annual report 2021

Centre for Quantum Technologies

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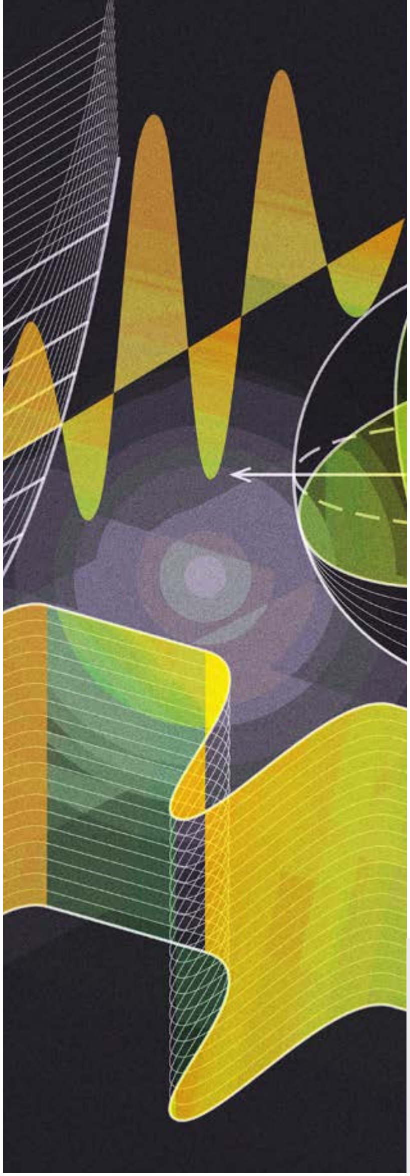

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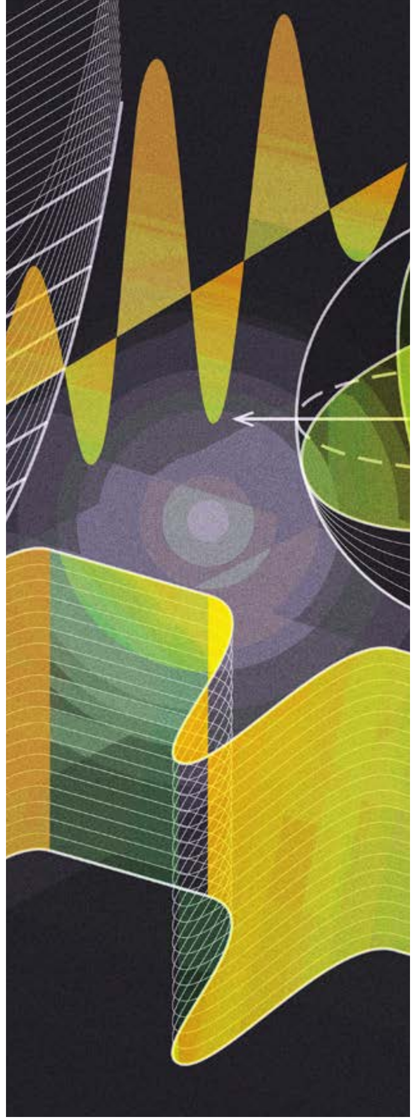
CQT AT A GLANCE



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

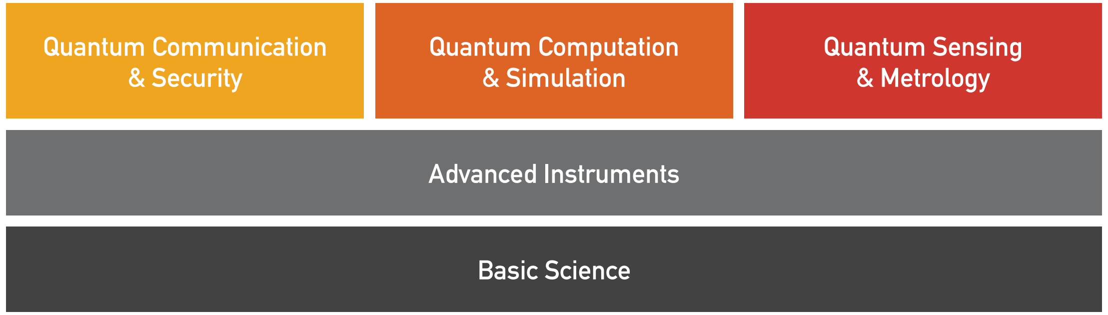
We pursue insight into the physics that describes light, matter, and information. We develop novel tools to study and control their interactions. Our research goals range from understanding the properties of materials to working out new encryption schemes.

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 planet is immersed in a quantum race. Many powerful nations have announced plans to build sovereign quantum capabilities, and Singapore will be no exception. In 2022, Singapore will establish a National Quantum Office charged with developing a full-fledged national quantum strategy. The Agency for Science, Technology and Research will be the implementing agency. Singapore's bet on quantum technologies is unequivocal.

As these national plans take shape, our goal is to make the Centre for Quantum Technologies the country's quantum flagship. CQT's research is already aligned in three main pillars on top of basic science, like those found in national strategies elsewhere: quantum communication and security, quantum computing and simulation, and quantum sensing and metrology. These commonly accepted thrusts can be completed with actions for enabling technologies, development of quantum talent, trustworthy outreach and international collaborations.

We highlight just some of CQT's ongoing work in these areas in this annual report, from experiments on superconducting cavities to camps for school students. There is much more to come.

In 2021, the Quantum Engineering Programme (QEP) supported by the National Research Foundation, Singapore, has started awarding grants under its second phase. Teams at CQT are receiving substantial amounts to begin new projects and programmes.

CQT will take leadership of the National Quantum-Safe Network that aims at securing communications for critical infrastructure and companies handling sensitive data, and the National Quantum Computing Hub that will deliver a quantum computer, middleware, applications and talent.

Further plans to secure solid funding for CQT are in the works. While QEP supports translational efforts, basic science remains essential for a pipeline of ideas and to attract good people.

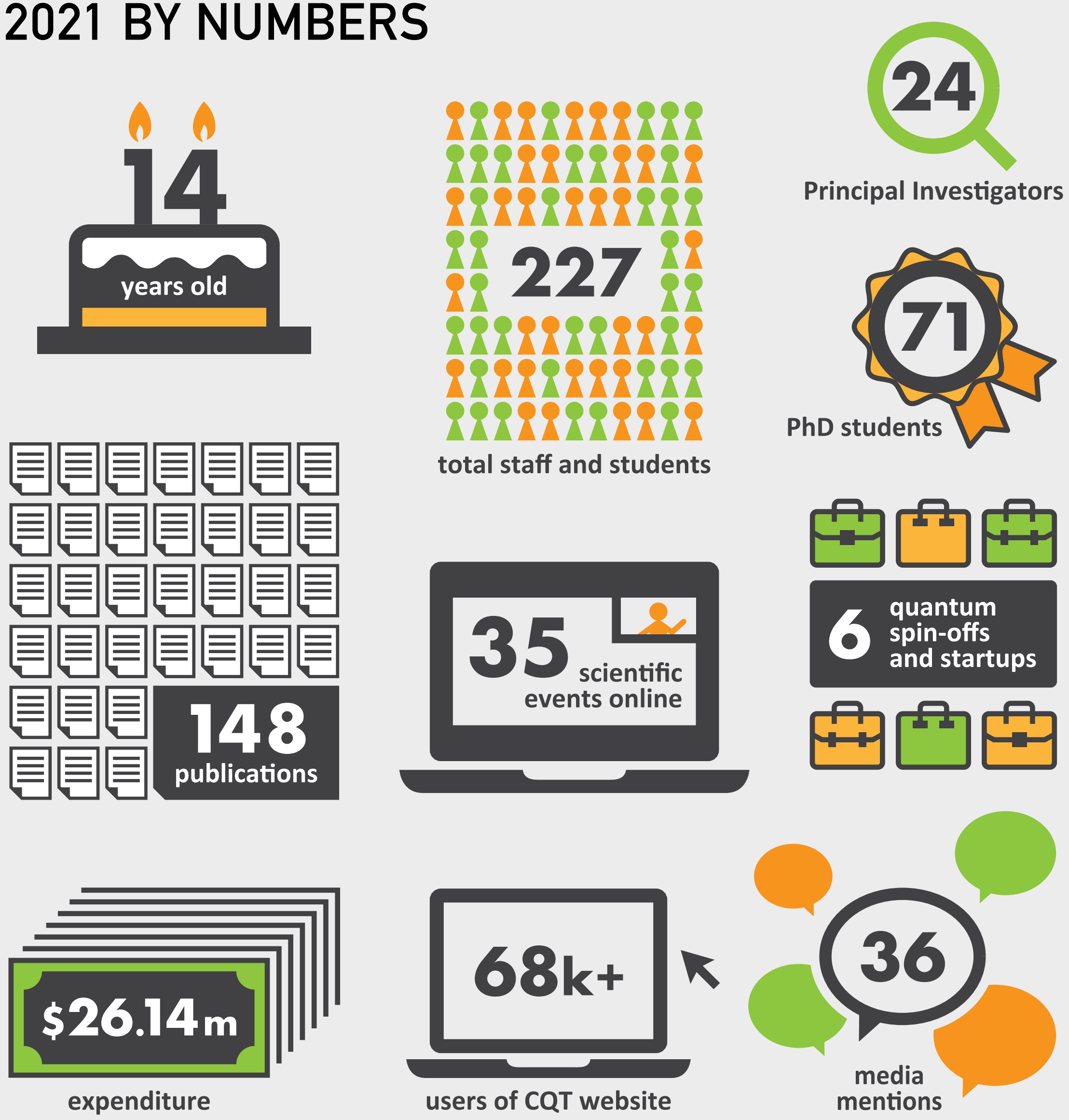
Quantum has been singled out as a strategic field by Singapore, and CQT must match this enormous national effort with excellence in research. Our colleagues in other countries are intelligent, well-prepared and well-funded. We need to focus, get coordinated, and move fast. We should collaborate rather than compete within Singapore to be internationally relevant. The creation of a full quantum ecosystem is at stake.

Many foreign quantum players are following closely our progress, as Singapore is seen as a technology hub for Southeast Asia. With actions to strengthen relations with the private sector, I'm convinced that quantum industry will flourish from Singapore. We see its beginnings in the startups that have emerged from CQT and the paths of our alumni.

Finally, let me repeat my mantra. Science is culture. Our discoveries and achievements are not just a means to meet performance targets or forge careers. Quantum science is far bigger: it is at the frontier of human understanding in our times. It is, in my opinion, a privilege to spend our lives working at the edge of knowledge.

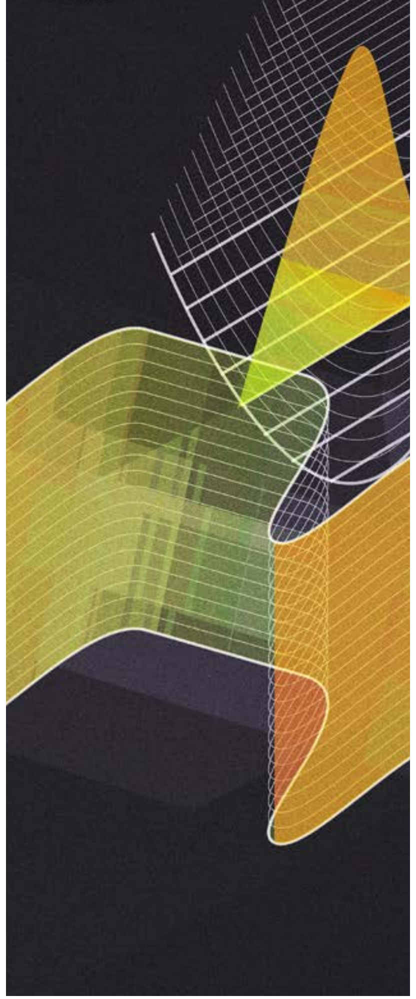
José Ignacio Latorre

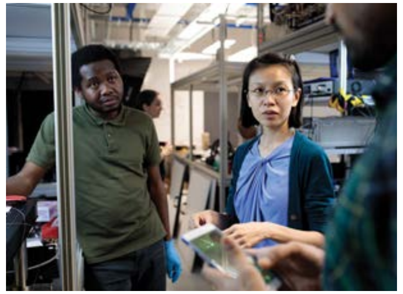
2021 BY NUMBERS



OUR PROJECTS

Highlights of CQT's work in quantum technologies in 2021

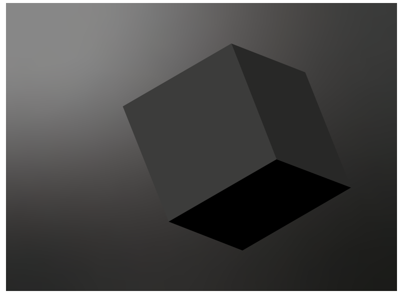




Magic wavelengths scale arrays

Cold atoms arranged in grid-like patterns and maintained in well-controlled quantum states are a powerful tool: they can be used to simulate the properties of materials or to perform quantum computations. The CQT research group of Loh Huanqian is pushing the frontiers of this approach, using arrays of optical tweezers to control the light alkali atom sodium. The team have reported being the first to use a class of 'magic wavelengths' that will allow scientists to scale up atom array numbers to an order of magnitude larger than was possible before. At the magic wavelength, only a small amount of tweezer power is required to load and detect single atoms using the D1 transition. PhD student Mohammad Mujahid Aliyu, who is first author of the paper, says "The hope is that our work would make it very common for people to go ahead and use the D1 magic wavelength for the alkali metals."

