quantum computing for finance – for instance, developing quantum algorithms for portfolio optimisation and derivative pricing – having first got interested in the area after graduate course in mathematical finance.

Patrick emphasises that it's a long-term ambition to put quantum computers to work in this field.

Travelpix/Shutterstock.com

"There is a lot of global interest in the financial community. Goldman Sachs and JP Morgan in the US for example have research teams that are looking ahead, but my impression is that they don't have immediate performance goals," he says.

Some kinds of quantum algorithms would need millions of qubits to run, on quantum computers that are corrected for errors caused by environmental noise. In the near term, scientists expect practical demonstrations to be limited to noisy intermediate scale quantum (NISQ) devices of up to a few hundred qubits.

Patrick is therefore cautious about anticipating that projects under QEP will have real-world applications straight away. Instead he highlights that pilot projects will support mutual education of academic and industry partners and train a talent pool. Beyond that, he says "We should have a better understanding of where quantum computing can and cannot help in finance and supply chain. We want to have the whole community participating, and I think that is happening."

When it comes to finance, Patrick also stresses that it's not only about profit. "Of course people are excited to think you could plug a quantum computer into the market and make a lot of money, but there's also a chance that quantum computations, for example for risk analysis and anomaly detection can help governments and regulators to strengthen the health of the financial system," he says.

Training the next generation of quantum technologists

A specialisation in quantum technologies for NUS undergraduates in physics nurtures young research talents

A major part of CQT's mission is education. The Centre has a well-established PhD programme that has already trained more than 80 students. The launch in 2019 by the NUS Department of Physics of a Specialisation in Quantum Technologies extends new opportunities to undergraduate students.

CQT Principal Investigator Valerio Scarani, who was then Deputy Head of Physics, drove the creation of the specialisation. To earn the qualification, students must concentrate their choice of modules in quantum topics (see box **How to become a quantum specialist**) and complete their final year research project in quantum technologies. Any project supervised by a CQT Principal Investigator is eligible.

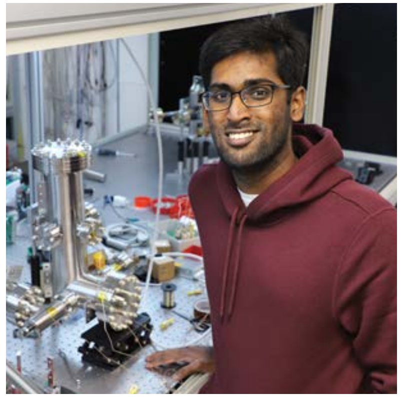
"Thanks to CQT, NUS was in a unique position to offer a certification of competence in quantum technologies for undergraduates, one of the very first of this type worldwide. Given its popularity, we shall soon propose a Masters program open to international students," says Valerio.

Introducing a Masters-level course would fit with moves at NUS to broaden undergraduate education. In 2020, the university announced the creation of the College of Humanities and Sciences, bringing together the Faculty of Science and Faculty of Arts and Social Sciences. Students accepted into either faculty will have flexibility to choose courses across disciplines, building on a new common curriculum.

Student takes

While these changes are ahead, enrolment in the Specialisation in Quantum Technologies has been open to existing physics students. Twenty-one students joined the first batch, graduating in June 2020. Some of these quantum technology specialists have stayed at CQT: three are enrolled in the CQT PhD programme, and others have continued as Research Assistants (RA) while deciding their next steps.

Among them is Ravinraj Ramaraj, who won an 'Outstanding Undergraduate Researcher Prize' from the University for his final year project on "Construction of an Experimental Platform for the Trapping and Cooling of Strontium" in the group of Travis Nicholson. He's continuing to work on this experiment while deciding where to do a PhD. He received offers from universities in the United States and, as a Singaporean, is keen to broaden his experience overseas.



"As a student, I've fallen in love with experimental atomic physics and would love to continue my work in this field." – Ravinraj Ramaraj

Esther Wong, now an RA in the group of Alexander Ling, also hopes to continue in research. She says, "I became interested in quantum physics after reading about how bizarre it was in a few books at the public libraries. I later decided to specialise in quantum technologies when I heard that I could make use of this phenomenon in real life applications." She is working to measure background light in Singapore's night sky, looking for wavelength ranges with little noise that could be used for quantum communication with satellites.

"I especially loved doing research projects where I got to gain deeper insights into devices for quantum technologies." – Esther Wong

Students graduating from the quantum specialisation can forge careers outside of research too. Among the graduates that did projects in CQT, one was hired as a technology analyst by the financial services provider Citi, for example, and another is working as a technical analyst for information technology company SimplifyNext. Another has found their way into Singapore's emerging commercial quantum ecosystem.

Isaac Tan, who worked in Loh Huanqian's lab for his final-year project, approached the startup Atomionics after spotting the company listed on the industry section of CQT's website. Atomionics is building a gravimeter based on atom interferometry. "My job involves planning and executing optics-related tasks together with our senior research scientist and CTO, who was also previously from CQT."

When Isaac first signed up to study physics, he was following his passion and wasn't sure where it would take him. "Everyone seemed to have the idea that someone with an education in physics will end up having only two career options: physics teacher or researcher. Along the way, I become more exposed to the working world and had a deeper understanding of job opportunities," he says.

