

# CONTENTS



- 2 CQT at a glance
- View from the Direct 3
- The year by numbe 4

**Exceptional resear** projects and peopl

- Science updates 6
- Elements of a world-c 9
- Randomness grant lea speed record
- New push in quantum engineering
- Freedom and interact
  - Bringing quantum communication to Sing and beyond
- Pioneers of quantum enterprise and innovat
- All Possible Paths take into the quantum wor

www.quantumlah.org facebook.com/quantumlah in linkedin.com/company/quantumlah

		Nurturing a community of quantum expertise
ector	28	Governing Board
ers		Scientific Advisory Board
rch	29	Staff and visitors
le	30	Students at CQT
	31	Recognition
class clock	33	Alumni
ads to	34	Events
n		Measuring CQT's achievements and impacts
n tions	36	Measuring CQT's achievements and impacts Research
class clock ads to n ions ngapore	36 37	Measuring CQT's achievements and impacts Research Collaborations
n tions ngapore	36 37 38	Measuring CQT's achievements and impacts Research Collaborations Industry
n tions ngapore	36 37 38 39	Measuring CQT's achievements and impacts Research Collaborations Industry Outreach
n tions ngapore ation	36 37 38 39 40	Measuring CQT's achievements and impacts Research Collaborations Industry Outreach Money matters

twitter.com/quantumlah

youtube.com/quantumblah

# CQT AT A GLANCE

The Centre for Quantum Technologies (CQT) is a national 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) and Singapore University of Technology and Design (SUTD).

## 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 with and consult for industry.

## **EDUCATION**

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

# VIEW FROM THE DIRECTOR

As we all know, it is difficult to make predictions, especially about the future. While our research community has long recognised the commercial potential of quantum technologies, I must admit the worldwide surge of investment, from big corporations, venture capitalists and national governments, took most of us by surprise. It happened sooner and more suddenly than we anticipated. Hype aside, this is both challenging and fascinating. I am confident that quantum technology will have a substantial impact on society in years to come, but its commercial potential in the next five to ten years is anyone's guess.

CQT was established with a mission to do basic research – and this goes on as usual. We have seen many beautiful research papers coming from CQT. We cannot, however, just wait for commercial things to happen. The time has come for a fruitful discussion among researchers, entrepreneurs, managers, and investors who share an interest in quantum technology, and CQT must play a leading role in such discussions. We want to work closely with industry and government agencies, to point out opportunities but also moderate expectations. This, in fact, we have been doing for some time and now with increasing intensity.

In this report, you will read that Singapore's new Quantum Engineering Programme is supporting more translational research, and that several CQT researchers and alumni have ventured outside academia and started their own companies. We have also announced two major new projects that build on the Centre's long history of expertise in quantum communication, and especially in quantum key distribution. On the domestic side, we will work closely with Singapore's Infocomm Media Development Authority (IMDA) to promote development of quantum technologies, in particular secure quantum communication, in Singapore. It will include outreach activities, competency development and training for the local industry and government agencies. With an international perspective, the Singapore and UK governments announced an \$18 million joint project to build and deploy a satellite quantum key distribution test bed.



Reaching into space is a strategic move towards global data security, and we are excited to be part of it.

This CQT annual report will tell you more about our science, outreach and contacts with industry. I hope you will learn more about what we do and how we do things at CQT. I hope you get to know our CQTians a little too. The most valuable part of any research institution is the people. In the corporate lingo, human capital is the ultimate intangible asset. To me, it is more: these friends and colleagues define CQT. I thank all CQTians for their hard work in 2018. Together we are well positioned to meet all the new challenges ahead.

Autur Ehert

![](_page_3_Figure_0.jpeg)

![](_page_3_Picture_1.jpeg)

Exceptional research, projects and people Highlights of CQT's work in quantum technologies in 2018

#### SCIENCE UPDATES

![](_page_4_Picture_1.jpeg)

#### Trust in the quantum cloud

CQT's Joseph Fitzsimons, Michal Hajdusek and collaborators proposed a scheme to safeguard customers and companies in the business of quantum cloud computing. Tech companies building quantum computers are already giving commercial access to their hardware.

"Our approach gives a way to generate a proof that a computation was correct, after it has been completed." explains Joseph. The customer can get assurance that their instructions were carried out and the company can show that it delivered the service.

Their proposal is an improvement over previous verification schemes because it does not require any back-and-forth communication with the computer during its operation. Instead, the scheme makes use of a 'witness state'. It will need bigger and networked quantum computers to become practical. Phys. Rev. Lett. 120, 040501 (2018)

![](_page_4_Picture_6.jpeg)

#### Quantum algorithm for AI

The first 'quantum linear system algorithm' proposed in 2009 kick-started research into quantum machine learning. In 2018, CQT's Zhikuan Zhao, Anupam Prakash and collaborator presented a new, faster version of this algorithm that also removes some restrictions on the kind of data that can be analysed.

In the future, the algorithm could help crunch numbers on problems as varied as commodities pricing, social networks and chemical structures. It will find correlations in a large matrix of data.

As a rough guide, for a 10,000 square matrix, a classical algorithm would take on the order of a trillion computational steps, the first quantum algorithm some 10,000s of steps and the new quantum algorithm just 100s of steps. Phys. Rev. Lett. 120, 050502 (2018)

![](_page_4_Picture_11.jpeg)

#### Saving memory in simulation

Computer models of systems such as a city's traffic flow or neural firing in the brain, known as continuous-time stochastic processes, tend to use a lot of memory. Taking a quantum approach to time could significantly cut that requirement, according to CQT's Mile Gu and Thomas Elliott.

A classical computer divides time into discrete steps to perform a simulation, taking smaller steps for greater accuracy. Storing the outcome of each step takes up memory.

"With a quantum simulator, you can avoid the precision versus storage trade-off that you have to suffer with a classical device," explains Thomas. The trick is to encode the temporal probability distribution of the process in a superposition of quantum states, which naturally evolves continuously in time. npj Quantum Information 4, 18 (2018)

![](_page_4_Picture_16.jpeg)

#### Sync survives quantum noise

A phenomenon that exists in the beating cells of your heart and the orbital periods of planets can persist in the quantum regime, predict CQT researchers and their collaborators.

The international team calculated that oscillating quantum systems can sync with each other or with an external driving frequency. Physicists had feared that noise at the quantum level would wash out such effects.

In a paper in *Physical Review Letters* that was highlighted as an Editors' Suggestion, the team further predict a boost for synchronisation if the external drive simultaneously 'squeezes' the state. Squeezing reduces the noise in the phase of the oscillation while increasing the fluctuations in average number of excitations. The effect might ultimately be harnessed for applications such as synchronising time across a network of atomic clocks.

![](_page_4_Picture_21.jpeg)

#### Rydberg atoms show promise for quantum networking

Future quantum networks may use a technology demonstrated in the CQT lab of Wenhui Li. The method converts microwaves to optical signals through nonlinear frequency mixing involving Rydberg atoms, which have one electron in a highly excited state.

"To build a quantum network, we will probably have to employ several different systems – microwave, terahertz, optical - so this kind of conversion between wavelengths will be generally useful," says Wenhui. For example, optical links may connect superconducting devices operating at microwave frequencies.

Compared to other schemes for microwave-to-optical conversion, the method has the advantages of being tunable, high bandwidth and preserving phase information. Phys. Rev. Lett. 120, 093201 (2018)

Phys. Rev. Lett. 120, 163601 (2018)

#### SCIENCE UPDATES

![](_page_4_Picture_31.jpeg)

#### Beautiful atomtronics

The CQT groups of theorist Kwek Leong Chuan and experimentalist Rainer Dumke are collaborating on 'atomtronics' - the idea of building devices based on circuits through which atoms, rather than electrons, flow.