Phys. Rev. Research **3,** 043059 (2021)



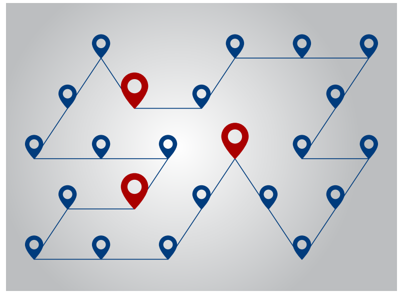
Better security settings

An international team including CQT's Charles Lim and Valerio Scarani offered an improved version of the ultra-secure cryptography protocol known as device-independent quantum key distribution (DIQKD). Critically, the security of DIQKD can be checked without needing to characterise the quantum devices used, treating them as black boxes.

In the new protocol, each party independently tests the other party's encryption device by generating a secret key from two randomly chosen key-generation measurement settings instead of the typical one. The team showed the extra setting makes it harder for the eavesdropper to steal information. "It's a simple variation of the original protocol that started this field, but it can only be tackled now thanks to significant developments in mathematical tools," says Valerio. Compared to the original, the new protocol is easier to set up and is more tolerant to noise and loss.

Nature Communications **12,** 2880 (2021)

SCIENCE UPDATES



Solving optimisation problems, efficiently

While quantum computers remain limited in scale, one way to bring applications closer is to design more efficient quantum algorithms. CQT's Dimitris Angelakis and his team achieved this for 'quadratic unconstrained binary optimisation' (QUBO) problems, which are encountered in industries from supply chain management to banking and can involve as many as 10,000 variables. The researchers' method gives an exponential reduction in the number of qubits required to tackle such problems. In a demonstration, they solved a randomly generated 64-variable QUBO problem using only seven qubits, and they project they can solve a few thousand variables with a few dozen qubits. First author Benjamin Tan, a CQT PhD student, says "Our encoding scheme lets us use fewer qubits to solve bigger problems, allowing us to solve real-world problems on existing or near-term quantum devices."

Quantum **5,** 454 (2021)

Tool checks quantum circuit design

It is an open challenge to get more computing power from today's noisy intermediate-scale quantum (NISQ) devices. CQT graduate Kishor Bharti and his collaborators think a measure known as quantum Fisher information could help by optimising the parametrised quantum circuits used in some hybrid quantum-classical approaches. The researchers showed that quantum Fisher information can characterise a circuit's expressibility – the range of quantum states it can explore – and identify redundant parameters. This could help balance power and efficiency in circuit design. "Because you need to get your task done while spending little resources, you need to think about all the hacks you can do," says Kishor, who completed his PhD in 2021 and is now at the University of Maryland. His collaborators included another CQT PhD graduate, Tobias Haug, now at Imperial College, London.

PRX Quantum **2,** 040309 (2021)

mikser45/Shutterstock.com

Predictions for photonic crystals

CQT's Dimitris Angelakis and Daniel Leykam found that a machine learning technique known as 'persistent homology' is useful for modelling photonic crystals. That could aid design of materials for devices such as lasers, sensors and solar cells.

Photonic crystals are fabricated with layers of materials, etched patterns or embedded structures. The nanoscale structure determines what wavelengths of light can flow through the material and in what directions, which is known as the material's band structure. The researchers showed that machine learning could predict features of a given material's band structure that were not easy to calculate. Daniel and Dimitris write in their paper: "The approach may be used to save many graduate student-hours, for example, if it is necessary to compute and check thousands of band structures to find an optimal lattice design subject to certain constraints."

APL Photonics **6,** 030802 (2021)

Aki Honda/CQT, NUS

jijomathaidesigners/Shutterstock.com

Logic before physics

Physics takes a back seat to logic in a new method to construct fluctuation relations proposed by CQT's Valerio Scarani and Clive Aw and their collaborator Francesco Buscemi in Japan. Fluctuation relations compare the probabilities of forward and reverse processes. They are used to study biomolecular systems, thermodynamics, electronics and more. Physics describes the forward process, while defining the reverse is less direct: consider how an egg shatters on the floor.

The researchers instead used logical retrodiction, which infers past events using present evidence. The researchers could rederive most known classical and quantum fluctuation relations with retroactive arguments, and their recipe applies for general quantum channels. The method hints that logic underlies the physical descriptions and could expand the range of systems that can be analysed with fluctuation relations.

Physical Review E **103,** 052111 (2021);
AVS Quantum Sci. **3,** 045601 (2021)

Power limiter protects QKD

While the security of quantum key distribution (QKD) is unbreakable in principle, if it is incorrectly implemented, vital information could still be stolen by attackers. These are known as side-channel attacks, where the attackers exploit weaknesses in the setup of the information system to eavesdrop on the exchange of secret keys.

Previously, experiments have shown that it is possible to inject bright light pulses into a quantum cryptosystem to break its security. The group of CQT's Charles Lim developed a first-of-its-kind device that defends QKD systems against such attacks. The optical device is based on thermo-optical defocusing. Bright light changes the refractive index of the transparent plastic in the device, directing some of the light out of the quantum channel. The team's power limiter can be seen as an optical equivalent of an electric fuse, except that it is reversible and reusable. It is cost-effective and requires no power.

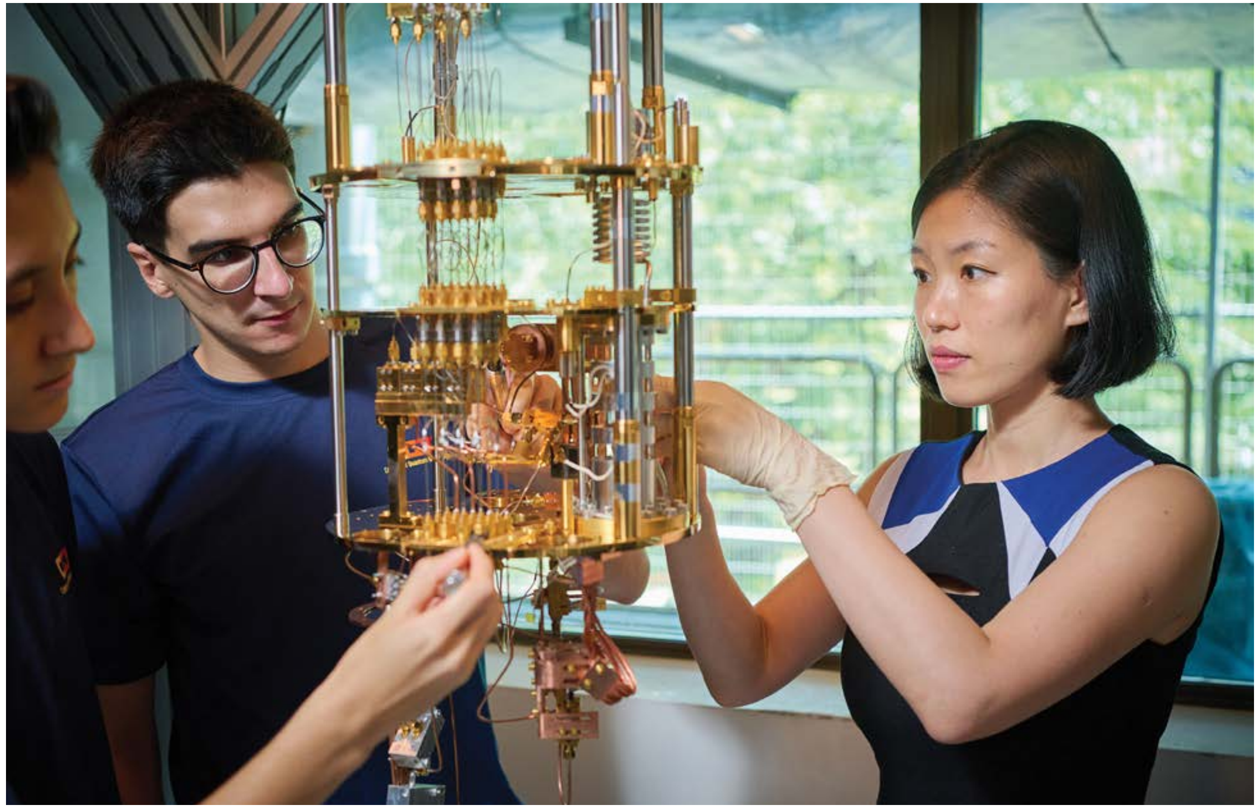
PRX Quantum **2,** 030304 (2021)

Securing keys from space

CQT's Charles Lim and Artur Ekert contributed to devising a new security proof method for short encryption keys. This could be useful for quantum satellites dealing with low data rates.

To guarantee some amount of secure final key typically needs data blocks containing about 10,000 bits. The team's new analysis method reduces the block length required by 14% to 17%. Charles and Artur collaborated with two members of the team behind China's Micius quantum satellite to calculate the satellite could produce keys with a security parameter 10^{-5}. This parameter measures the probability that some amount of the key has leaked to an eavesdropper. "How small is small enough? Ultimately, organisations using QKD systems will have to perform a trade-off between efficiency and security and pick the most sensible value based on their network security policies," says Charles.

Phys. Rev. Lett. **126,** 100501 (2021)



Agency for Science, Technology and Research

Golden moments

Quantum computing research draws national award

For CQT Principal Investigator Yvonne Gao, 2021 was a banner year. In January, she unboxed the giant, golden fridge her team needed to begin experiments in quantum computing. By the end of the year, she had collected a national prize awarded to young scientists showing potential to be world-class researchers.

Yvonne, who is also an Assistant Professor in the Department of Physics at the National University of Singapore, joined CQT in May 2020.

Her speciality is building superconducting quantum circuits. The devices, essentially patterns of aluminium on silicon or sapphire chips, can be used both for basic research on quantum phenomena and to perform quantum computing tasks.

Photo: Yvonne Gao (right) works with PhD students Clara Fontaine (left) and Adrian Copetudo Espinosa (centre) on the inner components of the dilution refrigerator that will cool their superconducting quantum circuits.

Superconducting technology is already a frontrunner for building quantum computers. When Google claimed the world's first demonstration of quantum advantage in 2019 – having a quantum computer perform a calculation massively faster than the world's best supercomputer could do the same – it used 53 superconducting quantum bits.

But even as commercial giants pursue the technology, university labs see potential to innovate. Researchers are working on new ways to design, control and extract better outcomes from superconducting qubits.

During her PhD at Yale University in the United States, Yvonne worked on ways to make quantum states encoded in superconducting cavities interact, co-authoring two patents that are licensed to a spin-off there. Cavities are high-dimensional quantum systems that can store and manipulate many bits of information simultaneously.

Now with her own group in Singapore (see box **Team building**) she is particularly interested in developing a modular architecture for superconducting circuits that exploits the potential of cavities. This could be a path to making bigger quantum computers that can work on real-world problems, from chemical simulation to weather forecasting.