"The physics curriculum was rigorous and helped us develop critical, mathematical, and analytical thinking skills." – Isaac Tan

How to become a quantum specialist

Physics majors enrolling from 2021 within the NUS College of Humanities and Sciences can graduate with a formal 'Specialisation in Quantum Technologies' by meeting these compulsory requirements:

- Doing their honours project in quantum technology
- Completing the course 'Device Physics for Quantum Technologies'

Students must also choose two modules from this list, including at least one at the most advanced level:

- Atomic and Molecular Physics I and/or II
- Advanced undergraduate research project
- Quantum Mechanics III
- Quantum Optics

The qualification is approved by the Singapore Ministry of Education.

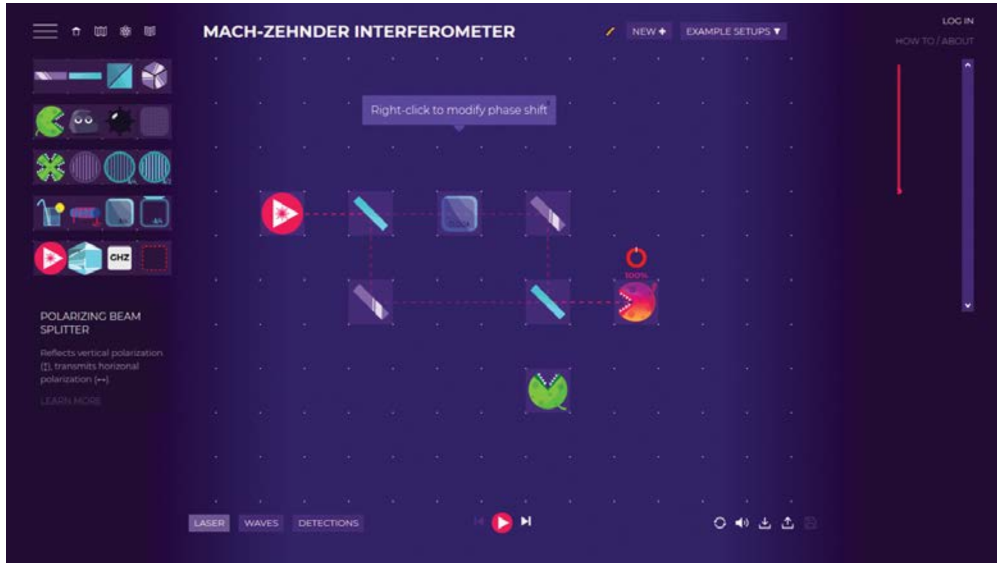
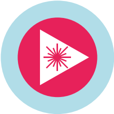


Image: The Virtual Lab, adapted from the game engine, allows users to create experimental setups.

Quantum physics in play

Cute components combine with real physics in CQT-backed online puzzle game and virtual lab

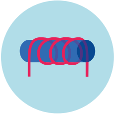
A quantum game that invites creative play like a box of lego bricks: that was the goal of the team of scientists, programmers and designers behind quantumgame.io.



CQT supported development of the educational Quantum Game which launched in a beta version in April 2020. The team has since adapted the underlying game engine to provide a 'Virtual Lab' for educators and students and plans to release the game's alpha version in 2021.

Quantum Game is a drag-and-drop puzzle game. Players clear a level when they manage to direct photons to the photon detectors, represented by Venus flytraps, according to the level requirements. The levels start as simple as steering photons to avoid rocks that absorb them, then increase in complexity. Some represent well-known quantum experiments. For example, players can construct their own interferometer.

Piotr Migdał, who led the game team, wanted to create a playful environment for people to explore quantum phenomena. "The world of quantum is so small. There is no way in daily life to create an environment to simulate the quantum world and let people play with that. This game is like lego blocks for quantum physics. Everyone can play it without knowing quantum physics."



Piotr is a former theoretical physicist who now works in data science. He launched the original Quantum Game with Photons back in 2016 along with a few collaborators. CQT's former Director Artur Ekert was impressed by the project and invited Piotr to host a team at CQT to further develop the game – his instruction: "All I want is the coolest quantum game in the known multiverse, please!"

Team members Piotr, Klem Jankiewicz, Philippe Cochin, Chiara Decaroli and Kuba Strebeyko were hosted at CQT at different times between August and November 2019. Ivana Kurecic, a CQT visitor with expertise in outreach, also contributed to the project. The current team consists of Piotr, Klem and Paweł Grabarz.

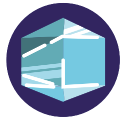
During the team's time at CQT, the group put their expertise in quantum physics, programming and web design to work. They built powerful and modular code that does sophisticated calculations in the background while the game runs in a web browser. They also created a set of cute experimental elements (inset images) with an encyclopaedia that explains to non-physicists what the devices are, how they work and how they are used in a lab and daily life.

The game visualises the photons as light waves with forms drawn directly from the quantum equations. In the interferometer, for example, players can see how two waves of light interfere with each other and how the amplitude and polarisation of light changes as the light is split, reflected and recombined.

Associate Professor Monika Schleier-Smith, who teaches quantum information at Stanford University, found the game useful for teaching. She used the game as a virtual optical table when experimental classes could not be held during the COVID-19 lockdown.

She told the team, "Even when it becomes possible to teach my class in person again, your website could help me scale to a larger class size than is possible when I require equipment for hands-on demonstrations."

CQT PhD student Adrian Utama, who has planned many physics outreach events, says, "I think you can teach a whole course of quantum mechanics to arts and social science students just by using this game. It can provide an intuitive sense to how quantum mechanics works, without needing to go through the unforgiving mathematics."

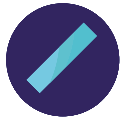


As an experimentalist, however, Adrian highlights that there's more to learn about real devices. He imagines that new lab members might be asked to complete the game as part of their induction. "Then, we would tell them that the experimental world is nothing like the game. Even just getting a single photon source is not trivial at all. That's why working as an experimental physicist is very interesting!" he says.