The researchers have simulated how superfluid atoms behave when distributed into a central pool and a corrugated ring. This structure is known as an atomtronic quantum interference device. Still and rotating states of the atoms could encode the 0s and 1s of data for quantum computing or detect rotational motion.

In the simulations, dense regions of the atom cloud (red) interfere and spread out into empty space (blue) over a few thousandths of a second. Singapore newspaper The Straits Times featured some of the striking images in its Beautiful Science section. Phys. Rev. A 97, 013633 (2018)

#### SCIENCE UPDATES

![](_page_5_Picture_1.jpeg)

#### Record-breaking source

Two innovations in the design of an entangled photon-pair source gave the CQT group of Alexander Ling a recordperforming device.

Entangled photons are ingredients for quantum communication and computing. The CQT source generates over 65,000 pairs of photons per second per milliwatt of input laser power. That's more than double the previous record for sources of the same mechanism. The source implements spontaneous parametric down conversion with singledomain, non-linear crystals.

The improvement came about through an idea that reduced the number of crystals needed from four to two, and by doing away with optical components typically used to shape the input laser beam. The source uses a laser diode that creates an elliptically-shaped beam. It turns out this works better than the circular beam used in older designs. Optics Express 26, 12396 (2018)

![](_page_5_Picture_6.jpeg)

#### Flipping time's arrow

A quantum computer is less in thrall to the arrow of time than a classical computer. suggest findings from an international team including CQT researchers.

A decade ago, complexity scientists found there is a computational overhead for modelling certain types of data sequences in reverse. This is known as 'causal asymmetry' and has been called an example of time's barbed arrow. The new work shows that models that use quantum physics can entirely mitigate the overhead.

"If causal asymmetry is only found in classical models, it suggests our perception of cause and effect, and thus time, can emerge from enforcing a classical explanation on events in a fundamentally quantum world," says CQT co-author Javne Thompson. The discovery may also point to practical advantages for quantum simulations. Phys. Rev. X 8, 031013 (2018)

![](_page_5_Picture_11.jpeg)

A quantum Foucault's pendulum

CQT researchers have shown atoms' spins behaving like a Foucault's pendulum.

A pendulum swinging freely on Earth appears to rotate because of Earth's rotation beneath it. Similarly, in experiments by CQT's David Wilkowski and colleagues, an atom's spin rotates with respect to the phase of laser light shone onto it. A unique quantum feature, known as a 'non-Abelian' geometric transformation. is that the rotation of the spin depends not only on the laser operation but also on the spin's starting point.

Monitoring changes in spin gave a quick way to measure the temperature of the atom cloud. With further work, the approach could also simulate 'gauge field' structures such as two-dimensional spin-orbit coupling, relativistic trembling motion (Zitterbewegung) and magnetic monopoles.

Nature Communications 9, 3580 (2018)

![](_page_5_Picture_17.jpeg)

## Elements of a world-class clock

See how Murray Barrett's group are building a novel optical atomic clock

Like watchmakers choosing superior materials to build a fine timepiece. CQT physicists have singled out an atom that could allow us to build better atomic clocks.

Back in 2015, the research group led by CQT Principal Investigator Murray Barrett identified Lutetium (Lu). a rare earth element, as having potential to improve on today's best clocks. With results published in Nature Communications in April 2018<sup>1</sup>, the group confirmed their hunch.

"The ultimate performance of a clock comes down to the properties of the atom – how insensitive the atom is to its environment. I would call lutetium top in its class," says Murray.

One source of inaccuracy in a clock frequency is sensitivity to the temperature of the environment surrounding the atom. The team measured the strength of this 'blackbody radiation shift' for clock transitions in lutetium, finding the shift for one energy level transition to be closer to zero than for any established optical atomic clock.

<sup>1</sup>K. J. Arnold, R. Kaewuam, A. Roy, T. R. Tan & M. D. Barrett, Blackbody radiation shift assessment for a lutetium ion clock, Nature Communications 9, 1650 (2018)

#### **RESEARCH IN FOCUS**

"We have definitively shown that Lu is the least sensitive to temperature of all established atomic clocks," says Kyle Arnold, a Senior Research Fellow in the group. That will not only help to make a lab-based clock more accurate, but also make clocks that come out of the labs more practical, allowing them to operate in a wider range of environments.

Photo: Welcome to the atomic clock lab of Murray Barrett (left). He is pictured with team members (from left to right) Kyle Arnold, Rattakorn Kaewuam and Arpan Rov. Kyle is a Senior Research Fellow, Rattakorn a PhD student, and Arpan was a Research Fellow who now works in industry in Singapore. Also working on the project is Tan Ting Rei, a NUS Lee Kuan Yew Postdoctoral Fellow.

These measurements add to earlier results showing lutetium could make a high-performance clock. One reason lutetium has not been tried by other groups is that it needs a 'hyperfine averaging technique', discovered by Murray and his collaborators, to cancel certain sources of inaccuracy. "I don't see it as being an overly technical, difficult thing to do, but I think people are waiting to see how this works out," says Murray.

To chase down all possible sources of measurement noise, the team also studied the impact of magnetic fields induced by the trap's operation. Alternating fields induced in the trap electrodes have not been thoroughly characterised in clocks before, the team say, but could be significant at the level of precision experiments are reaching. They collaborated with the CQT group of Dzmitry Matsukevich to trial a technique for measuring these fields, publishing their findings in September 2018 in *Physical Review A.*<sup>2</sup>

The group's research has been supported by CQT core funding and a grant from Singapore's Agency for Science, Technology and Research (A\*STAR). Starting in 2019, the group will also receive funding under Singapore's new Quantum Engineering Programme (see pp.16–17) to develop chip-based versions of their technology. The group's two laboratories are now packed with equipment – take a pictorial tour over the following pages - to make

lutetium into a record-breaking optical atomic clock.

#### Atomic clocks 101

Since the second was defined with reference to caesium atoms in the 1960s, there has been world-wide competition to improve the accuracy and stability of atomic clocks.

Time signals from caesium clocks still support the Global Positioning System and help to synchronise transport and communication networks, but atoms of many other species, such as ytterbium, aluminium and strontium, now vie to make the most precise measurements of time. These new generation clocks, with uncertainties around one part in a billion billion, are proving their mettle in testing fundamental physics – from measurements of gravity to looking for drifts in fundamental constants.

The 'tick' of an atomic clock comes not directly from the atom, but from the oscillation of a light wave. The oscillation frequency is fixed by locking it to a resonant frequency of the atom. Caesium clocks run at microwave frequency, or exactly 9,192,631,770 ticks per second. The most recent generation of atomic clocks run at optical frequencies, which tick some ten thousand times faster. A lutetium clock will be optical too. Counting time in smaller increments allows for more precise measurement.

![](_page_6_Picture_11.jpeg)

This unassuming object is a strip of lutetium, a rare earth element of atomic number 71, purchased from a supplier. The strip will be loaded into an oven connected into the team's setup, so that some of the material

can be sublimated off. Some of these vapourised atoms are stripped of an electron by a laser to give them a positive charge so they can be caught in an ion trap.