"Compared to scaling up by simply adding more and more qubits on a single chip, a modular architecture allows better reconfigurability and enhanced robustness against local failures," explains Yvonne.

Racing for more qubits is a feature of the quantum computing field. For example, IBM, which is also working with superconducting technology, announced in November 2021 that it had broken "the 100-qubit barrier" with a 127-qubit processor.

But it's not just the count that counts. Powerful quantum computers need both quantity and quality in their components. Quality for a qubit depends on factors such as how long it can maintain a quantum state before errors creep in from outside influences, and how accurately it can be controlled to perform error-correction or logic.

With their major equipment in place and in-house qubit fabrication processes worked out, Yvonne's team started with simple experiments to characterise and iterate their qubit design and control stack. They expect to advance in 2022 to pushing scientific frontiers. The golden fridge cools the group's sapphire chips down to just tens of milli-Kelvin above absolute zero (around -273K). This makes the aluminium circuits into superconductors and removes almost every last photon that could disturb the qubits.

> *"Quantum computing capabilities will be of strategic importance for Singapore."*

Yvonne was named a recipient of the Young Scientist Award 2021 "for her work on developing the key hardware building blocks for quantum computers". The award, administered by the Singapore National Academy of Science and supported by the Agency for Science, Technology and Research (A*STAR), was presented in December.

In a video interview A*STAR filmed for the occasion[1], Yvonne said "Quantum computing capabilities will be of strategic importance for Singapore and my work here hopes to establish the foundation for us to build hardware locally, such that we can have reliable and secure access."

Her research is supported by a fellowship from the National Research Foundation, Singapore, start-up funding from NUS and core funding from CQT.

[1] Watch Yvonne's interview at https://youtu.be/w5VaX2ktSFM

RESEARCH IN FOCUS

Team building

From a one-woman show, Yvonne's group has grown to have two postdocs, five PhD students, a research assistant and a roster of NUS undergraduates working on projects. Read more about the group at quantumcrew.org

She thanked her team "for their trust and audacity in starting this exciting journey with me" when the group was put in the spotlight by her award. Handily for her young group, Yvonne has co-authored a paper that provides "an introductory tutorial for experimentalists at the early stages of their venture in developing superconducting quantum systems"[2].

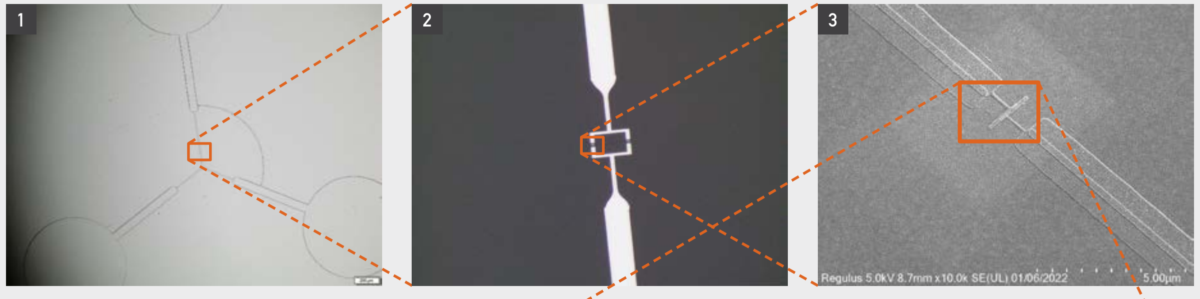
Yvonne also cares about mentoring the next generation. For example, she is helping to curate a short course on quantum computing for high school students (see pp.24–25). She believes that educating and empowering young science enthusiasts is essential to create a sustainable ecosystem for developing cutting-edge technologies.

Photo:
▲ Yvonne Gao (centre) calls her team the Quantum Circuits Research & Engineering Workgroup – the QCrew! The young group is building up their experiment from scratch, and in 2022 will move into newly renovated lab space in CQT.

◀ How it began. The team's key piece of equipment arrived in Singapore in crates in January 2021.

[2] Y. Y. Gao et al, Practical Guide for Building Superconducting Quantum Devices, *PRX Quantum* **2,** 040202 (2021)

Meet a qubit



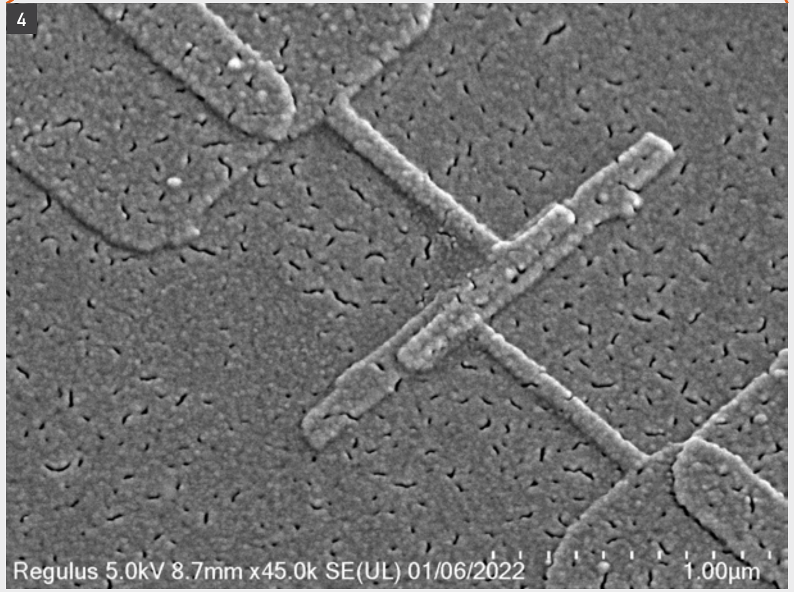
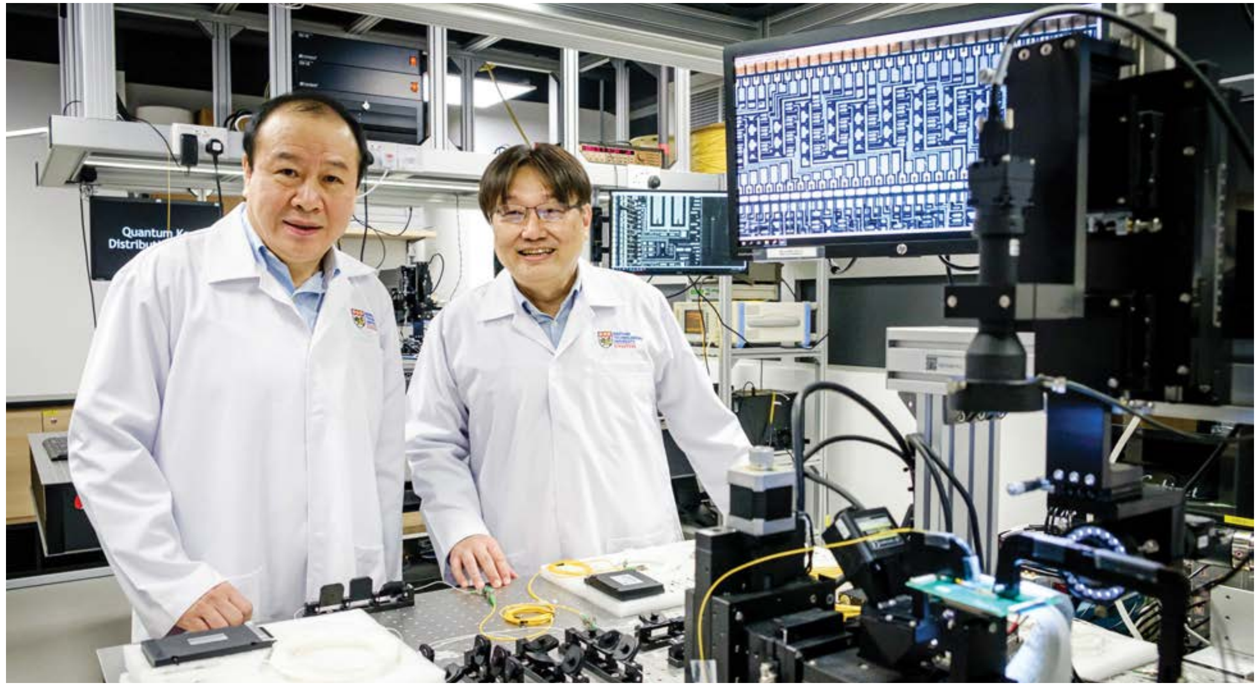


Photo: Yvonne's team make their superconducting qubits with steps in CQT's wet lab and at the E6NanoFab facility in NUS. The optical microscope images (1, 2) show a single qubit, created by depositing aluminium in this pattern on a sapphire chip. A scanning electron microscrope reveals more details of the structure (3, 4). The overlapping layers of metal define a Josephson junction, which is at the heart of superconducting quantum systems.



Nanyang Technological University

Photonics to the west

Working with a new quantum centre in Singapore specialised in silicon photonics

With CQT Principal Investigator Kwek Leong Chuan as co-director, the Quantum Science and Engineering Centre (QSec) officially launched at the Nanyang Technological University (NTU) Singapore on 7 December 2021.

The Centre is focused on making quantum devices on silicon photonic chips. These chips control and manipulate light to process quantum information carried by the particles of light, photons.

With a team of some 30 researchers, QSec aims to use established semiconductor fabrication technology to create photonic chips for quantum communication, computing and sensing.

Kwek co-leads QSec with Liu Ai Qun, Professor in NTU's School of Electrical and Electronic Engineering, who has expertise in integrated photonic chips.

Attending the QSec opening ceremony, Singapore's Education Minister Mr Chan Chun Sing said "Quantum science, technologies, and engineering have drawn huge investments worldwide. Singapore is a long-standing investor in its potential and remains at the forefront of this field."

Photo: The Quantum Science and Engineering Centre at the Nanyang Technological University (NTU) is led by CQT's Kwek Leong Chuan (right) and Liu Ai Qun from NTU's School of Electrical and Electronic Engineering.

Previously, Kwek was co-director for Singapore's Quantum Engineering Programme in its first phase from 2018 to 2020. Supported by the National Research Foundation and now led by CQT Principal Investigator Alexander Ling, the programme is investing a total of $121.6 million up to 2025 in projects that apply quantum technologies for solving user-defined problems and in building the quantum ecosystem in Singapore.

The QSec team began its research projects in 2018, jointly funded by a research grant from the Ministry of Education, Singapore, and by NTU.

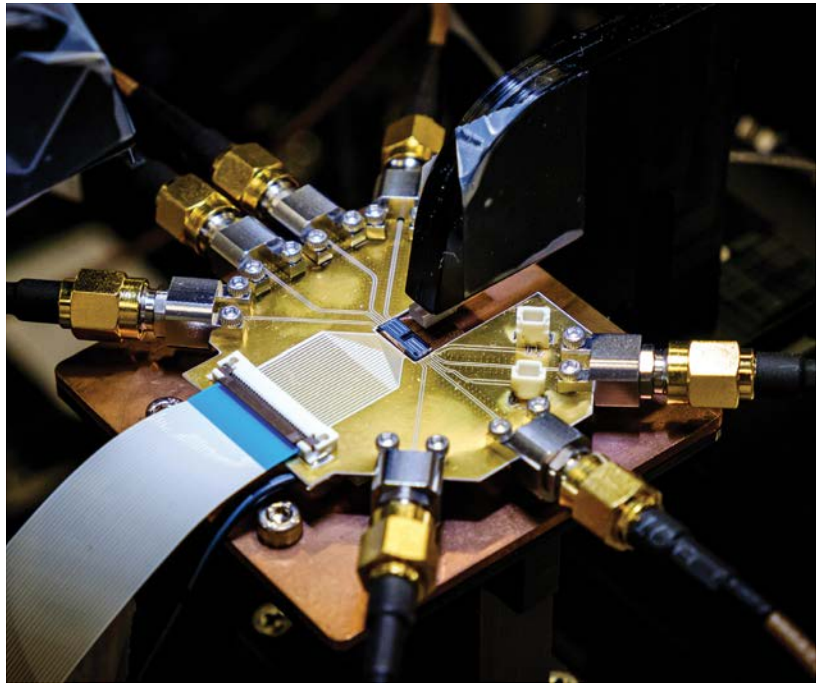


Photo: Chip-based devices are seen as a promising route to commercialisation for quantum technologies because they can be compact, robust and cost-effective. Pictured is an integrated photonic chip for quantum key distribution.