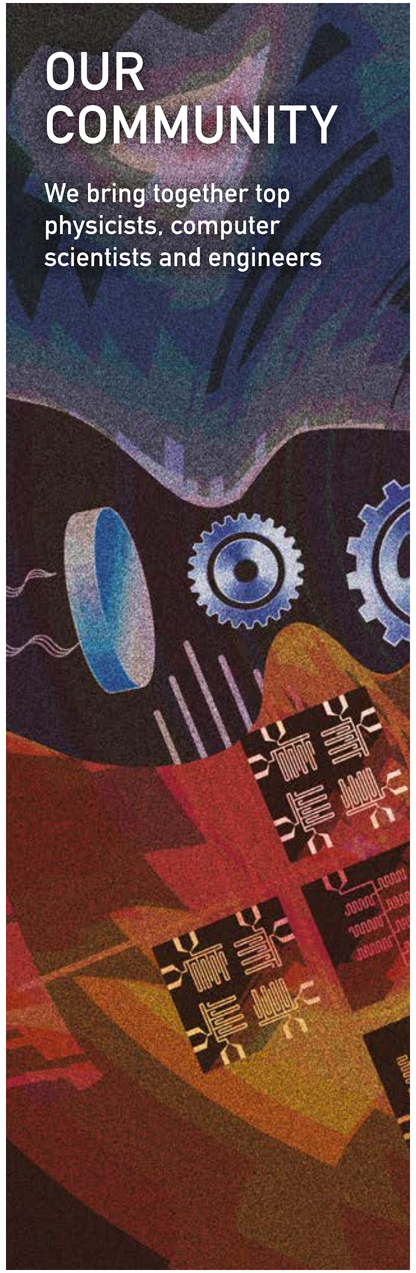
In 2020, Piotr and Klem received a small grant from the Unitary Fund, a non-profit organisation that describes itself as "working to create a quantum technology ecosystem that benefits the most people". With that funding, they developed widgets that can embed visualisations of quantum states and operations into online content, an extension of their work on the game. They call these Bra-ket-vue tools. The team also received private investment from an angel investor from Poland.

Before releasing the Virtual Lab in December, the team also improved the simulation run speed to make sure that advanced experiments can run in real time in the browser. The Virtual Lab can simulate up to three photons and make quantum measurements.

The code for the game's quantum numeric simulation engine and the visualiser for quantum states and operations have been made open source at https://github.com/Quantum-Game. "Quantum Game is more than just a game," says Klem, the team's lead graphics and user-experience (UX) designer. "What is most important is that it can have many different purposes."



Images: Dotted through the text are the elements that players of the Quantum Game and experimenters in the Virtual Lab can drag and drop in their setups. They correspond to devices used in optics labs, such as photon detectors, polarisation rotators, waveplates and non-linear crystals.



OUR COMMUNITY

We bring together top physicists, computer scientists and engineers

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Principal Investigators

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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
Dagomir Kaszlikowski	theory
Hartmut Klauck	theory
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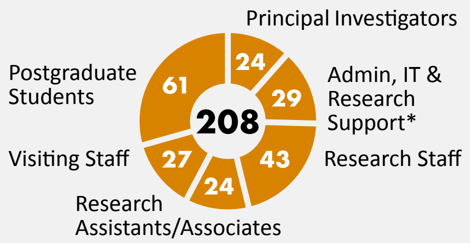
Kwek Leong Chuan	theory
Wenhui Li	lab
Charles Lim	theory, lab
Alexander Ling	lab
Dzmitry Matsukevich	lab
Manas Mukherjee	lab
Travis Nicholson	lab
Miklos Santha	theory
Valerio Scarani	theory
Marco Tomamichel	theory
Vlatko Vedral	theory
David Wilkowski	lab

theory lab

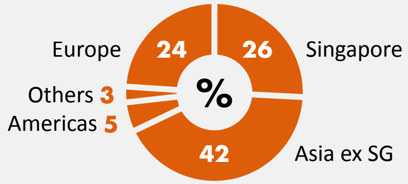
Headcount



Count of CQT staff and students as of 31 December 2020

* Admin and IT count includes a cluster of 6 staff working across University centres

Nationalities



Nationalities of CQT staff and students as of 31 December 2020

https://www.quantumlah.org/people

*CQT acknowledges changes to its Governing Board in 2020, welcoming José Ignacio Latorre as he takes over from Artur Ekert as CQT Director and Andy Hor succeeding Tan Sze Wee as representative from A*STAR. Chang Yew Kong, a founding member of CQT's board and Chairman of the Industry Advisory Committee, Singapore Institute of Technology, has stepped down in 2020. We thank our former board members for their service. Board and Principal Investigator listings are as of 31 December 2020.*

Students at CQT

61 CQT PhD students as of 31 December 2020

9 CQT PhD graduates in 2020

84 CQT PhD graduates since CQT founded

PhD programme

CQT is expanding its PhD programme. The Centre accepted a record number of 29 students in 2020 with a similar number of studentships available in 2021. We offer high-quality education and support graduate students in making original contributions to research. We accept applications throughout the year, with successful students of all nationalities receiving a generous scholarship plus allowances. 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.