<sup>2</sup> H. C. J. Gan, G. Maslennikov, K.-W. Tseng, T. R. Tan, R. Kaewuam, K. J. Arnold, D. Matsukevich, and M. D. Barrett, Oscillating magnetic field effects in high precision metrology, *Phys. Rev. A* **98**, 032514

![](_page_6_Picture_15.jpeg)

## **RESEARCH IN FOCUS**

The portions of the experiment where the atoms live are fully enclosed and air-tight. A vacuum pump removes all the air – effectively unwanted atoms – so that a single ion can be kept for more than a day. The pressure inside the system is below 10<sup>-11</sup> Torr, roughly the pressure on the Moon.

Here Murray Barrett inspects an ion trap: the copper wires will carry alternating currents, creating electric fields to catch the positively charged Lutetium ions in the central area between them. The researchers are first working towards building clocks with single ions, but ultimately they'd like to make clocks based on lattices or networks of many ions.

![](_page_7_Picture_1.jpeg)

The ion trap is located within a cylindrical chamber. You can just see the ions glowing under the illumination of laser light in the middle of the window. Zinc selenide windows (not shown) allowed for a high-power CO2 laser, the type used for industrial cutting, to pass through onto the ion. This laser has a similar wavelength to blackbody radiation but is much more intense. Focusing a few Watts of laser power on the ion, the measured optical frequency shifts by only a few Hz. This measurement of the blackbody radiation shift was a six month long effort.

![](_page_7_Picture_3.jpeg)

Altogether, operating the atomic clock takes some dozen lasers. This optical table holds the most important of them all. It's a clock laser – meaning that it locks to a very narrow energy transition of the atom – operating at a wavelength of 848nm, which is red light just at the edge of the visible spectrum. The tick of the clock is counted by measuring the oscillations of this light wave.

![](_page_7_Picture_5.jpeg)

## **RESEARCH IN FOCUS**

L Some components of the lasers are built in-house by the CQT team. This structure is an external cavity to constrain the frequency of a commercial laser diode.

**R** The group also create their own electronics to control systems, such as this frequency generator that can provide fine adjustment to the laser frequencies required for a clock. This is one of several devices designed and made in CQT.

The clock apparatus spreads across two laboratories. The clock chamber and laser live to the right. To the left, the team installed an ultralow noise frequency comb and hydrogen maser in 2018. These help to transfer the stability of the 848nm clock lasers to lasers at 804nm and 577nm, two other clock transitions in lutetium the team is exploring. The hydrogen maser, together with a Global Positioning System receiver which tracks signals from GPS satellites, enables long term comparison of their clock to Coordinated Universal Time (UTC). Ultimately, this will enable comparisons of the CQT clock with other atomic clocks around the world.

![](_page_8_Picture_1.jpeg)

# Randomness grant leads to speed record

One outcome of a five-year programme exploring quantum randomness is fast generation of secure random numbers

The processes described by quantum physics are intrinsically random: in other words, those processes are natural random number generators. This randomness can be a resource for sampling, algorithms and cryptography.

An interdisciplinary team of CQT Principal Investigators set out in 2013 with a five-year grant from Singapore's Ministry of Education (MOE) to harness quantum randomness in theoretical and experimental studies. That programme "Random Numbers from Quantum Processes" concluded in 2018 with more than 160 articles published. Some results from earlier years have been covered in the Centre's previous annual reports. A significant milestone reached in 2018 was the generation of 'certified' random numbers, described in a paper published in October in *Physical Review Letters*<sup>1</sup>. "To the best of our knowledge, we have currently the fastest source of certified random numbers on the planet," says CQT Principal Investigator Christian Kurtsiefer, who led construction of the experiment.

By measuring pairs of light particles using extremely sensitive detectors, the team created around 240 random bits per second. The rate has been creeping up in experiments performed around the world for different levels of certification, with a team in China reporting just weeks earlier in Nature a rate of 181 bits/s.

The CQT work involved collaboration with researchers from the US National Institute of Standards and Technology (NIST) in Colorado, the University of Texas at Austin, United States, and the University of Basel in Switzerland.

The researchers estimate the approach could reach an upper limit of 1300

<sup>1</sup>L. Shen, J. Lee, L.-P. Thinh, J.-D. Bancal, A. Cerè, A. Lamas-Linares, A. Lita, T. Gerrits, Sae Woo Nam, V. Scarani, C. Kurtsiefer, Randomness extraction from Bell violation with continuous parametric down conversion, *Phys. Rev. Lett.* **121**, 150402 (2018)

random bits per second while keeping the same stringent security guarantees. "We used a very paranoid extractor of randomness," says CQT's Valerio Scarani, who led work on the theory side and was the lead Principal Investigator on the MOE grant.

Having truly random numbers is important for applications. Software methods can generate 'pseudo-random' numbers, but subtle patterns in their output can lead to failures or security holes that can be exploited. There's also a problem of ensuring the randomness in security applications is 'private' – that no one else has a copy.

Quantum physics offers solutions to both problems. The behaviour of two particles that share the quantum property of entanglement is unpredictable but correlated. A pattern of measurements known as a 'Bell test' can confirm the presence of entanglement, in turn guaranteeing that the measurement outcomes are both random and private. The Bell test effectively certifies the output.

PhD students Lijiong Shen and Jianwei Lee built a setup that makes entangled light particles by shining a UV laser onto a particular crystal. The continuous pumping of the crystal creates pairs of infrared photons entangled in their polarisation. The photons are sent to a pair of photon detectors, which record when light particles of different polarisations arrive. The Bell test was applied to these bits.

To close a detection loophole in the setup that could give adversaries a way to hack the output, the team had to capture as many photon pairs as possible. They used extremely sensitive photon detectors supplied by NIST. They also simplified the design to minimise losses of light, achieving an 82% efficiency overall. "We care about every single percent," said Lijiong.

The researchers invented a new method of analysing the data to test for entanglement, looking at their detector outputs in chunks of time, rather than trying to identify pairs in the data. It follows the idea of making a scheme 'device-independent'. The team expect this innovative scheme for applying a Bell test to be widely adopted.

Once entanglement is confirmed, the bits are further processed to give the random output. The team confirmed that their results passed the tests established by NIST for testing random number generators.

The device itself is unlikely to be widely adopted for random number generation just yet, however. The photon detectors it requires run at temperatures just

#### **RESEARCH IN FOCUS**

milliKelvin above absolute zero, so operate in a specialised and bulky fridge. "With currently available photon detectors it's not a practical system, but it's quite conceivable that could change in the future if somebody comes along with a new photon detector," says Christian.

For practical solutions, the team has developed a quantum random number generator that creates almost 500 million bits per second in a pocketsized device that operates at room temperature. It extracts randomness from the intensity fluctuations of a laser. The difference is that it does not perform a Bell test, so the random numbers fall short of being certified. This has been the object of a patent and has been licensed to a spin-off of CQT, S-Fifteen Instruments (see pp.22–24).

From the academic perspective, says Valerio, the most exciting future areas are in the study of quantum information with many-body systems and quantum thermodynamics. Work done under the MOE grant lays the ground for exploring these directions next. "With the results obtained in this programme, we have positioned ourselves very visibly in this field," he says.

Photo: CQT's Jianwei Lee, Lijiong Shen and Le Phuc Thinh (pictured from left to right) are part of a team extracting randomness from nature.

![](_page_9_Picture_1.jpeg)

# New push in quantum engineering

\$25 million national programme will drive translation of quantum science and technology

In September 2018, Singapore's National Research Foundation (NRF) announced that it will invest \$25 million over five years in a new Quantum Engineering Programme (QEP).

The funding comes as new initiatives in quantum technologies kick off around the globe. In Singapore, QEP will build engineering capabilities in quantum secure communication, quantum devices, and quantum networks. CQT is set to play a major role in the programme.