Nanyang Technological University

Small secrets

Quantum key distribution (QKD) is a physics-based method to securely share encryption keys that are resistant to computational hacking. Measurement-device-independent QKD (MDI-QKD) is a version of the technique that prevents some implementation attacks and splits the equipment needs across the network. Users need to have only a simple transmitting device, while a server hosts the more complex and expensive measurement device.

The QSec researchers described in 2020[1] a proof-of-concept demonstration of MDI-QKD with chip-based designs for both transmitters and server. It achieved a key rate of 1.46 bits per second over a distance corresponding to 50 km.

Other groups in Singapore are also working on improving QKD systems. For example, CQT Principal Investigator Charles Lim has collaborations with imec and ST Engineering to develop chips for MDI-QKD that use different measurements to generate the key. Whereas the QSec device relies on measurement of the polarisation of transmitted light signals, Charles' devices will derive keys from the arrival times of the signals.

[1] L. Cao *et al*, Chip-Based Measurement-Device-Independent Quantum Key Distribution Using Integrated Silicon Photonic Systems, *Physical Review Applied* **14,** 011001 (2020)

Silicon know-how

Chip-based devices are seen as a promising route to commercialisation for quantum technologies.

Compact, robust and cost-effective chip-based devices could be appealing, for example, to parties wanting to secure their communications using quantum key distribution (QKD). The chips are even small enough to fit into everyday devices such as laptops or smartphones.

For quantum computing, where the technology's potential to surpass supercomputers depends on being able to build devices with more well-controlled quantum bits than is possible today, silicon manufacturing know-how offers hope of scaling up.

Singapore has a strong semiconductor industry and established foundries working in photonics. QSec researchers are working with the Advanced Micro Foundry, a spin-off since 2017 from the Institute of Microelectronics at the Agency for Science, Technology and Research (A*STAR) in Singapore, to produce their devices.

So far, the QSec team and their collaborators have already published results from a chip-based measurement-device-independent quantum key distribution system (see box **Small secrets**), and from an optical neural chip implementing features useful for a quantum computing chip, too (see box **Light bits**) Development and trials of the quantum computing chip are underway, with CQT Director José Ignacio Latorre collaborating in the project.

QSec is housed at NTU's College of Engineering, located some 15 km to the west of CQT's headquarters at the National University of Singapore. CQT also has two Principal Investigators based in NTU's School of Physical and Mathematical Sciences.

Drawing more engineers to participate in quantum technologies is one of QSec's aims. "The Centre hopes to enhance Singapore's impact on quantum science, engineering, and technologies by leveraging on our capability in chip-based devices. We are also hoping to train and enthuse more engineers and secondary school students in this emerging direction," said Kwek.

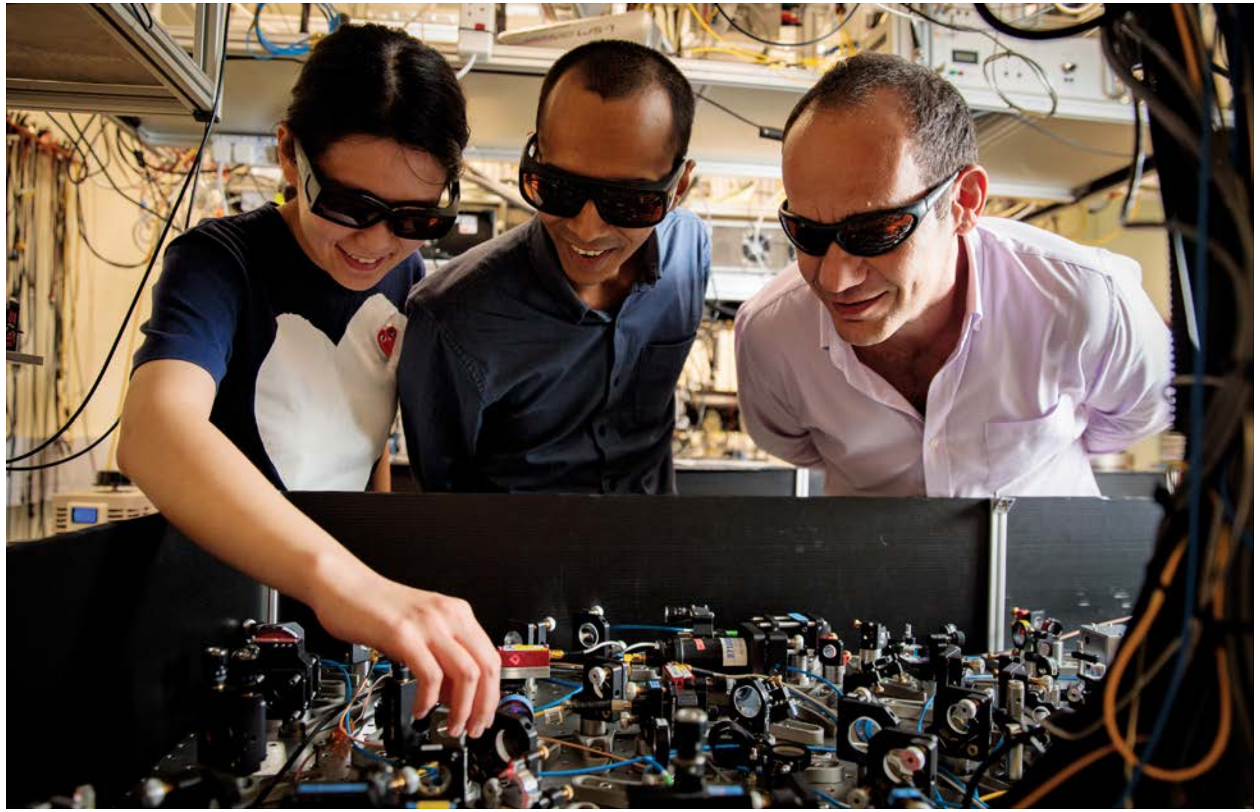
Light bits

Quantum advantage is a performance benchmark for quantum computers, reached when a device performs some calculation demonstrably faster than a supercomputer could. A large and complex optical setup at the University of Science and Technology of China, Hefei, is one of the few quantum computers worldwide to have claimed this achievement.

The QSec team aims to do optical quantum computing on a silicon photonic chip. In 2021, they published results from an optical chip that implemented a series of Mach-Zehnder interferometers[2]. Their goal then was to trial the chip's performance as a neural network using classical light inputs, but with quantum light inputs, similar structures could be deployed for quantum calculations. Starting from boson sampling, they could try to demonstrate some specific algorithms, such as a quantum variational autoencoder and quantum generative adversarial network.

Evidence that photonic qubits are a contender as a commercial technology comes from industry too: the US-based startup PsiQuantum raised $450 million in 2021 towards its vision of building a quantum computer with silicon photonics.

[2] H. Zhang *et al*, An optical neural chip for implementing complex-valued neural network, *Nature Communications* **12,** 457 (2021)



Spotlight on international collaborations: MajuLab

CQT contributes to long-standing collaborations between Singapore and France

While CQT researchers collaborate with scientists all over the world (see p.35), the Centre's connections with French quantum scientists run particularly deep.

Since 2014, Singapore has hosted the research unit MajuLab, supported by the French National Centre for Scientific Research (CNRS) and other partners, that works on quantum matter physics, quantum information and computation, and quantum materials and photonics.

The MajuLab has over 40 staff with plans to grow. Its members include researchers employed by French institutions and

Photo: Since David Wilkowski moved to Singapore in 2009, his group has built up three cold atom experiments, two with strontium atoms and one with caesium. David (right), who acts as Associate Director for MajuLab, is pictured in his lab with PhD students Li Jianing (left) and Mehedi Hasan (centre). Mehedi graduated in 2021. This picture was taken before COVID-19.

researchers who share 30% or more of their time from appointments with Singapore universities. That includes a handful of CQT Principal Investigators, research fellows and PhD students.

Christian Miniatura, who is a Research Director at CNRS and a CQT Visiting Research Professor, has led the lab through its first term and renewal in 2018. "I am definitely changed by my experience in Singapore and very proud of what has been achieved," says Christian, who is handing over planning for a third term of MajuLab to Alexia Auffèves (see box **Meet the Director Designate**). "The time is ripe for new energies," he says.

The seed for MajuLab was planted when Christian first came to Singapore in 2005 on a visiting appointment with Berge Englert's group at the National University of Singapore (NUS) Department of Physics, before CQT was founded.

A few years later, Miklos Santha and David Wilkowski, both now CQT Principal Investigators and MajuLab staff, joined CQT from France in visiting positions to build up CQT's capabilities in computer science and cold atom physics, respectively.

Exchange and interaction

"It is really the same story that happens always in science. Concretely here, visitors came from France with some ideas that get developed while collaborating with scientists in Singapore," says Miklos.

Photo: The MajuLab was renewed for a second term of five years in an agreement signed in January 2018. Since then, its researchers have co-authored about 230 papers. Pictured at the signing, from left, are Mr Marc Abensour, Ambassador of France to Singapore; Prof Frédérique Vidal, French Minister for Higher Education, Research and Innovation; Dr Antoine Petit, President and CEO of CNRS; Prof Ho Teck Hua, NUS Senior Deputy President and Provost; Prof Lai Choy Heng, CQT Deputy Director and Prof Christian Miniatura, MajuLab Director.

For example, Miklos and other CQT colleagues collaborated with Antoine Joux, visiting from Paris, to propose a new public-key cryptosystem that was submitted in 2017 to the post-quantum cryptography competition run by the US National Institute of Standards and Technology. The researchers plan to build a quantum safe signature scheme based on this work when Antoine can visit CQT again.

Meanwhile, David has established cold atom experiments (pictured) in labs at Nanyang Technological University Singapore (NTU Singapore).

The early links between French and Singaporean researchers grew into what's known as an International Research Lab (IRL) under the CNRS structure. MajuLab is one of five IRLs in Singapore. The others are in engineering, artificial intelligence, biomechanics and mathematics. "For CNRS, Singapore is a strategic place," says Christian.

France and Singapore have a Joint Committee on Science and Innovation, which met for the second time in June 2021. The online meeting involved public sector agencies from both countries, including funding agencies and research institutions, and companies.

Singapore's Deputy Prime Minister, Coordinating Minister for Economic Policies and Chairman of the National Research Foundation Mr Heng Swee Keat, said, "Singapore and France have a long-standing and strong partnership in the area of science and innovation. At the 2nd meeting of the Joint Committee on Science and Innovation, we noted the good progress. We commit to deepening our partnership in areas including pandemics, sustainability, and clean energy; and to promote greater collaboration among companies and research institutions on both sides. I am confident that these initiatives will create value not only for both our countries but also for the global community."

The meeting also included exchanges on potential cooperation opportunities in quantum technologies, among other areas. Both countries are investing strongly in quantum research. In 2021, French President Emmanuel Macron announced a five-year €1.8 billion investment for quantum technologies. Meanwhile, Singapore's National Research Foundation has allocated $121.6 million to the country's Quantum Engineering Programme since 2018, funding projects up to 2025.

MajuLab supports collaboration between French and Singaporean research institutions, having five signatory partners: CNRS; the Université Côte d'Azur in Nice; Sorbonne Université in Paris; NUS; and NTU Singapore.

An important aspect of the France-Singapore collaboration, according to both Christian and Alexia, is the community it builds.

Back in 2009, Christian helped to coordinate with the prestigious French Les Houches School of Physics and the Embassy of France to hold a summer school in Singapore on ultracold gases and quantum information. The summer school lasted four weeks and saw up to 100 students from all over the world attend.

In similar spirit, MajuLab plans with partners to present in Singapore the HPC School on Quantum Computational Materials Science, as a sister school of the Paris International School for Advanced Computational Materials Science, to train young researchers and professionals. Originally scheduled for 2020, it was postponed because of the pandemic.

"To me, what's most important is the brotherhood formed where different people from different cultures communicate and work towards the same goal – doing science," Christian says.