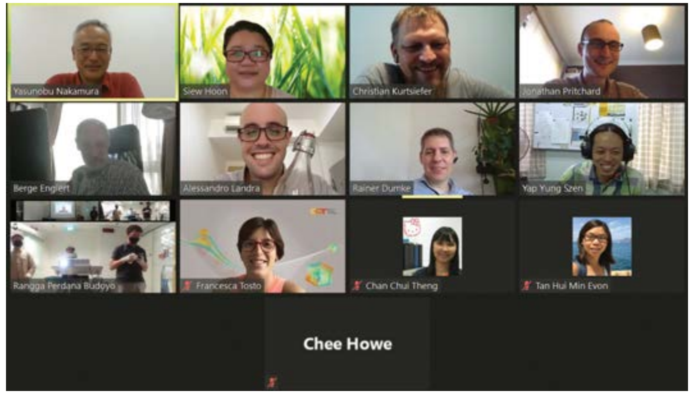


Photo: Many students finishing their PhDs in 2020 during the COVID-19 pandemic had the unusual experience of defending their theses fully online. Pictured is the defence of Alessandro Landra who moved after graduating to Finland to join the quantum computing hardware company IQM, along with fellow CQT PhD graduate Francesca Tosto (see p.36).

Internships

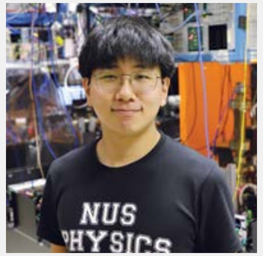
30 CQT Interns in 2020

Global travel restrictions in 2020 meant that we hosted some internships remotely, but we were still able to have many students come to work with us in person. CQT supports internships for masters students or undergraduates nearing the end of a relevant degree. Students should apply to the PI with whom they would like to work. Successful interns may be invited to join the CQT PhD programme.

"Embarking upon a PhD can be a daunting task, but CQT offers a warm and friendly environment to truly realise one's best potential and exposes students to cutting-edge research via a plethora of talks and events."

Pooja Jayachandran
PhD student in theoretical physics

"CQT offers PhD students countless opportunities to be creative with their research problems and solutions. But most importantly, the people here make it fun and exciting the entire way through!"



Kim Mu Young
PhD student in experimental physics

Recognition

The research we do at CQT is a team effort, but we are happy to celebrate individual successes too. Congratulations to our staff who received awards in 2020!

- **Loh Huanqian** was named among 15 **International Rising Talents** worldwide in 2020 by the **L'Oréal-UNESCO For Women in Science** awards. Huanqian is a Principal Investigator at CQT and President's Assistant Professor in the NUS Department of Physics. The International Rising Talents were selected from some 260 scientists previously honoured by L'Oreal with regional fellowships. Huanqian was previously recognised in the Singapore awards in 2018 in physical and engineering sciences for her research on quantum simulation. Interviewed on receiving the international award, she said: "As a quantum physicist, my dream is to use quantum simulators to guide the search for new materials that could help manage the world's rising energy needs."

- When Singapore celebrated its birthday in August 2020, National Day Awards were presented to recognise merit and service to the country. Two of the Centre's admin team were among the recipients. **Evon Tan**, Associate Director at CQT and Deputy Director (Operations) for the Quantum Engineering Programme, received **The Commendation Medal** (Pingat Kepujian). This is presented to "persons who has distinguished himself through commendable performance and conduct, or significant efficiency, competence and devotion to duty". **Lim Siew Hoon** received **The Long Service Medal** (Pingat Bakti Setia). As Academic Programme Executive, Siew Hoon handles the needs of both students and their supervisors as they navigate the students' start in research. To receive this medal, a person must be "of irreproachable character" and have completed at least 25 years' service in certain fields, including education.

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 2020:

- **Kwek Boon Leng, Joven** - for building skills and contacts to support the experimental labs beyond the scope of his job description
- **Lim Siew Hoon** - for her dedicated effort, reassuring calm and reliable knowledge in handling student matters beyond PhD administration
- **Mohammad Imran** - for having a positive attitude however heavy his workload or challenging the circumstances
- **Adam Florentin Thierry** - for his enthusiasm and effort in organising activities that encourage connections among CQTians

L'Oreal-UNESCO For Women in Science

Loh Huanqian

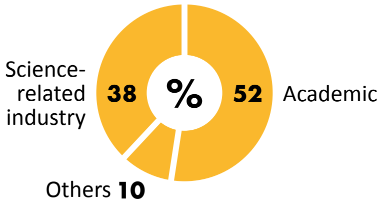
Evon Tan

Lim Siew Hoon

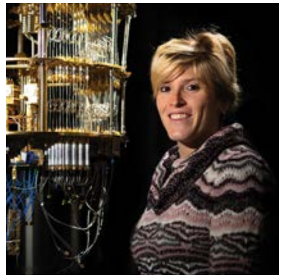
Alumni

Researchers and technical staff who once worked at the Centre for Quantum Technologies are now employed all over the world in all kinds of roles, some using their quantum expertise directly and others translating their skills to new industries. A majority continues in academic research, often taking the opportunity after a PhD or postdoc position to expand their experience in new universities or countries. We summarise in the chart, right, the next job types of 21 staff who left in 2020 for whom we have data on their next job, and share below stories of where two recent alumni are now.

Job types for 2020 alumni



Life after CQT



Francesca Tosto
Quantum Engineer, IQM

CQT PhD graduate Francesca earned her PhD for “On-demand Atomtronic Architectures on a Superconducting Atom Chip” in the group of Rainer Dumke in 2020. She was then hired to be a quantum engineer at IQM, a quantum computing hardware startup. The company is based in Helsinki, Finland, and has about 70 employees at its headquarters. Its goal is to deliver full-stack superconducting quantum computers to research laboratories, supercomputing centres and industrial customers.