CQT's Kwek Leong Chuan is a co-director of the initiative (see box **Biodata**), along with John Thong from the Faculty of Engineering at NUS.

On announcing the programme, Singapore's Minister for Finance and Chairman of NRF, Heng Swee Keat, said it is "related to our efforts to help Singapore's industries compete at the global forefront of innovation and enterprise, by tapping world-class expertise in our scientific research community."

Seven projects have been selected for funding under QEP. Of these, two are led by CQT Principal Investigators and one by a CQT Fellow (see box QEP Projects). Three of the remaining projects have CQT researchers as collaborators or co-Pls.

A Steering Committee, chaired by Chua Kee Chaing, Dean of NUS Engineering and having CQT's Director Artur Ekert as a member, oversees the programme.

"QEP is an exciting and ambitious R&D programme that will accelerate the translation of research in quantum phenomena into robust and scalable quantum technologies," said John, the programme co-director.

#### Biodata: Kwek Leong Chuan

Kwek is a Principal Investigator at CQT co-appointed with the National Institute of Education at NTU. He's one of the founding members of the centre – a participant in the 'quantum lah' group that preceded CQT and bequeathed the Centre its unusual web domain.

A theoretical physicist, his research interests include atomtronics, hybrid quantum systems and photonic devices. He was previously a teacher and remains active in outreach, supervising projects, judging competitions and serving as President of the Asia Physics Olympiad International Board.

On QEP, he said "Singapore has been actively involved in quantum research for about 20 years. The timely establishment of this new programme will attract more people working in engineering to contribute to these efforts, so that in the long run, we can play a greater role in commercialising quantum technologies."

#### **QEP Projects**

- A CMOS ion trap for integrated clocks – CQT's Murray Barrett is already building a labsized atomic clock with ambitions to make it the world's most accurate (see pp.9–13). This complementary project under QEP will pursue miniaturisation of the components. His group will partner with pioneers of chip-based ion traps to design, build and test similar CMOS technology for optical atomic clock operation.
- A fibre-based quantum device

   Led by Lan Shau-Yu at NTU, this project aims to develop a long-lived quantum memory that can be integrated into photonic waveguide systems. The quantum memory will be based on cold atoms inside hollow-core fibres. As co-PI, CQT's Dzmitry Matsukevich will integrate the memory with an ion trap quantum processor.
- Cost-effective and fast multiuser quantum key distribution (QKD) network with an

untrusted centralized quantum server – Charles Lim. at the NUS Department of Electrical and Computer Engineering (ECE) and a CQT Fellow, will lead an interdisciplinary team towards the development of a novel quantum-secured network architecture. Existing QKD networks like those built in China rely on 'trusted nodes' to relay keys between users. The project aims to avoid that weakness by using a measurement-deviceindependent protocol, developing chip-based components. CQT's

Alexander Ling will take part as a Two funded projects are focused collaborator in the project. on improving technology for single-photon detection. Quantum Foundry – New services Cesare Soci at NTU will lead at the Microsystems Technology a team building expertise on Development Centre at NTU, 'Superconducting Nanowire led by CQT's Rainer Dumke, Single Photon Detectors' with will bring capability to fabricate CQT's Christian Kurtsiefer as co-PI high quality superconducting and Rainer Dumke as collaborator. circuits. Such circuits are a Gong Xiao in ECE. NUS will lead leading hardware contender for a separate project to create an 'Integrated Quantum Receiver quantum computing. The Centre is installing new equipment. QEP for Single Photon Detection' for supports manpower for design chip-based devices. and manufacturing.

#### **RESEARCH IN FOCUS**

ntum • NUS and (ECE) d an vards novel work QKD China relay oject ss by viceoping CQT's t as a

 Quantum Photonics for Superresolution Confocal Fluorescence Microscopy – Mankei Tsang in ECE, NUS invented a method to increase the resolution of fluorescence imaging techniques beyond presumed limits. CQT's Alexander Ling was among the experimentalists to prove it works. He will be a co-PI in this new project led by Mankei to develop the technique for fluorophores in biological imaging.

Photo: QEP co-directors Kwek Leong Chuan (left) and John Thong (right).

![](_page_10_Picture_1.jpeg)

## Freedom and interactions

Theoretical physicist Michele Dall'Arno explains his research – and why CQT is a good place for it

"It was love at first sight," says Michele Dall'Arno. Around a decade ago. Michele found his passion in quantum information. That passion took him from his native Italy to do research in Spain, Japan and Singapore. His travels have also taken him deeper into the quantum world.

Michele has been a Research Fellow at CQT since 2014. He is interested in the problem of what we can learn about quantum processes solely through the data they generate. He describes his research as being about "datadriven characterisation of quantum

18

devices". That's important for quantum technology. It has also led Michele and his collaborators to a discovery about the nature of quantum theory itself.

Even as a teenager, Michele felt a pull towards maths and physics. "To me, maths is like a playground where I can have fun in total safety because nothing weird happens. If there is a problem it is just a mistake of mine. while the rest of the world at times can be much less nice and reasonable," he says.

After his masters degree, he applied to the PhD programme at Pavia University in Italy because of the international reputation of its quantum information theory group. He did his thesis on the optimisation of quantum communication protocols, then moved into postdoctoral positions, first at the Institute of Photonic Sciences (ICFO) in Barcelona, Spain and then at Nagoya University in Japan.

In Japan, Michele fell in love again. He met his wife, with whom he now has a young daughter, in the bakery where she worked. "It is a very romantic story. As an Italian I need bread, so I was there almost every day," he says.

Michele then moved to Singapore to join the CQT group of Vlatko Vedral, and in 2019 starts a new position in Valerio Scarani's group. "When I came to CQT, I had already been a postdoc for three years, so I had developed strong interests and lines of research. I was looking for a position in theoretical physics that would allow me to continue along this path. Singapore offered exactly this opportunity," he says.

Earlier in his career. Michele looked at the idea of 'device independence'. This means the ability to characterise a device's quantum behaviour without needing to assume anything about its inner workings.

Traditionally, researchers would turn to a process known as tomography to characterise a quantum device. This

involves making many measurements of the device. There's a problem. however, because strictly you should also characterise the measurement device. "Somewhere you have to break the chain," says Michele. Deviceindependent assessments do this by looking for a statistical pattern in the output that is unique to the quantum process, making no assumptions about what may be creating it. The classic example is the pattern seen for entangled particles – a correlation that is measured by testing a Bell inequality.

Michele's more recent work is in the same spirit, but it isn't limited to testing Bell inequalities. He aims to provide general rules that you apply to work

#### No hypersignaling

It's not every day you discover a new principle of physics. In 2017. Michele Dall'Arno and collaborators revealed in Physical Review Letters<sup>i</sup> that their new principle of 'no hypersignaling' can distinguish quantum physics from other theories one might dream up. The principle states simply that the amount of information that can be sent with one particle versus two scales in a certain way. "Quantum theory satisfies this very natural constraint, but there are other theories that do not, and out what inner process may explain the input-output patterns of a quantum device.

"Say you give me a black box device. We believe that quantum theory is right, or at least the best theory we know, so we believe there is a quantum description of what the box does. Our formalism allows us to do an experiment to get the minimal quantum description of the box," he explains. It could, for example, be applied to find a lower bound on the performance of a quantum logic gate in a computing device.