Alexia agrees, "From what I could experience each time I came here, MajuLab is the result of a very special atmosphere where friendship plays a strong part – the pleasure of doing science together."

Meet the Director Designate

A Research Director with the French National Centre for Scientific Research (CNRS), Alexia intends to move to Singapore in 2022 to plan a third term for the MajuLab research unit. She is expected to take over as MajuLab Director in 2023.

Alexia first visited Singapore over a decade ago at the invitation of CQT Principal Investigator Kwek Leong Chuan and former CQT Visiting Senior Research Fellow Marcelo Santos. Her ties with Singapore have only grown since.

In 2016, she and Kwek led the organisation of the Quantum Engineering Science and Technologies Symposium, a meeting supported by the Embassy of France in Singapore, MajuLab and CQT to bring together experts from the two countries.

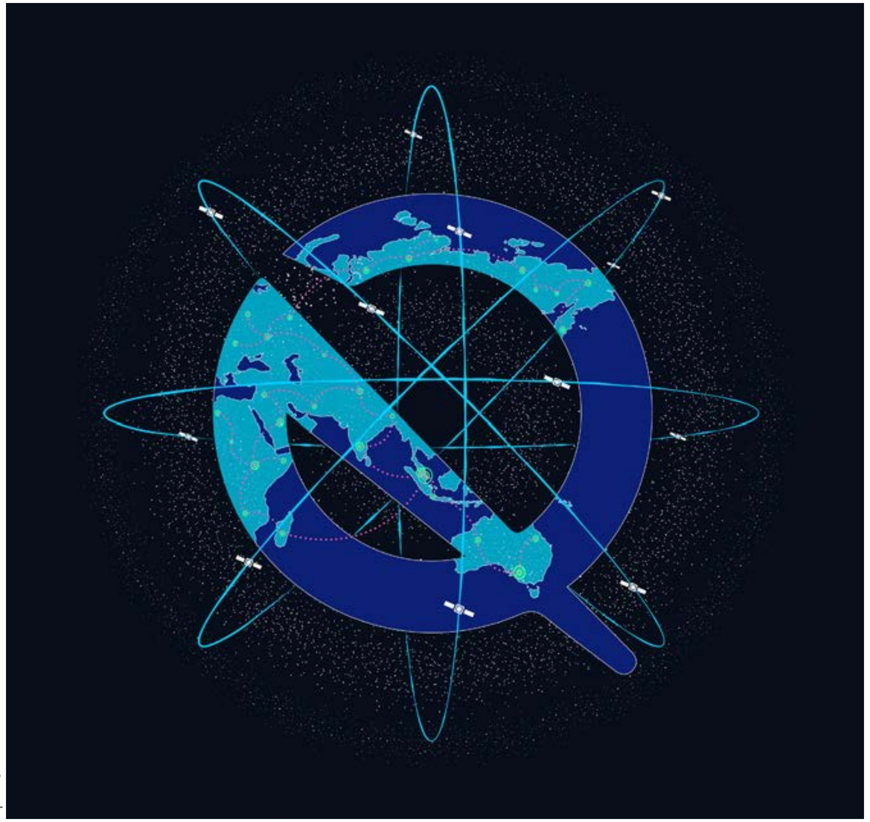
Since 2017, Alexia has collaborated with CQT Fellow Ng Hui Khoon, who is also a researcher at MajuLab. Their interdisciplinary work asks questions such as how much energy a fault-tolerant quantum computation would need and whether quantum technologies can give an energetic quantum advantage.

The topic is becoming Alexia's main research line. She notes that energetic monitoring of quantum technologies is not part of current deployment strategies, although energy use is an important societal problem.

Alexia earned degrees in physics and philosophy at Ecole Normale Supérieure in Lyon, France. Having always felt the pull towards philosophy and physics, and the hard and human sciences, quantum physics was the perfect solution for her. "You can transfer nitrogen in your cryostat while thinking about the nature of reality and the difference between observing and measuring," says Alexia. She did her PhD in the group of Nobel laureate Serge Haroche fabricating Schrödinger cat states.

Outside of work, Alexia enjoys exercising, reading novels, and meeting close friends. Her favourite places to visit include beaches and botanical gardens. On what she is looking forward to in Singapore, she says, "Enjoy all the places I know as an insider and do beautiful science with friends!"


Olivier Ezratty



SpeQtral

Go for launch

The CQT spin-off SpeQtral has earned a double boost towards its vision of building secure quantum networks

The Singapore-based quantum startup SpeQtral received a US$8.3 million vote of confidence in November 2021, closing a second funding round after its first seed financing in 2019.

SpeQtral states that it "is on a mission to transform the world's networks for the fast-approaching quantum revolution". The company aims to provide communications that are secure against innovations in quantum computing and technologies that could build the backbone of a future quantum internet.

It is known that some types of encrypted communication are vulnerable if scientists and engineers are successful in building quantum computers much larger and better controlled than the ones available today. That is because of Shor's algorithm, a computational method that works only on quantum computers, which can reverse engineer the mathematics public-key encryption is based on.

SpeQtral is a spin-off from CQT research in quantum key distribution (QKD), a technology to create encryption keys that are computationally unhackable both by today's computers and future quantum computers. Its founders have a specific focus on doing QKD from satellites, which is a way to extend range limits terrestrial QKD faces in optical fibres.

The new financing was led by Xora Innovation, an early-stage deep science investment platform of Temasek. Temasek is a global investment company headquartered in Singapore with a portfolio valued at $381 billion in March 2021.

Photo: SpeQtral plans to work with international partners to realise global quantum key distribution.

"Secure data communication is foundational to the 'web of trust' between buyers, sellers, and intermediaries in the modern digital economy," said Donna See, CEO of Xora Innovation. "SpeQtral's QKD technology enables critical solutions for governments and enterprises seeking to ensure this web of trust in the quantum age. We are very excited to be a part of accelerating SpeQtral's growth and success."

Chune Yang Lum, co-founder and CEO of SpeQtral, said "We feel very fortunate to have investors who are committed to rolling up their sleeves and helping us deliver best-in-class quantum technologies to governments, defence agencies, financial services institutions, data centres, cloud and telecommunication service providers." Chune Yang was formerly CQT Head of Strategic Development, Industry Relations.

SpeQtral's mission received a second boost in February 2022, with an announcement that Singapore's national space office, the Office for Space Technology and Industry (OSTIn), would support the company to launch its first quantum satellite, dubbed SpeQtral-1. The initiative is under OSTIn's Space Technology Development Programme.

"The development and launch of the SpeQtral-1 satellite will be an important milestone that marks the commercialization of QKD capabilities that have been built up through Singapore's investments in quantum research. OSTIn is pleased to support this mission by SpeQtral, which is testament to the deep technical capabilities of our local space startups and the richness of our space ecosystem.", said David Tan, Executive Director, OSTIn.

CQT researchers pioneered work on quantum satellites in Singapore with the development of SpooQy-1, which was in orbit from June 2019 until October 2021. That nanosatellite demonstrated a quantum light source of the type required for QKD. Some of the SpooQy team have since moved to SpeQtral and will work on this next mission, which will take a further step to implement QKD from space to ground.

The group of CQT Principal Investigator Alexander Ling, who led the SpooQy mission, will collaborate with SpeQtral towards this goal. Singapore's DSO National Laboratories is supporting CQT in research collaboration on an optical ground station for satellite quantum communications. If all goes to plan, SpeQtral-1 will launch in 2024.

Tie-up for terrestrial fibres

While SpeQtral innovates in space-based quantum key distribution (QKD), it will work with established player Toshiba Digital Solutions Corporation on terrestrial QKD. Toshiba offers fibre-QKD platforms that can provide secure communication over metropolitan-scale areas. Satellites offering QKD could later provide connections across continents.

The two companies announced in August 2021 that they had reached an agreement to market and deploy QKD solutions. "Toshiba has established industry partnerships in Japan, US and UK on early deployments of quantum secure communications. Together with SpeQtral, we are excited to support businesses in Singapore and Southeast Asia, and can accelerate the global expansion of our QKD business," said Taro Shimada, President and CEO, Toshiba Digital Solutions Corporation.

SpeQtral CEO Chune Yang Lum said "Southeast Asia is conducive for the adoption of new and leading-edge technologies such as QKD. There is strong emphasis on the cybersecurity of our digital ecosystem and creation of a resilient communications infrastructure."

Introducing AngelQ

Quantum computing startup founded by CQT's Dimitris Angelakis to build hardware-optimised quantum software

"I wanted to do something that impacts more people – it's as simple as that," says Dimitris Angelakis, a CQT Principal Investigator who is also founder and Chief Scientific Officer of AngelQ, the newest startup to join Singapore's quantum ecosystem.

Dimitris is a theoretical physicist who has done research in quantum simulation and quantum computing for almost three decades. "As the field now is changing, it invited me to think how I can transfer what I do to a bigger audience," he says.

His vision for AngelQ is to help businesses benefit from the noisy intermediate-scale quantum (NISQ) devices that have become available for commercial users, without waiting for progress in hardware to deliver on dreams of an error-corrected quantum computer. He also sees potential for quantum-inspired algorithms that run entirely on classical computers.

Both approaches appealed to Kantar, a data and consulting company that operates in over 90 markets. Dimitris started working with the Kantar Brand Growth Lab in Singapore a few years ago, exploring how quantum computing could help with market research.

In January 2020, Kantar announced that their joint work had led to a patent granted by the Intellectual Property Office of Singapore.

Dimitris and the company collaborated to analyse real consumer data, aiming to identify groups of consumers with shared traits, a marketing approach known as segmentation. They found that quantum-inspired segmentation algorithms run on classical hardware did better than traditional methods. They also experimented on a five-qubit quantum computer at IBM to establish the feasibility of using a quantum computer for such problems. The patent is for a method of optimising machine learning predictions from a classical data feed with a hybrid simulator generated from classical and quantum model structures.

Global demand

Not long before, Dimitris had incorporated AngelQ in Singapore with Nick Dukakis serving as the company's Chief Commercial Officer. They kept the company under wraps until 2021, when they launched a website to promote its bespoke consulting services to new customers, while continuing to work with Kantar on new problems.

The company also employs researchers in Singapore and Greece, where Dimitris holds an appointment as an Associate Professor with the Technical University of Crete, as part-time consultants.

AngelQ joins two other startups in Singapore working on software for quantum computing: Entropica Labs and Horizon Quantum Computing. Both of these companies were founded by CQT alumni.

Dimitris expects customer demand can more than support three local startups. He points to a survey carried out in December 2021 by the US-based quantum computing company Zapata in partnership with Wakefield Research. They asked 300 leaders from large global enterprises about their views of and investment in quantum computing. Some 69% of enterprises had already adopted or were planning to adopt quantum computing in one year, and 28% of those reported having budgets for quantum computing over US$1 million.

For now, AngelQ is working one-to-one with companies doing dedicated software development. The target sectors include marketing, finance, logistics and energy. Later, the company intends to offer software for certain applications under license.

Power up

Having worked closely with people building quantum computers – his past collaborators include Google's quantum computing team – Dimitris advocates for what he calls a 'hardware-optimised approach'.

Computations on NISQ devices need to work around errors that creep into the device's quantum bits. These errors arise from the sensitivity of quantum states and imperfect control systems. Eventually, quantum computers could run algorithms that correct errors as they crop up, but these carry a heavy overhead, multiplying the number of qubits required for any task.

Today, commercial providers of quantum computing offer tens of qubits and roadmaps to hundreds or thousands of qubits over the next few years. "We will be NISQ for many years to come. The power is there, we just have to figure out how to extract it," says Dimitris, noting that even 100 qubits cannot be simulated on classical computers.

AngelQ will pay special attention to the 'middleware' that translates an algorithm into instructions for specific quantum computing hardware.

"If you write a generic algorithm and try it on a NISQ device, it will require a million qubits and a billion operations – and that we don't have. You have to really understand how the device works. We want to develop the middle layer because it's very important to squeeze out as much as you can from these devices," Dimitris explains.

Photo: CQT's Dimitris Angelakis (left) has launched AngelQ with a small team of experts in Greece and Singapore. CQT PhD student Benjamin Tan (right) has done part-time consulting for the company, acquiring commercial experience and research experience in parallel.