On a usual day, Francesca works on the calibration and benchmarking of IQM’s processors. She enjoys working closely with diverse people who have highly specialised skills. Francesca credits the training she received during her PhD for laying the foundations for her new role, even if the technology is a little different. “I learnt the methodology of working in the lab, from setting up an experiment, measuring and characterising it, to identifying and fixing issues that occur,” she says.

Davit Aghamalyan
Research Scientist, Singapore Management University

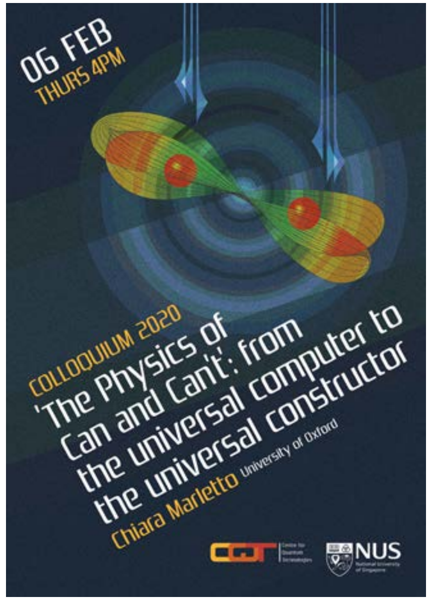
Over the years, Davit has worked in many different areas of quantum physics. “It’s been a big journey,” he says. Joining CQT’s PhD programme in 2011, he completed his thesis on “Atomtronics: Quantum Technology with Cold Atoms in Ring Shaped Optical Lattices” supervised by Kwek Leong Chuan. After graduating, he moved to France for a postdoctoral stint where he worked on cold atom collisions. He returned to CQT in 2017 as a Research Fellow. Then, Davit was part of a collaboration between CQT and A*STAR’s Institute of High Performance Computing on quantum optical systems.

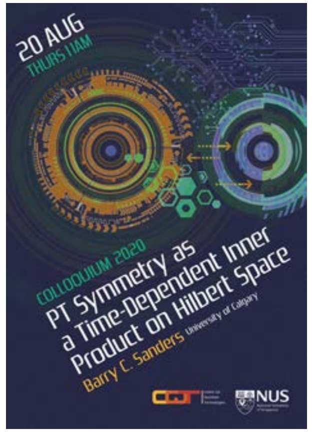
Now, Davit has moved his quantum expertise into machine learning. Davit joined Singapore Management University in July 2020 as a Research Scientist. With his supervisor, Paul Griffin, he is exploring the potential of quantum machine learning to make better predictive models for credit scoring. Singapore’s Quantum Engineering Programme (see pp. 24–27) has identified quantum computing for finance as a focus area.

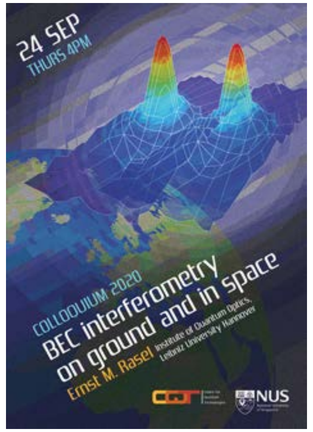
Scientific events

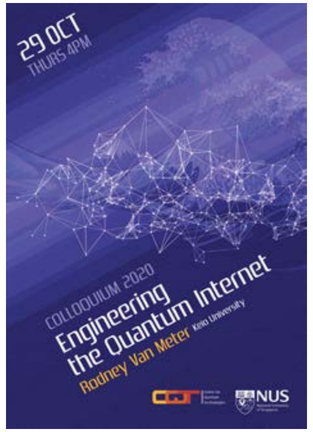
We organised some 50 scientific talks and journal club sessions in 2020, including six colloquia by distinguished speakers that inspired the posters shown here. Most of our events programme moved online, and with the speakers’ permission, we have shared recordings of many of these talks at youtube.com/quantumlah.

A symposium on 16 January 2020 marked the Centre’s 12th birthday. We also co-hosted the workshops **QTX4: Quantum Technologies in Space** (30 October) with partners in Europe and the **HPC Online Lectures on Quantum Computational Materials Science** (16-18 November) with Majulab in Singapore.



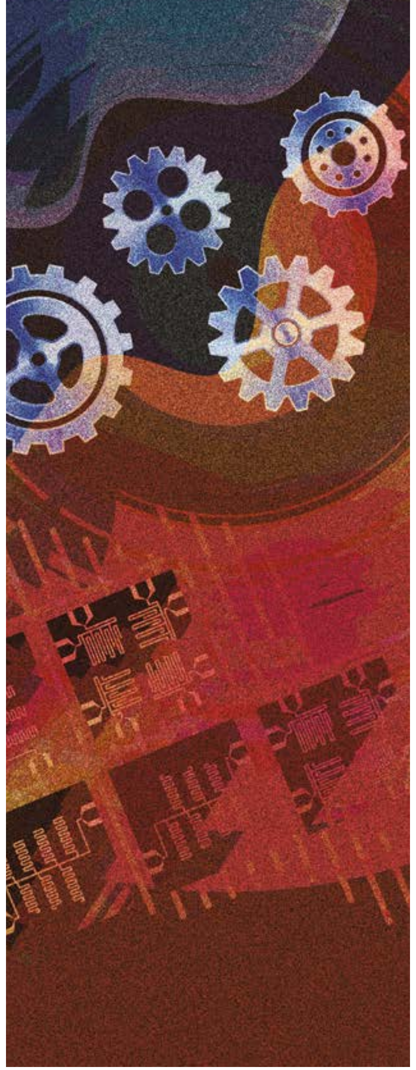






OUR IMPACT

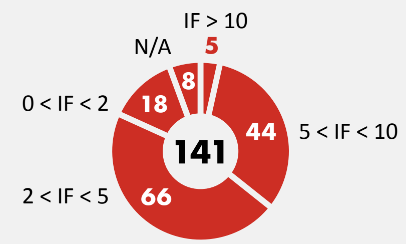
A look at CQT's outputs and spending in 2020



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 performed in January 2021.