Michele and his collaborators also previously tried using this approach to characterise quantum physics as a

such theories cannot be ruled out in terms of any other known principle. For example, they are perfectly fine when you look at entanglement, but they fail our test," says Michele. Quantum physics has provided our best description of nature since it was devised in the early 20<sup>th</sup> Century. Physicists are, however, still searching to see if deeper, more intuitive ideas lie behind it, similar to the way that Einstein's special relativity derives from the principle that the speed of

<sup>1</sup>M. Dall'Arno, S. Brandsen, A. Tosini, F. Buscemi, and V. Vedral, No-Hypersignaling Principle, *Phys. Rev. Lett.* **119**, 020401 (2017)

#### **RESEARCH IN FOCUS**

whole, rather than devices. Michele says "we thought, we are testing devices in guantum theory, what happens if we test the theory itself?" It led them to propose a new physical principle (see box: No hypersignaling). "Thinking about applications is right, but pure research remains very important in the longerterm and at a social level," says Michele.

Now his work on data-driven characterisation is ongoing with Valerio and his group members. "Valerio is very supportive and we have insightful conversations. We have a lot of interests in common. I have just the right amount of freedom and the right amount of constructive interaction with others in the group," says Michele.

light is the same for all observers. The result caught the attention of the community. The paper was highlighted in the journal as an Editors' Suggestion, and Michele gave talks on the result at the Asian Quantum Information Science Conference in Singapore in 2017 and the Quantum Computing and Measurement Conference in the United States in 2018.

Photo: CQT's Michele Dall'Arno is working on the data-driven characterisation of quantum devices.

#### INDUSTRY

![](_page_11_Picture_1.jpeg)

# Bringing quantum communication to Singapore and beyond

New partnerships with Singapore's Infocomm Development Authority and the UK's RAL Space build on CQT's expertise

The Centre for Quantum Technologies is working with partners towards quantum networks within Singapore and across its borders.

Two major new projects announced in 2018 build on the Centre's long history of expertise in quantum communication, and especially in quantum key distribution (QKD), through which encryption keys are created by the transmission and detection of single light particles.

Quantum networks can offer advanced security for governments and industry

concerned about protecting their data in transit. That's because QKD cannot be hacked by computational methods. It also automatically reveals any attempted intercepts.

Interest in QKD has intensified as researchers make progress towards building bigger quantum computers, which could break today's most widely used encryption systems.

On the national stage, CQT, acting through the National University of Singapore, and Singapore's Infocomm Media Development Authority (IMDA) signed a Memorandum of Intent (MOI) in June that aims to promote development of quantum technologies, in particular QKD, in Singapore.

"In building a more digitalised and connected Singapore, it is important to future-proof our infrastructure and prepare our industry to adopt advanced, even if nascent, technologies such as quantum key distribution. The MOI with the Centre for Quantum Technologies at NUS will help to build competencies in Singapore, setting the foundation for Singapore's quantum key distribution deployment," said Aileen Chia, IMDA's Deputy Chief Executive (Policy, Regulation & Competition Development).

With an international perspective, the Singapore and UK governments announced in September an \$18 million joint project to build and deploy a satellite quantum key distribution (QKD) test bed. Satellites offer a way of enabling long-distance quantum communication, surpassing the range possible in fibers. Work on this project will be led by CQT in Singapore and the Science and Technology Facilities Council's RAL Space in the UK.

Artur Ekert, Director of CQT said: "Having access to quantum-secured communication is a smart step for cybersecurity. We already have trials over fibre for secure communication

#### within Singapore, building on CQT's decade of development of this quantum technology. Reaching into space with our UK partner is a strategic move towards global data security."

#### On the ground

Initiatives under the MOI with IMDA will include outreach activities, competency development and training for the local industry and government agencies, and piloting QKD implementation and trials.

A first workshop held in July 2018 featured CQT speakers and other experts on QKD and post-quantum cryptography, which involves development of new mathematical approaches to encryption resistant to attack by quantum computers. It drew 107 participants from 39 organisations including network operators, security companies, government agencies, and end users such as banks and data centres. CQT and IMDA are planning a second workshop in 2019.

The collaboration with IMDA complements an existing project with Singtel, Asia's leading communications group. Under the NUS-Singtel Cyber Security Corporate Research and Development Laboratory established in 2016, CQT researchers have developed sources of quantum entangled photons that are compatible with telecom fibres. They have begun testing the transmission of these photons over Singtel's local fibre network, with results to be published.

A new project to begin in 2019 under Singapore's new Quantum Engineering Programme (see pp.16–17) will explore novel quantum network architectures.

#### Into space

Optical fibres absorb some of the light passing through them, which limits the distance over which sending and receiving single-photon signals is possible at high rates. The range for QKD perfectly suits Singapore, measuring only some 50km across.

To exchange encryption keys with parties further afield, Singapore may use satellites. CQT has been developing rugged and compact QKD instrumentation for satellites since 2010, with one successful launch in 2015 and a next generation instrument due for launch in 2019.

In the new collaboration with the UK, supported in Singapore by the National Research Foundation and other sources, CQT will contribute its expertise in building QKD instruments suitable for deployment in space. RAL Space will contribute its expertise in innovative space technology and optical links needed for beaming QKD signals.

CQT's other missions have not aimed at QKD with the ground, performing

#### INDUSTRY

only tests of the photon source in orbit. The project will differ from China's demonstration in 2016 of QKD via the Micius satellite because it will use nanosatellites. Smaller and lighter satellites are cheaper to build and launch.

The Principal Investigators for the project are Alexander Ling, CQT Principal Investigator, and Andy Vick, Head of Disruptive Space Technologies at RAL Space. Christian Kurtsiefer at CQT is a co-Pl.

George Loh, Director, Programmes at the National Research Foundation (NRF) in Singapore said: "Singapore and UK share the same outlook to leverage research & innovation to develop capabilities and derive benefits for our respective countries. This collaboration with UK is significant for both countries, in bringing together our experts to demonstrate satellite-based QKD communication capability. Singapore will also bring in local companies to develop and commercialise products and services in the QKD market, as well as other forms of space and quantum technologies."

There are two spin-offs from CQT (see pp.22–24) that aim to support QKD on the ground and in space, called S-Fifteen Instruments and S-Fifteen Space Systems.

Photo: CQT's Artur Ekert (left) and IMDA's Aileen Chia (right) signed a Memorandum of Intent in June 2018 to support outreach, training and trials with industry on quantum technologies.

# Pioneers of quantum enterprise and innovation

Some CQTians are turning entrepreneur. Learn more about the startups and spin-offs recently established by CQT researchers and alumni

Driven by dreams of bringing their discoveries into the world, of having an impact on society and of business success, some CQT researchers and alumni have chosen the high-risk path of starting their own companies. Together they are creating a fledgling quantum industry in Singapore.

Two companies seek to commercialise CQT's expertise in quantum-safe communications. S-Fifteen Instruments. spun-off by PIs Christian Kurtsiefer, Alexander Ling and CQT's former Head of Strategic Development, Lum Chune Yang, has received a grant from Temasek Foundation Ecosperity to productise

terrestrial quantum key distribution (QKD) technology. Alexander, Chune Yang and Senior Research Fellow Robert Bedington have also co-founded S-Fifteen Space Systems, planning to provide QKD via satellites.

There are three early-stage companies in the quantum computing space. Horizon Quantum Computing (see box) is focused on software, while Innovatus Q – The Quantum Technology Company, co-founded by Rainer Dumke and Manas Mukheriee, will work on superconducting gubits and trapped ions. Entropica Labs, co-founded by CQT alumni Tommaso Demarie and Ewan Munro, aims to develop quantum software for life sciences.