The talent pipeline starts in schools

CQT offers two in-depth quantum experiences for students who are deciding their paths in life

As the quantum ecosystem grows, so does its demand for people. Academic research groups and quantum companies find themselves competing to hire staff with quantum know-how.

The problem was recognised in an October 2021 US government report on the role of international talent for quantum information science and technology (QIST). The report stated “Talent required to develop QIST is currently in short supply, both nationally and internationally. Global investments in QIST are intensifying the workforce shortage as countries strive to produce, attract, and retain top talent.”

Developing quantum talent in Singapore is one of CQT’s aims – and the Centre’s efforts reach beyond its established PhD programme (see p.29) and undergraduate teaching to students still in school.

Since 2015, the Centre has run an annual QCamp for students who are in their final years of pre-university education. The week-long camp introduces the science behind quantum technologies, offer hands-on experience with devices and builds awareness of the diversity of jobs in the field. For some students, the camp lit a spark (see box **Choosing a quantum path**).

QCamp was held at CQT until the COVID-19 pandemic forced a hiatus in 2020 and a move online in 2021 (see box **QCamp: the virtual edition**). If circumstances allow, it will return to participation in person in 2022.

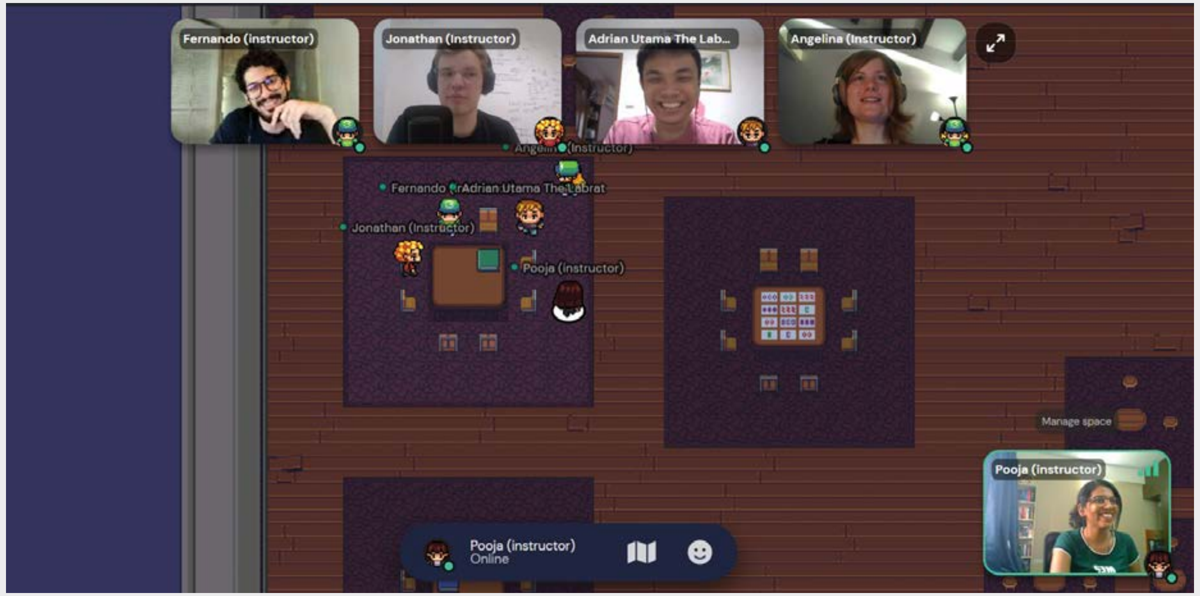
QCamp is mainly organised and taught by the Centre’s PhD students. Angelina Frank, the chair of the organising committee in 2021, said “QCamp is a wonderful opportunity for us to convey core concepts of quantum mechanics to a curious and diverse audience in an authentic and supportive space.”

Starting in 2022, CQT will also offer a two-day course called “What is Quantum Computing?” to invited schools. This course, curated by CQT Principal Investigators Yvonne Gao and Berge Englert, can suit younger classes and students not specialising in sciences.

It is part of a new programme series developed by NUS School of Continuing and Lifelong Education and supported by Temasek Foundation. Called “Temasek Foundation-NUS Youths for SG: Building a Shared Future”, the programme aims to help youths facing challenges in knowing where their interests, strengths and values lie, as well as identifying their future career aspirations.

Photo: Lab tours went virtual for students enrolled in QCamp 2021. Research Fellow Jaren Gan live-streamed from the ion trapping lab where he earned his PhD. “Our most recent work is on implementing quantum machine learning algorithms,” he told the students, explaining how they build traps to hold atoms and laser systems to control them.

QCamp: the virtual edition



Some 40 students from 11 Singapore schools joined the online edition of QCamp held 7-11 June 2021. The fully subscribed camp featured online lectures, live-streamed lab tours and activities such as a cryptography treasure hunt.

“Despite the camp being held over Zoom, it was extremely engaging and interesting. Over the last five days, I have learnt a lot of new things which have allowed me to become more interested in this realm of physics,” said one student. “Will encourage my juniors to attend future versions of this camp!” said another.

These comments come from a post-camp survey of participants, in which all respondents said they would recommend their teachers send students for QCamp again. Camp spots are allocated considering both nominations from teachers and direct applications from students.

QCamp has benefits for its lecturers, too. CQT PhD student Gan Beng Yee, whose talk on “Entanglement and Teleportation” has attracted over 1000 views since it was added to CQT’s YouTube channel, says, “For me, the biggest takeaway is that I learned how to distil the complex concepts into simple ideas with intuitive examples and convert them into a proper lecture.”

Links to the camp lecture notes and recorded talks are available at the QCamp website.

qcamp.quantumlah.org

Choosing a quantum path

After QCamp 2021, one participant said, "I feel more inspired to contribute to the quantum frontiers." Mok Wai Keong, who goes by Dariel, knows that feeling.

Dariel was a participant in the Centre's first ever QCamp in 2015. Back then, he was a student at National Junior College. He is now completing his final-year undergraduate research project in CQT, taking the Specialisation in Quantum Technologies offered by the NUS Department of Physics. In 2022, he will head off to begin a PhD at Caltech, aiming to work at the Institute for Quantum Information and Matter.

Attending QCamp, says Dariel, left him thinking that quantum physics was really interesting even when some of the content went over his head. "There are three things that I remember very fondly," he says. One was lectures that showed, he recalls, "how quantum mechanics gives you these weird behaviours, yet the rules that govern it are quite simplistic but profound," the second was visiting labs and the third was learning more from the textbook *Six Quantum Pieces* by CQT Principal Investigator Valerio Scarani, given to all participants.

"My time at QCamp certainly inspired me to want to do research at CQT," says Dariel. "That's why in my first year at NUS I approached Professor Kwek."

Dariel's final year project on "Quantum dynamics of nonlinear dissipative systems" supervised by CQT Principal Investigator Kwek Leong Chuan ends four years of research in the group, which has also earned him co-authorship on seven research papers.

On his next steps, Dariel says "I decided to do my PhD in the US to gain fresh experience. Part of me wants to experience how research is being done in other areas and see if I can apply what I learnt in Singapore, and maybe take some interesting things back when I come back to Singapore hopefully in the future."

Photo: The journey of young quantum physicist Mok Wai Keong, Dariel at CQT stretches from his school days to his application to PhD programmes. In the bottom photo, Dariel (standing centre) was a participant in QCamp 2015. In the top photo, Dariel (at the whiteboard) is talking with his research collaborators.

OUR COMMUNITY

We bring together top physicists, computer scientists and engineers

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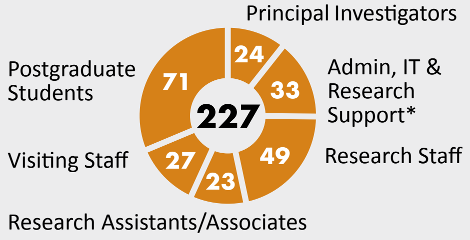
Yasunobu Nakamura
RIKEN Center for Quantum Computing
Research Center of Advanced Science and Technology, The University of Tokyo

Principal Investigators

Divesh Aggarwal	theory
Dimitris G. Angelakis	theory
Murray Barrett	lab
Kai Dieckmann	lab
Rainer Dumke	lab
Berge Englert	theory
Yvonne Gao	lab
Loh Huanqian	lab
Rahul Jain	theory
Dagomir Kaszlikowski	theory
Hartmut Klauck	theory
Christian Kurtsiefer	lab
Kwek Leong Chuan	theory
Wenhui Li	lab
Charles Lim	theory, lab
Alexander Ling	lab
Dzmitry Matsukevich	lab
Manas Mukherjee	lab
Travis Nicholson	theory, lab
Miklos Santha	theory
Valerio Scarani	theory
Marco Tomamichel	theory
Vlatko Vedral	theory
David Wilkowski	lab

theory lab

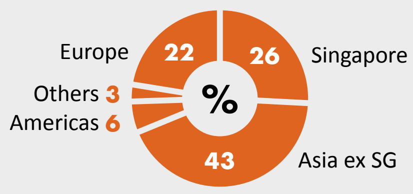
Headcount



Count of CQT staff and students as of 31 December 2021

* Admin and IT count includes a cluster of 8 staff working across University centres

Nationalities



Nationalities of CQT staff and students as of 31 December 2021

https://www.quantumlah.org/people

CQT acknowledges changes to its Governing Board (GB) and Scientific Advisory Board (SAB) in 2021. The GB welcomed Shen Zuowei to succeed Freddy Boey as a representative from NUS and said goodbye to Russell Tham from Temasek International Pte Ltd who stepped down. The SAB welcomed Antonio Acín and Yasunobu Nakamura as new members, while Ignacio Cirac from the Max-Planck-Institut für Quantenoptik and Jun Ye from the University of Colorado and the National Institute of Standards and Technology stepped down. We thank our former board members for their service. Board and Principal Investigator listings are as of 31 December 2021.

Students at CQT

71 CQT PhD students as of December 2021

6 CQT PhD graduates in 2021

90 CQT PhD graduates since CQT founded

Internships

Although COVID-19 kept CQT's international internship scheme on hold in 2021, we hosted 30 local students for experience in quantum research. 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.

PhD programme

CQT offers high-quality education and supports 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.

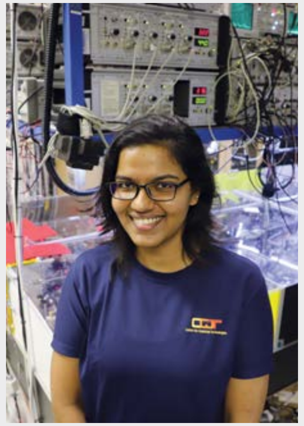
Photo: Srijita Kundu (centre) was among the CQT PhD students to graduate in 2021. She is pictured defending her thesis on "Direct Product, Function Composition And Device-Independent Cryptography". Srijita is now a postdoctoral fellow at the Institute for Quantum Computing at the University of Waterloo, Canada.

"My choice of doing my PhD in CQT was motivated by being in an institute where one has many like-minded people around. This allows, e.g., learning about many related and possibly important developments over a cup of coffee."

Jonathan Schwinger
PhD student in experimental physics

"A PhD at CQT is an intellectually vibrant experience – getting to work with a bunch of smart people, making good friends, travelling, and learning to be on your own. The skills you acquire and the learning environment will bring out the best in you."

Sreedevi Athira Krishnan
PhD student in experimental physics



Recognition

Congratulations to our staff who received awards in 2021! We are also proud of the way CQT's some 200 staff and students come together to make a Centre that is more than the sum of its parts.

"For her work on developing the key hardware building blocks for quantum computers," CQT Principal Investigator **Yvonne Gao** received a national science award in 2021. She was selected as a winner of the **Young Scientist Award 2021**, presented to researchers up to 35 years old who have shown great potential to be world-class researchers in their fields of expertise. This prize is administered by the Singapore National Academy of Science and supported by the Agency for Science, Technology and Research. Yvonne, who is also an Assistant Professor in the NUS Department of Physics, received the award from Singapore's Deputy Prime Minister at a ceremony in December. Read more about Yvonne's research at pp.9–12.