Publications



Publications during 2020 by journal impact factor (IF)

- 3 npj Quantum Information
- 9 IEEE Transactions on Information Theory
- 21 Physical Review Letters
- 4 Quantum
- 1 Nature Photonics
- 2 Nature
- 2 Optica
- 2 Nature Physics

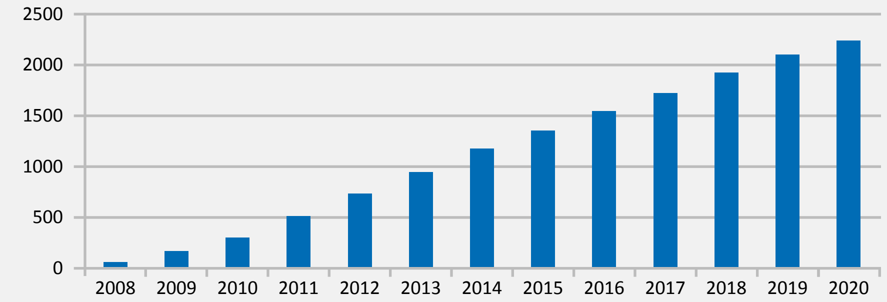
Publications during 2020 in high impact journals

There are **2,238** publications in total from CQT's first 13 years.

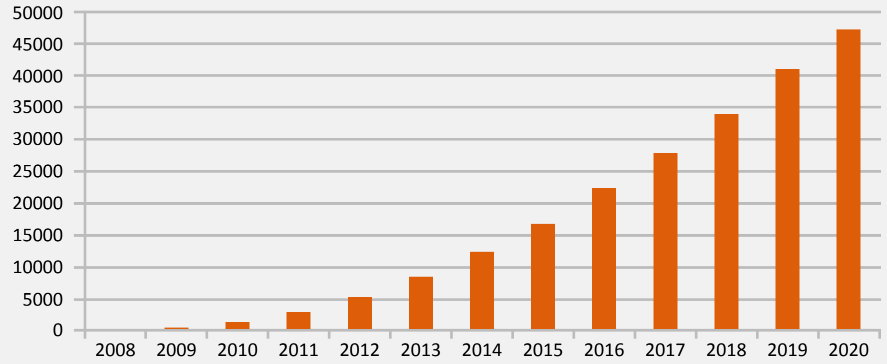
The body of work has accumulated **47,736** citations. That's an average of 21.3 citations per paper.

As a centre, our h-index is **83**.