There's a backstory to Entropica. Tommaso and Ewan participated in 2018 in Singapore's EntrepreneurFirst programme, which fosters the development of technology startups. A third CQT alumnus was also in the programme: Ravi Kumar co-founded Atomionics to build atom-interferometry based sensing systems for navigation and exploration.

The impacts of expertise cultivated at CQT reach beyond quantum, too: see overleaf.

![](_page_12_Picture_10.jpeg)

![](_page_12_Picture_11.jpeg)

![](_page_12_Picture_12.jpeg)

innovatus

ATOMION CS

![](_page_12_Picture_14.jpeg)

![](_page_12_Picture_15.jpeg)

#### Focus on Horizon Quantum Computing

"How strongly do I believe quantum computing has a bright future? Strongly enough that I've just resigned from a tenured faculty position to be chief executive at @horizon guantum."

That was how Joe Fitzsimons announced to the world in November 2018, through a tweet, that he would be leaving academia to devote his attention to his spin-off Horizon Quantum Computing. Joe, who has worked at CQT since 2010 and was a Principal Investigator from 2017, will retain a research affiliation with the Centre when he moves full-time to Horizon in 2019.

Horizon aims to accelerate the development of quantum software. The company has no plans to build quantum computing hardware. Instead, the Horizon team will build tools that make quantum computers easier for others to use: in particular. providing tools that simplify the process of algorithm design both for experts with experience in quantum computing and for programmers new to the field.

Joe says his vision is "bridging the gap between quantum computers and conventional software development, enabling software developers to harness the full power of quantum processors without requiring a PhD". His past research contributions include schemes for secure quantum cloud computing.

Scientists have discovered a few standout algorithms that show that large quantum computers, when they exist, will outperform the fastest supercomputers, and they expect to find more.

In 2017, a group of European researchers produced a Quantum Software Manifesto that says "we currently only have a rough idea of potential applications, even though they will be key to the economic success of quantum computers". The document, since endorsed by hundreds of researchers around the world, encourages action: "Given the recent rapid advances in quantum hardware, it is urgent that we step up our efforts in quantum software."

Horizon has already got financial backing. The seed funding round was led by SGInnovate, a Singapore-Government owned company that promotes deep tech in Singapore. Other investors include Abies Ventures. Data Collective, Qubit Protocol, Summer Capital and Posa CV.

#### INDUSTRY

![](_page_12_Picture_29.jpeg)

Horizon has also struck a deal with the US-based hardware company Rigetti to work on their existing quantum computer and future larger machines. Users of Rigetti's cloud platform will be able to access Horizon's tools as they become available.

Joe is now hiring people to join him at Horizon. There's a lot of competition for talent given government and commercial investments in quantum technologies worldwide. In October 2018, the New York Times ran an article with the headline 'The Next Tech Talent Shortage: Quantum Computing Researchers'. However, Joe is optimistic that his startup's vision, the expertise already in Singapore and the city's attractions will make a winning combination.

![](_page_12_Picture_32.jpeg)

http://horizonguantum.com/

#### INDUSTRY

#### Not everything needs to be quantum

Physics is often sold to students as offering transferrable problem-solving skills. That's not just a marketing tactic. The story of Sambit Pal is a case in point.

Sambit, who graduated with a PhD from CQT in 2017, is now the Chief Technology Officer of a company he co-founded called mVizn. The company has commercial contracts with PSA Corporation (formerly Port of Singapore Authority) to deploy automated safety supervision systems on various cranes and heavy machinery that move shipping containers in ports.

mVizn's system uses deep-learningbased machine vision to automatically flag violations in safe work procedures and standard operating procedures, such as people entering restricted areas or vehicles manoeuvring incorrectly. It is trained on vast amounts of video of port operations.

mVizn grew out of Sambit's entrepreneurial experiments. "After the first couple of years of my PhD, I knew I wanted to go into something where I could apply the knowledge I had been picking up," he says.

Sambit's PhD was in the experimental group of Kai Dieckmann, creating

ultracold molecules for research in many-body physics. Day-to-day, this involved designing and troubleshooting optical and mechanical equipment. He also coded to automate portions of the experiment.

Those hands-on skills were good preparation for his current role, even if his thesis – on "Molecular Spectroscopy of Ultracold 6-lithium and 40-potassium molecules: Towards STIRAP Transfer to Absolute Ground State" – is far removed from his current work.

During his PhD, Sambit played with business ideas in his free time, from building accessories for smartphones to creating a Bengali meme-generator. The turning point came when he participated in a two-day hackathon organised by Mercedes-Benz to look for solutions for problems in manufacturing and warehousing.

Sambit's prototype system for tracking cars through a warehouse, which combined deep learning and machine vision, was selected as a finalist.

Sambit and his co-founder developed their business out of this initial idea. In the early stages, mVizn received support from the Startup Autobahn

![](_page_13_Picture_12.jpeg)

Singapore program powered by Mercedes-Benz, including office space, hardware and networking opportunities. It was through the networking sessions that the team first started talking to PSA Singapore about their business needs.

mVizn is now scaling up their deployment within PSA Singapore Terminals. The company is also going international, with a contract in the logistics industry in Vietnam.

Being a startup founder is different to lab life in many ways, says Sambit. "There is a lot more legwork to be done," he says – and it's not only business admin. Sambit sometimes climbs the cranes himself to fix issues or retrieve video footage. "I love the technical bits, but I cannot restrict myself to just doing that," he says.

https://www.mvizn.com/

![](_page_13_Picture_17.jpeg)

# All Possible Paths takes visitors into the quantum world

CQT contributed to an exhibition on Richard Feynman's life and physics at Singapore's ArtScience Museum

Quantum physics went on show in one of Singapore's cultural landmarks in 2018, in an exhibition at ArtScience Museum at Marina Bay Sands to mark the centenary of physicist Richard Feynman.

All Possible Paths: Richard Feynman's Curious Life, which ran October 2018 to March 2019, explored all facets of the Nobel prize-winner's life, from his deep contributions to physics to his charismatic teaching and notorious pranks.

CQT was a partner in the exhibition, which was curated by ArtScience Museum, the Nanyang Technological University (NTU) and Nobel Museum.

The ArtScience Museum occupies a distinctive lotus-inspired building on the city's harbour, drawing visitors to explore where art, science, culture and technology come together.

The exhibition's opening ceremony was officiated by Mr Heng Swee Keat, Minister for Finance and Chairman of the National Research Foundation, who said "The best ideas emerge from the intersection of technology with the arts, when people from different disciplines collaborate to learn from each other."

CQT has a history of bringing science and art together, through past residencies for artists and writers, as a creative partner of the NUS Arts Festival and as organiser of the international Quantum Shorts competitions for film and fiction.

For All Possible Paths, CQT provided scientific input, participated in the public programming and co-commissioned with ArtScience Museum one of the artworks included in the show. That work is *Quantum* by Malaysian artist Jun Ong,

#### OUTREACH

an immersive installation inspired by the notion of quantum computing.

The artwork was included in a section of the exhibition devoted to Feynman's contributions to physics. Taking inspiration from Feynman's own visual way of thinking, sculptures, installations and photographs by 12 contemporary artists were presented to "articulate the uncanny quantum world in a visual way".

Feynman was among the first to see the potential for quantum computing. Noting how difficult it is to calculate what's happening in physical systems, he famously said in 1981: "Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better

Photo: The exhibition about Richard Feynman explored his life as a scientist, musician and storyteller.

#### OUTREACH

make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

Showing how far this idea has gone, the first item in the exhibition was a quantum computing chip donated by the quantum computing team at Google. The group is one of a handful at big tech companies and startups racing to build this new kind of computer.