Agency for Science, Technology and Research

Yvonne Gao

CQT Admin Director **Kuldip Singh** was awarded the **Public Administration Medal (Bronze)** when Singapore celebrated its 56th birthday in August 2021. The medal makes Kuldip a double recipient of the country's National Day Awards. In 2011, he received the Commendation Medal. Kuldip has led CQT's administrative team since CQT was founded in December 2007. His hard work and managerial skills helped CQT grow and thrive. The Public Administration Medal (Bronze) (Pingat Pentadbiran Awam) (Gangsa), instituted in 1963, is bestowed to persons "for outstanding efficiency, competence and industry". Kuldip is also an Associate Professor in the NUS Department of Physics and the University Scholars Programme, and Master of King Edward VII Hall.

Kuldip Singh

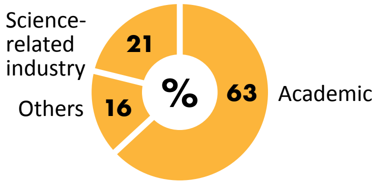
The Institute of Physics Singapore presented its **Cadi Scientific Medal and Prize for The Public Awareness of Physics** to CQT's **Jenny Hogan** in March 2021. Jenny, who is Associate Director for outreach and media relations in the Centre's admin team, was nominated "for her outstanding outreach contributions, like the curation of the Quantum Exhibit at the Science Centre, the Quantum Shorts texts and videos competition, and for the promotion of physics through highlights of CQT research." Jenny was also named a recipient of the **Commendation Medal (Pingat Kepujian)** in Singapore's National Day Awards. This medal is presented to persons who distinguish themselves "through commendable performance and conduct, or significant efficiency, competence and devotion to duty".

Jenny Hogan (second from the right)

Alumni

The Centre for Quantum Technologies has employed hundreds of scientists and trained tens of PhD students since it was established. Our former colleagues have since taken their skills into a variety of new roles. Many of our alumni continue in academic research, but others work across a wide range of industries. CQT alumni are found in banking, consulting, and in technical jobs, including data science and engineering. The chart gives an overview of CQT alumni's current jobs, summarising responses from 160 former staff and students to a survey carried out in August 2021.

Job types: 2021 survey



Life after CQT

Jirawat Tangpanitanon
Chief Executive Officer, Quantum Technology Foundation (Thailand)

As a CQT PhD student and then Research Fellow, Jirawat had a chance to work with companies including the quantum AI team at Google. The experience inspired him to cofound the startup QTFT to address the gap between academia and industry after he left CQT in 2020.

Based in Jirawat's home country Thailand, QTFT is a consulting agency for quantum technologies, currently serving clients from the logistics, aviation and finance industries. Jirawat draws on his deep knowledge of quantum computing to bring ideas to clients that could add business value. "It is a completely different scenario from when I was a scientist exploring new knowledge," he says. The company announced a seed funding round of about S$1.2 million in March 2022 and has found partners such as Fujitsu (Thailand). QTFT will use Fujitsu's quantum-inspired digital annealer for optimisation problems.

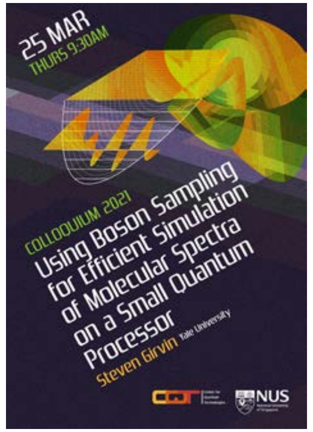
Anurag Anshu
Assistant Professor, Harvard University

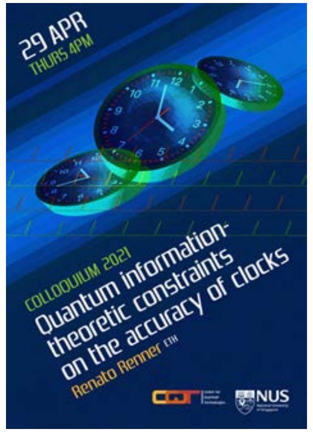
After completing his PhD in computer science in CQT in 2018, Anurag went on to postdoctoral positions in Canada and the United States. In 2022, he joins the faculty at Harvard University. "The self-improving nature of research can be pleasingly addictive: good questions lead to better questions which lead to even better questions," he says.

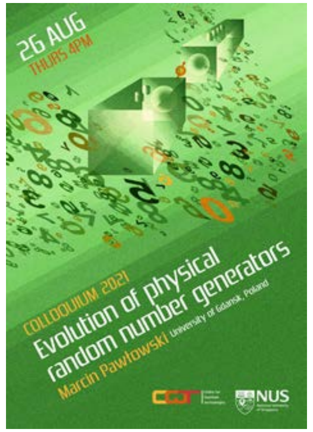
Anurag credits his graduate life for shaping his research interests in quantum information and quantum Hamiltonian complexity. He believes there is value in delving into research areas that are confusing, where he thinks important discoveries lie. He says "The resources at CQT are really helpful for pursuing research in such areas. Our tendency is to gravitate away from them and move towards well-established fields with deeply founded knowledge. But it can be hard to discover new principles in the latter".

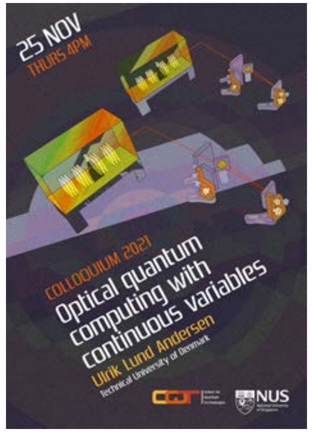
Scientific events

CQT hosted online events such as talks and journal club sessions throughout 2021 for researchers to hear about scientific advances and interact with each other. Altogether, CQT hosted some 35 events. These included seven colloquia by distinguished speakers that inspired the posters on this page and a symposium in January 2021 with five guest speakers organised to celebrate CQT's 13th birthday. Recordings of many of these talks are available to watch on CQT's YouTube channel.



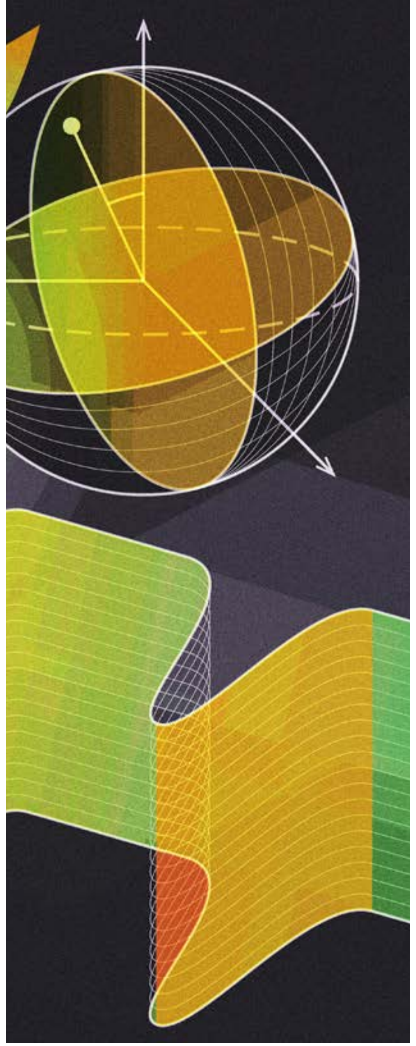






OUR IMPACT

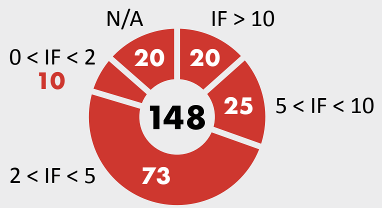
A look at CQT's outputs and spending in 2021



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

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

Publications



Publications during 2021 by journal impact factor (IF)

- 4 Quantum
- 7 Physical Review Letters
- 8 npj Quantum Information
- 6 PRX Quantum
- 3 Nature Communications
- 1 Nature Physics
- 1 Physical Review X
- 1 Science Advances

Publications during 2021 in high impact journals

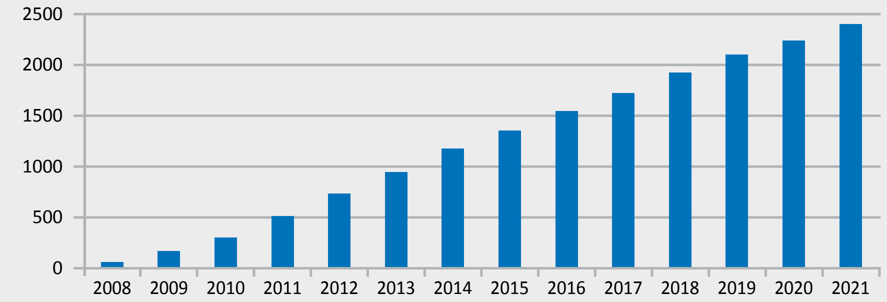
* Search by address field for (Natl Univ Singapore AND Ctr Quantum Technol) OR (Ctr Quantum Technol AND Singapore)

There are **2,432** publications in total from CQT's first 14 years.

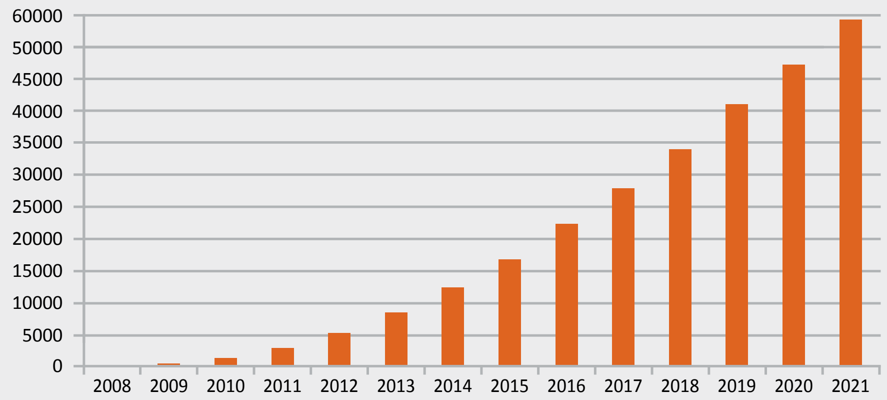
The body of work has accumulated **58,054** citations. That's an average of 23.87 citations per paper.

As a centre, our h-index is **93**.