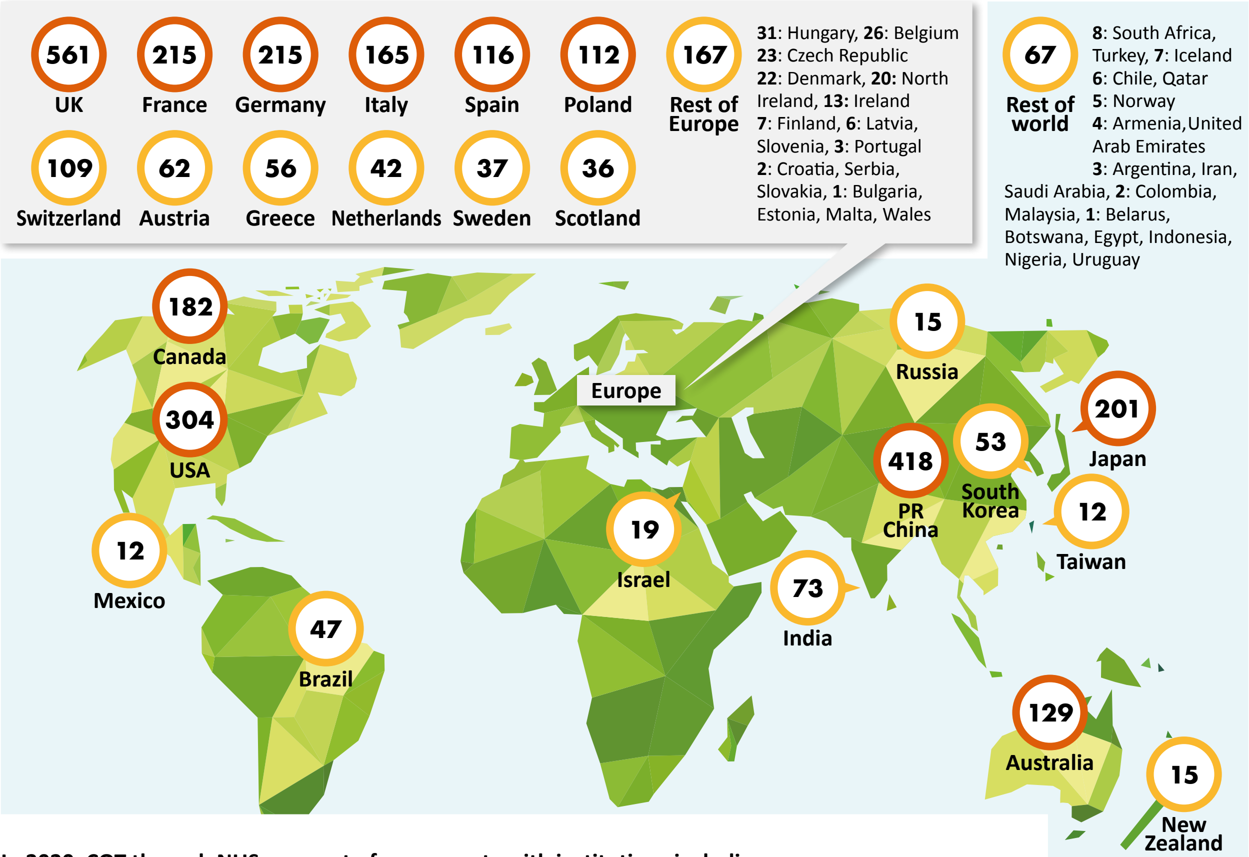
Cumulative Publications 2008-2020



Cumulative Citations



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 2020, 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 each of TCG Centres for Research and Education in Science and Technology, India; University of Catania, Italy; Graduate School of Information Science and Graduate, School of Mathematics, Nagoya University, Japan; University of Otago, New Zealand; and National Institute of Metrology, Thailand

Source: Clarivate *Web of Science.* Data captured for publications 2008-2020.

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

CQT has close links with five quantum startups in Singapore, which together employ more than 30 people. S-Fifteen Instruments and SpeQtral are spin-offs that have licensed technology for advanced instruments (see p.15) and satellite quantum communication (see pp.18–20) respectively. The others are founded by CQT alumni. Atomionics is building sensing systems for navigation and exploration (see pp.28–29 for the story of a student hired there). Entropica Labs and Horizon Quantum Computing are developing algorithms and software for quantum computing. Both had funding news in 2020. In May, Entropica announced seed funding of $2.6 million. In June, Horizon Quantum Computing announced funding topped up to $4.5 million in a seed-plus round. Dr Lim Jui, Chief Executive Officer of SGInnovate which led Horizon Quantum Computing's initial seed round in 2018, said "Five, 10 years or beyond, we are certain that quantum technology will be a game-changer and will have a tremendous impact on the world – from how governments and organisations work, right down to our everyday lives."

Industry projects

To bring quantum technologies to market takes both technical expertise and commercial acumen. We combine skills with industry partners to maximise the chances of success and impact. For example, CQT Principal Investigator Charles Lim is working with imec, known for its work in nanoelectronics and digital technologies, on developing QKD chips. He is also working with ST Engineering to develop network encryption technology based on measurement-device-independent quantum key distribution (see p.25). Meanwhile, at the NUS-Singtel Cyber Security R&D Lab established in 2016, CQT leads a theme on future-ready technologies through which CQT Principal Investigator Christian Kurtsiefer and his team are testing quantum communication on Singtel's deployed fibre (see p.9).

Engagement & training

On request, we organise in-depth training workshops for industry, organising two such events in 2020. This builds on wider engagement to answer company's questions and understand industry needs, for example through more than 40 private meetings in the year. More activities are happening through the national Quantum Engineering Programme (see pp. 24–27). CQT is also working with SGInnovate, a company supporting the development of deep tech in Singapore, under a Memorandum of Intent signed in 2019 to grow the quantum ecosystem. In 2020 we co-organised six events for industry audiences on topics such as "The Asia Race for Quantum Computing" and "Towards a Quantum Internet", available to watch online.

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

Educational outreach

CQT supports education for students in all stages up to PhDs (see p.34). Our Principal Investigators help teach a "Specialisation in Quantum Technologies" for undergraduates (see pp.28–29). In previous years, we have also hosted a week-long camp for pre-university students. Q Camp did not happen in 2020 because of COVID-19, but some of the student organising team still managed to share their teaching methods.

Adrian Utama, Jianwei Lee and Mathias Seidler published in the *American Journal of Physics* a paper detailing a hands-on quantum key distribution workshop they developed for Q Camp participants[1]. "We wanted to share the blueprint of this system and students' responses to this form of hands-on-learning because we saw how engaged the participants were," says Jianwei. The workshop introduces the idea of creating an encryption key from photons with a surprise learning moment. (Read the paper for spoilers.)

Younger school groups, and curious people of all ages, encountered quantum technologies at Science Centre Singapore (SCS). The centre hosted Quantum: The Exhibition, organised by CQT in collaboration with other local partners and the Institute for Quantum Computing at the University of Waterloo in Canada, from 19 August 2019 to 10 March 2020. SCS received over 200,000 visitors during this period.

Science in culture

Seeing science as part of culture, we have brought quantum physics to projects in the performing arts (see p.20), fiction and film. In June 2020, we concluded a flash fiction contest that received 647 entries from all over the world. CQT has organised the Quantum Shorts contests since 2012, alternating between annual calls for quantum-inspired short stories and short films. Quantum Shorts is supported by media partners *Scientific American* and *Nature*; and by scientific partners in Australia, Canada, the Netherlands, New Zealand, the United Kingdom and the United States. Find more details and view the film and fiction finalists at shorts.quantumlah.org. In October 2020, we co-presented an event with the Singapore Writers Festival. The panel "Does Another You Exist in A Parallel Universe?" featured authors Tania De Rozario, Michael Brooks and Chad Orzel on ways that writers use quantum ideas. Tania was previously a writer-in-residence at CQT, and all three have been judges for Quantum Shorts.