The CQT group of Dimitris Angelakis collaborates with the Google team, and the 9-qubit chip displayed at ArtScience Museum was hand-carried to Singapore by Pedram Roushan, a Google quantum electronics engineer, when he visited CQT to give a colloquium and public talk in March 2018.

Jun Ong, who is based in Kuala Lumpur, Malaysia, also visited CQT – spending one day at CQT in May to learn about quantum computing, tour the Centre's research labs and present to CQT staff.

Trained as an architect, Jun is interested in pairing artificial light and technology. He was nominated for Best in Spatial Art at the Media Architecture Biennale 2016 in Sydney, Australia.

His new work Quantum makes use of lasers and mirrors in a darkened room to create continuous and continuously changing laser paths. His idea is that viewers experience the distortion of

![](_page_14_Picture_7.jpeg)

dimension and spatial logic, as created by the quantum phenomenon known as entanglement.

"I think as artists, or as creatives, we should be able to extract certain complex ideas and reflect them in a very visceral and visual manner that is accessible to all kinds of people, of all ages and all walks of life." said Jun.

The exhibition was planned in conjunction with a conference held at NTU's Institute of Advanced Studies, 22-24 October, to celebrate the centenary, with speakers including Feynman's daughter, Michelle Feynman, Feynman's former students and Nobel laureate Frank Wilczek.

CQT's Director Artur Ekert was also a speaker at the conference, on the topic on quantum computing. He says "It was because of Feynman's lectures that I

decided to study physics. It was almost an intellectual transformation, seeing how even difficult physics could be made so clear and fun. I hope that visitors to ArtScience Museum's new exhibition get to experience some of this feeling."

Those who missed the show in Singapore may get a second chance: the exhibition could travel and CQT will be considering other venues to display Quantum.

CQTians who supported the collaboration with ArtScience Museum include Dimitris Angelakis, Murray Barrett, Berge Englert, Joseph Fitzsimons, Jenny Hogan, Kwek Leong Chuan, Lai Choy Heng, Alexander Ling, Nana Liu, Oh Choo Hiap and Zhao Liming.

Photo: Quantum by Jun Ong (b.1988) is a mixed media installation commissioned in 2018 by ArtScience Museum and CQT.

![](_page_14_Picture_16.jpeg)

## Nurturing a community of quantum expertise We bring together top physicists, computer scientists and engineers

## **Governing Board**

Quek Gim Pew (Chairman) Chief Defence Scientist Ministry of Defence

#### Nicholas Bigelow

Lee A. DuBridge Professor of Physics Professor of Optics University of Rochester

#### Freddy Boey

Senior Vice President (Graduate Education & Research Translation) National University of Singapore

#### Chang Yew Kong

Chairman Industry Advisory Committee (Information and Communications Technology) Singapore Institute of Technology

#### Artur Ekert

Director Centre for Quantum Technologies Lee Kong Chian Centennial Professor National University of Singapore Professor of Quantum Physics University of Oxford

#### Ho Teck Hua

Senior Deputy President & Provost Tan Chin Tuan Centennial Professor Professor National University of Singapore

## George Loh

Director (Programmes) National Research Foundation. Singapore

#### Lui Pao Chuen Advisor National Research Foundation, Singapore

Tan Sze Wee **Executive Director** Science and Engineering Research Council A\*STAR

#### **Russell Tham**

President New Enterprises and Ventures Singapore Technologies Engineering Ltd

#### Vincent Wu

**Divisional Director** Academic Research Division and Higher **Education Planning** Higher Education Group Ministry of Education, Singapore

## Scientific Advisory Board

#### Ignacio Cirac Max-Planck-Institut für Quantenoptik

Klaus Mølmer Institute of Physics and Astronomy University of Aarhus

#### Christopher Monroe

Joint Quantum Institute NIST and University of Maryland

## Michele Mosca

Institute for Quantum Computing University of Waterloo

Christophe Salomon Laboratoire Kastler Brossel Ecole Normale Supérieure Paris

#### Umesh Vazirani

Berkeley Quantum Computation Center University of California at Berkeley

#### Jun Ye

JILA University of Colorado and the National Institute of Standards and Technology

## **Principal Investigators**

#### EXPERIMENTAL PHYSICS

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

#### nolson

Vlatko Vedral

#### Headcount

Principal Investigators Postgraduate Admin, IT & Students 25 Research 182 Support Visiting Staff **Research Staff** Research Assistants/Associates

Count of CQT staff and students as of 31 December 2018

CQT also hosted 150 visitors in 2018

CQT welcomed two new members to its Governing Board in 2018: Freddy Boey and Russell Tham. In April 2019, Freddy Boey will be appointed NUS Deputy President (Innovation & Enterprise). We also note that from March 2019, George Loh will be NRF Director (Services & Digital Economy). We thank Tan Eng Chye, NUS President, who stepped down from our board in 2018 after ten years' service on assuming leadership of the University.

## THEORETICAL PHYSICS

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

#### COMPUTER SCIENCE

- **Divesh Aggarwal**
- **Joseph Fitzsimons**
- Rahul Jain
- Hartmut Klauck

## Miklos Santha

![](_page_15_Figure_61.jpeg)

https://www.quantumlah.org/people

![](_page_15_Figure_63.jpeg)

## Students at CQT

![](_page_16_Figure_1.jpeg)

#### PhD programme

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

![](_page_16_Picture_4.jpeg)

CQTians gather to celebrate when PhD students defend their theses. These happy faces are for Thi Ha Kyaw (front row, third from right), who defended his thesis on quantum computing, supervised by Kwek Leong Chuan (far right) in November 2018.

#### Internships

CQT supports internships for students near the end of an undergraduate degree or during masters studies who are contemplating a career in research. Applications should be made directly to the PI with whom the student would like to work. A successful intern making a follow up application to the PhD@CQT programme will be given high priority.

"The environment at CQT feels like it's catered for a PhD student to excel and realise their best potential – from the regular talks that expose you to fresh ideas to the opportunities to share work with others" Jaren Gan, PhD student EXPERIMENTAL PHYSICS

"It is easy to spot dedicated computer scientists, theoretical physicists and experimentalists in a single building. This ecosystem has provided me with ample possibilities for productive collaboration" **Kishor Bharti,** PhD student **THEORETICAL PHYSICS** 

"I like that there are many opportunities to teach, participate in outreach, and be involved with industry visits, which prepares us for a future career in science beyond research." Srijita Kundu, PhD student

COMPUTER SCIENCE

## Recognition

Great work is not always recognised with awards, but we are happy to report occasions when it is. CQT's staff and students have received awards both for their research and for their contributions to the Centre.

For their work in collaboration with Google's quantum computing team, CQT Principal Investigator **Dimitris Angelakis** and student **Jirawat Tangpanitanon** received three **Google Quantum Innovation Awards** in 2018. The awards were presented for "Quantum simulation of exotic physics in driven quantum hardware architectures". The teams' ongoing collaboration already resulted in one paper in *Science* in 2017.

Google's Pedram Roushan with Dimitris Angelakis and Jirawat Tangpanitanon

CQT Principal Investigator Valerio Scarani and alumnus Jean-Daniel Bancal were named in 2018 among the winners of the Paul Ehrenfest Best Paper Award for Quantum Foundations for the year 2017. The award was presented for the paper "Bell Correlations in a Bose-Einstein Condensate" *Science* **352**, 441 (2016), with the prize committee citing the work for "confirming the presence of quantum effects at the mesoscopic scale".