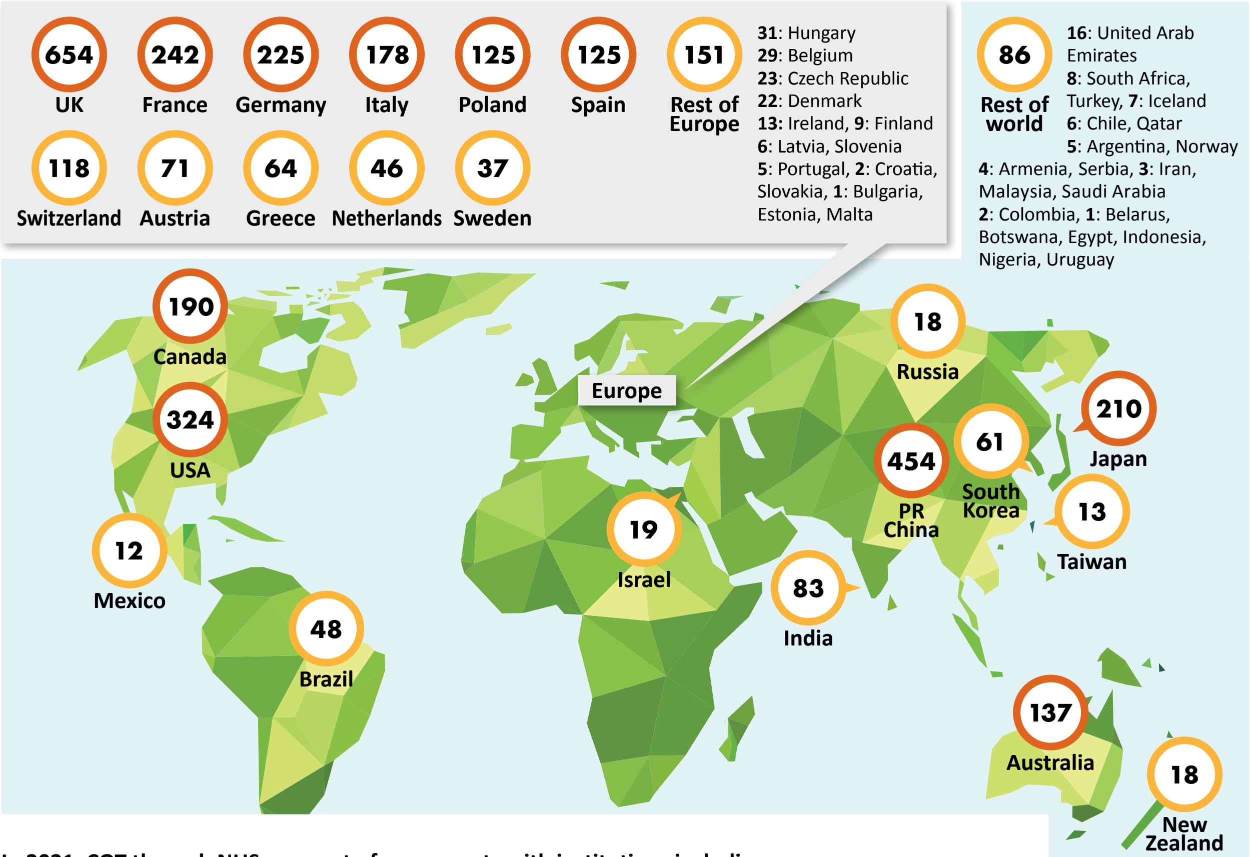
Cumulative Publications 2008-2021



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 2021, CQT through NUS was part of agreements with institutions including:

- UMI MajuLab agreement with the Nanyang Technological University, the French National Centre for Scientific Research (CNRS), the Université Côte d'Azur and the Sorbonne University, France
- Partner Organisation Agreement with the ARC Centre of Excellence for Quantum Computation and Communication Technology (CQC2T) at the University of New South Wales, Australia
- Memorandum of Understanding with each of TCG Centres for Research and Education in Science and Technology, India; University of Catania, Italy; Graduate School of Information Science and Graduate, School of Mathematics, Nagoya University, Japan; University of Otago, New Zealand; National Institute of Metrology, Thailand; and the University of Applied Sciences Northwestern Switzerland

Source: Clarivate *Web of Science.* Data captured for publications 2008-2021.

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

In 2021, the number of Singapore-based startups closely associated to CQT grew to six. AngelQ is the newest arrival (see pp.22–23). It joins the startups Entropica Labs and Horizon Quantum Computing, both founded by CQT alumni, in working on software for and applications of quantum computing.

Two other local companies are S-Fifteen Instruments, a spin-off from CQT which sells instrumentation for single photon generation, detection and counting, and SpeQtral, which spun off from CQT's work on quantum satellites and has announced new funding and its first space mission (see pp.20–21).

AngelQ

ATOMIONICS

ENTROPICA LABS

HORIZON QUANTUM COMPUTING

S FIFTEEN INSTRUMENTS

SPEQTRAL

Finally, Atomionics, co-founded by a former CQT postdoctoral fellow, is building sensing systems for navigation and exploration. In 2021, Atomionics disclosed the company had earlier received $2.5 million in venture funding to start its operations. The funding round was led by Wavemaker Partners with SGInnovate and Cap Vista and included other prominent angels. In a statement, Zhen Hao Chng, CEO at Cap Vista, Singapore Defence Science and Technology Agency's investment arm, said "Quantum sensing is an emerging area that we believe will have significant effect in national security and defence."

Quantum Engineering Programme

Six calls for proposals were held under the Quantum Engineering Programme (QEP) in 2021 for research projects that will advance quantum technologies towards solving challenges defined in consultation with industry. QEP, supported by the National Research Foundation, Singapore, and hosted at the National University of Singapore, is Directed by CQT Principal Investigator Alexander Ling. It will invest $96.6 million over the period 2020-2025 in research and ecosystem building. CQT researchers received QEP grants in 2021 for projects including the development of quantum sensors and quantum internet technologies, with other awards still to be announced. Learn more at qepsg.org.

Industry engagement

CQT's engagement with industry spans from exploratory meetings to collaborative research projects. Ongoing projects include work with DSO National Laboratories on satellite quantum communication and sensing (see quantumlah.org/page/key/industry-projects). To raise broader awareness of developments in quantum technologies, CQT also coordinates sessions for relevant conferences. In 2021, for example, CQT organised quantum tracks for the Supercomputing Asia event in March and the Deep Tech Summit, held in connection with the Singapore Week of Innovation and Technology, in November. CQT can also offer customised training for companies inspired to dive deeper.

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

Educational outreach

Becoming an expert in quantum technologies takes many years of training. CQT has an established PhD programme for the most advanced students (see p.29). At the National University of Singapore (NUS), our Principal Investigators contribute to teaching a "Specialisation in Quantum Technologies" for undergraduates and a "Master of Science in Physics for Technology" with quantum module options, both hosted in the Department of Physics. For younger students, the Centre's flagship outreach initiative is QCamp, a week-long workshop held once a year for up to 40 students aged 16-19. The camp was held online in 2021 (see pp.24–26). In 2022, CQT will in addition be offering a two-day course on quantum computing to invited schools in a programme coordinated by the NUS School of Continuing and Lifelong Education and supported by Temasek Foundation.

Gods

Science in culture

Three quantum-inspired films under five minutes long claimed prizes in 2021 in the Quantum Shorts contest organised by CQT. They were among ten finalists screened at events held online and around the world, selected from 224 submissions.

CQT has run Quantum Shorts for a decade, alternating between annual calls for short stories and short films. This film edition was 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 and their screening partners. In Singapore, the ArtScience Museum at Marina Bay Sands showed the Quantum Shorts films throughout January 2021.

The film Gods (pictured) took first prize. It presents the last message of a civilisation which has deciphered the secrets of quantum physics but faces an existential threat. "I am absolutely happy to receive this award, especially since this festival is very special to me," said the film's director Sitoh Ortega, from Spain. "It is more than a short film festival. It is a fantastic means for scientific diffusion, which is so important these days."

Find us online

CQT exists across social media as @quantumlah. We post regular updates about our research, events and job opportunities, reaching an audience that has grown to over 18,000 followers across our four channels: Facebook, Instagram, LinkedIn and Twitter. We also added 49 new videos to the Centre's YouTube channel in 2021, including recordings of scientific talks presented online and shared with the speaker's permission. Viewers spent 8,700 hours in 2021 watching videos from CQT's full archive. Our home base is the Centre's website at quantumlah.org which had over 68,000 users in 2021.

Expenditure in 2021

	Manpower	Equipment	Other	Total
Core Funding	10.65	1.25	9.24	21.14
Competitive Grants	2.38	1.66	0.96	5.00
Total	13.03	2.91	10.20	26.14

All figures in million SGD.

Stakeholder support

CQT was established in 2007 as a national Research Centre of Excellence with core funding from the National Research Foundation, Prime Minister's Office, Singapore, and the Singapore Ministry of Education. The total core funding allocated for the period 2017–2022 is $100 million. The Centre also receives substantial core support from its host institution, the National University of Singapore (NUS), where the majority of its staff and students are based. This includes some salary costs and building space. CQT researchers at Singapore's Nanyang Technological University (NTU) receive additional support from NTU.

Competitive grants

CQT researchers also compete for grant funding. In 2021, the Centre won some $20 million in new grants, including a number of awards under the second phase of the Quantum Engineering Programme (QEP) supported by the National Research Foundation, Singapore. QEP projects will run over the next three years. Other active grants in 2021 include awards from the Ministry of Education, the Agency for Science, Technology and Research, and DSO National Laboratories, all in Singapore. Some CQT research is funded through NUS competitive funds. International grants come from sources including the USA Air Force Office of Scientific Research.

Thanks to our supporters

Ministry of Education SINGAPORE

National Research Foundation
Prime Minister's Office
Singapore

Nanyang Technological University Singapore

NUS National University of Singapore

MajuLab

CNRS

Upcoming events:

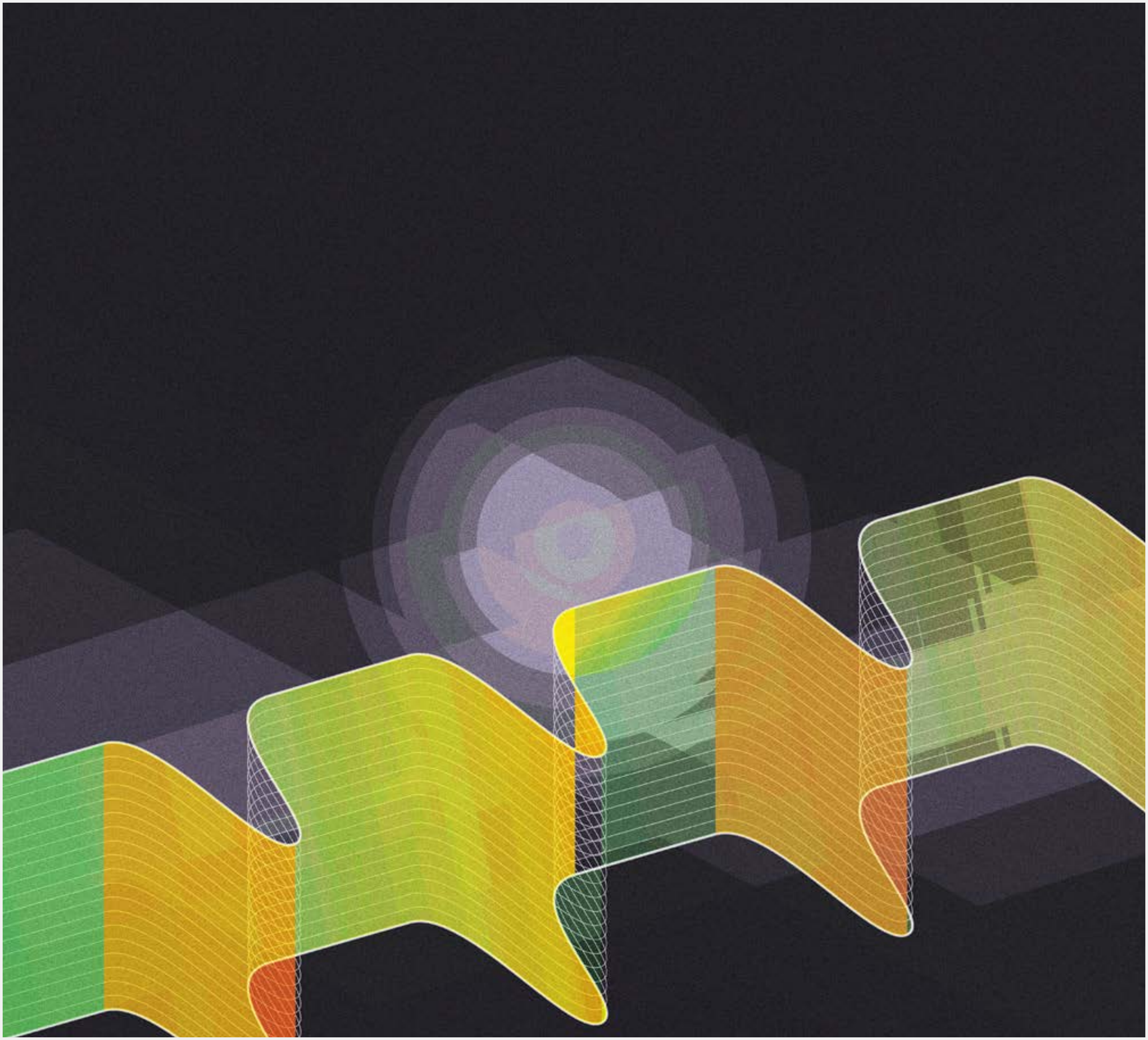
https://www.quantumlah.org/events/upcomingevents.php

Jobs:

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

Contact us:

cqtsec@nus.edu.sg



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