CQT communication

We can always be found online. CQT's website had over 53,000 users in 2020. On social media, we made our debut on Instagram, adding to our presence on Facebook, Twitter, and LinkedIn which together drew a combined 14,000+ followers. Many of our online events have an extended life on YouTube, where our videos received over 50,000 views in the year.

[1] A. N. Utama, J. Lee and M. A. Seidler, A Hands-On Quantum Cryptography Workshop For Pre-University Students, *American Journal of Physics* **88,** 1094 (2020)

Expenditure in 2020

	Manpower	Equipment	Other	Total
Core Funding	9.95	1.65	8.36	19.96
Competitive Grants	1.81	0.95	1.03	3.79
Total	11.76	2.60	9.39	23.75

All figures in million SGD.

Stakeholder support

CQT was established in 2007 under the Research Centres of Excellence programme supported by the National Research Foundation (NRF) Singapore, and the Ministry of Education, Singapore. 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. The total core funding allocated for the period 2017-2022 is $100 million. CQT researchers at Singapore's Nanyang Technological University (NTU) receive additional support from NTU.

Competitive grants

CQT researchers also compete for grant funding. In 2020, the Centre won over $6 million in new grants. Active grants in 2020 include awards from the Ministry of Education, the National Research Foundation, the Agency for Science, Technology and Research, DSO National Laboratories and the Quantum Engineering Programme, 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, the Silicon Valley Community Foundation (FQXi) and companies.

Thanks to our supporters

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

Jobs:
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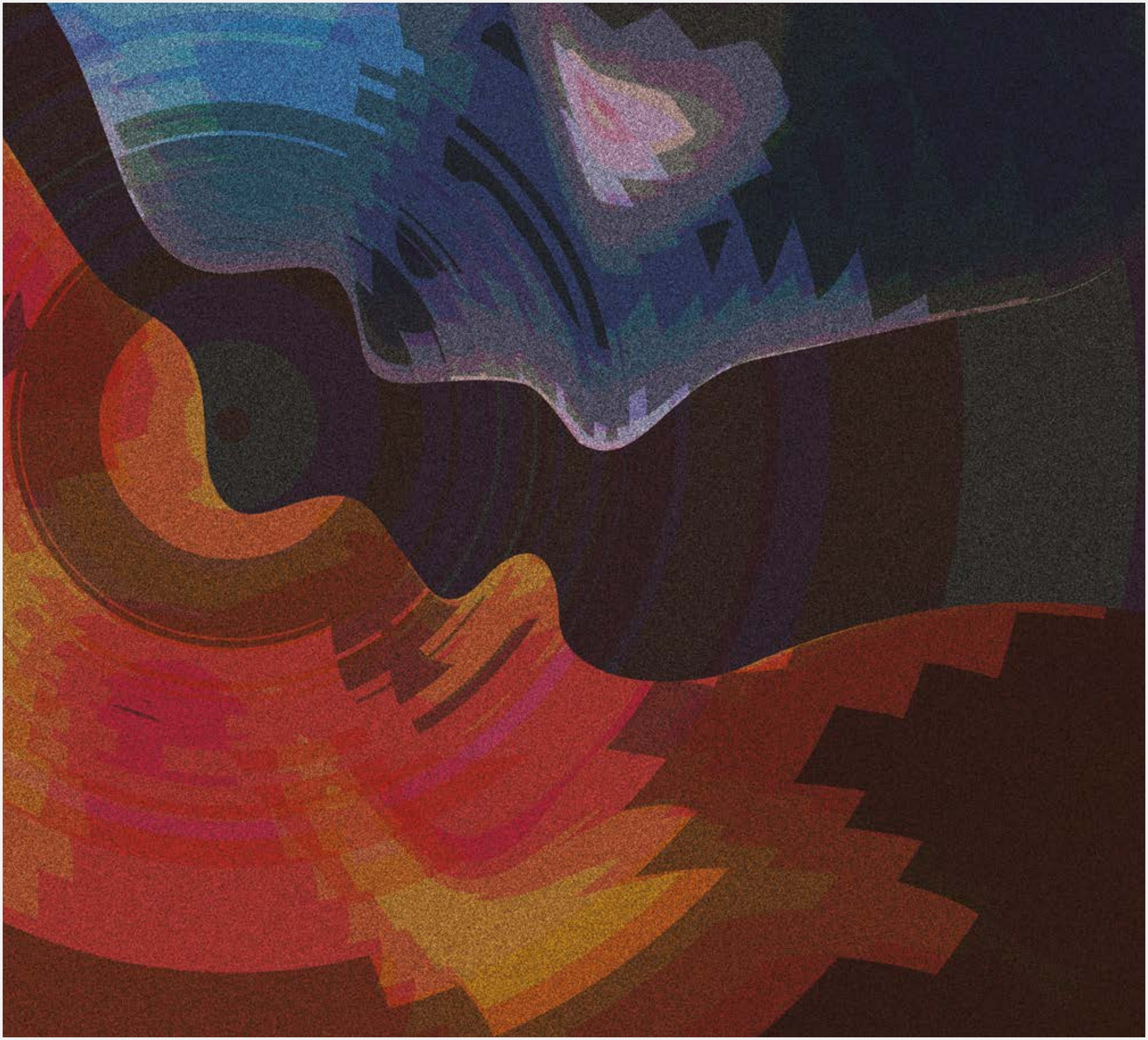
Contact us:
cqtsec@nus.edu.sg



Centre for Quantum Technologies

National University of Singapore

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