CQT Principal Investigator Loh Huanqian was awarded a Singapore National Research Foundation Fellowship, class of 2018, for research "Designing Novel Quantum Materials at the Microscopic Level with Ultracold Molecules". She was also named a winner of the 2018 L'Oréal Singapore for Women in Science National Fellowship, being appointed the 2018 Physical & Engineering Sciences Fellow.

30

![](_page_16_Picture_19.jpeg)

![](_page_16_Picture_20.jpeg)

![](_page_16_Picture_21.jpeg)

Valerio Scarani

![](_page_16_Picture_23.jpeg)

Loh Huangian

Two CQT researchers were spotlighted by MIT Technology Review as 'Innovators Under 35' in the Asia Pacific region. Senior Research Fellow Robert Bedington won the recognition for his work building quantum satellites, while Nana Liu, who moved from CQT to a faculty position in China in 2018, won for her work at the interface of quantum computing, security and machine learning.

![](_page_17_Picture_1.jpeg)

**Robert Bedington** 

Chan Chui Theng, CQT Associate Director for Admin, received a Singapore National Day Award in 2018. Chui Theng, who has coordinated CQT programme activities since the Centre was founded in 2007, received The Commendation Medal. This is presented for "commendable performance and conduct, or significant efficiency, competence and devotion to duty".

![](_page_17_Picture_4.jpeg)

CQT presents its own prizes for staff who contribute to the CQT community in ways that go beyond their job requirements. Congratulations to the winners of the CQTian Awards in 2018:

- Adrian Nugraha Utama "for his passion and generosity with his time for both research projects in his group and for outreach"
- Auntie Ah Bee "for being a friendly and welcoming presence in the Quantum Café and for all she does to keep us organised and tidy"
- Mohammad Imran "for always being ready to help and getting things done efficiently, with a smile"
- Kishor Bharti "for his initiative and effort in coordinating the Quantum Machine Learning journal club"

# Alumni

Over its 11-year history, the Centre has employed hundreds of scientists and trained tens of PhD students who have since taken their skills into new roles. We are happy to see our alumni contribute to physics, business and society. While a majority of CQT alumni take their next job in academia, our former staff have also moved to work in banking, consulting and technical industries. Here are some examples of the career paths of our alumni, with the chart showing the next job type for 28 staff and student leavers in 2018 who shared this data.

#### Life after CQT

Wilson Chin Yue Sum Physicist, Schlumberger, Singapore

#### Penghui Yao Assistant Professor, Nanjing University, China

After completing his PhD in quantum optics in 2018, Wilson looked for a job outside academia. Another CQT alumnus working at Schlumberger, a provider of technology to the oil and gas industry, introduced Wilson to the company. Wilson is employed as a physicist in the Singapore Well Testing Center developing a multiphase flowmeter based on Gamma spectroscopy. He enjoys the opportunity to apply physics to commercial technology. "I appreciate the company's capability as the technology lead in its field," Wilson says. "The PhD training as a physicist has shaped my problem solving approach and perspective, which is perhaps the key differentiator in my new role." he says. Wilson completed his PhD supervised by Christian Kurtsiefer on "Light-atom coupling with 4PI Microscopy".

computing.

![](_page_17_Figure_19.jpeg)

In February 2018, Penghui received a prestigious award in China under the Thousand Talents Plan for Young Researchers. Penghui graduated from the CQT PhD programme in 2014 with a thesis on "Studies in Communication Complexity and Semidefinite Programs" supervised by Rahul Jain. He moved to Nanjing University after a postdoctoral position at the University of Maryland in the United States. The Thousand Talents award, for scientists under 40 who show promise as future leaders in their field, provides a research subsidy of up to RMB 3 million to pursue research in China. "It was a surprise and pleasure to receive this award," Penghui said. He continues to do research in theoretical computer science and quantum

![](_page_18_Picture_0.jpeg)

![](_page_18_Picture_1.jpeg)

## Conferences & Workshops in 2018

7 - 12 Feb	Julian Schwinger Centennial Conference	NUSS Guild House, NUS
19 - 23 Feb	Quantum Correlations Week	CQT, NUS
26 Feb - 2 Mar	Workshop on Quantum Algorithms and Complexity Theory 2018	CQT, NUS
20 - 21 Mar	MajuLab/CQT/NUS workshop on Localization, Quantum Chaos and Topology with Matter Waves	NUS
16 - 18 May	Quantum Technologies in Space	CQT, NUS
24 May	1 <sup>st</sup> Quantum Vision Meeting	CQT, NUS
21 Nov	2 <sup>nd</sup> Quantum Vision Meeting	SPMS, NTU

![](_page_18_Picture_4.jpeg)

Measuring CQT's achievements and impact A look at CQT's outputs and spending in 2018

#### RESEARCH

![](_page_19_Figure_1.jpeg)

#### **Cumulative Publications 2008-2018**

![](_page_19_Figure_3.jpeg)

#### **Cumulative Citations**

![](_page_19_Figure_5.jpeg)

\*Citations: Thomson Reuters' Web of Science on Jan 30, 2019.

![](_page_19_Figure_8.jpeg)

In 2018, CQT through NUS was part of the following agreements:

- UMI Majulab agreement with the Nanyang Technological University, the French National Center for Scientific Research (CNRS), the University of Nice Sophia Antipolis and the Sorbonne University, France
- Memorandum of Intent with Singapore's Info-communications Media Development Authority (IMDA)
- Memorandum of Understanding with the Graduate School of Information Science and Graduate School of Mathematics, Nagoya University Japan
- Memorandum of Understanding with the University of Vietnam, Ho Chi Minh City, Vietnam
- Partner Organisation Agreement with the "ARC Centre of Excellence for Quantum Computation and Communication Technology (CQC2T)" at the University of New South Wales, Australia

### COLLABORATIONS

#### 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.

Source: Thomson Reuters' Web of Science on Jan 30, 2019. Data captured from 1 Jan 2008 to 31 Dec 2018

#### INDUSTRY

Here's a snapshot of CQT's activities over 2018 to engage with the translation of quantum technologies. Scientific progress and global investment is driving growing commercial interest.

6 Spin-offs and startups

Direct translation of CQT research is starting through four spin-offs cofounded by CQT Principal Investigators. CQT alumni have founded a further two start-ups in quantum technologies. Read more on pp.22–24.

#### 1 Memorandum of Intent

CQT agreed to work with the Infocomm Media Development Authority (IMDA) to promote the development of quantum technologies, particularly quantum key distribution, in Singapore. Read more on pp.20-21.

## 2 Evening talks

Over 100 people came for two evening events on quantum computing, held in March and November. These paired CQT researchers with representatives from start-ups and industry, including speakers from Google and IBM, for talks and panel discussions. We

![](_page_20_Picture_8.jpeg)

![](_page_20_Picture_9.jpeg)

organised the November event in partnership with SGInnovate, a Singapore-government backed organisation fostering deep tech, as the first of a series of events on quantum technologies.

## **Conference presentations**

CQT Principal Investigators are increasingly bringing their expertise to technology conferences. In 2018, for example, Joseph Fitzsimons spoke at EmTech Asia and the Deep Tech Summit, and Alexander Ling presented at GovernmentWare, all in Singapore.

![](_page_20_Picture_13.jpeg)

## 2 Training workshops

Some 100 delegates attended a Quantum-Safe Industry Workshop we organised with IMDA and another 20 came to learn about quantum computing in a workshop at the Internet of Things Asia 2018 conference.

#### Exhibition

CQT exhibited by invitation at the inaugural Singapore Defence Technology Summit, attended by some 400 delegates from around the world.

![](_page_20_Picture_18.jpeg)

#### 20+ /isits

We are building awareness and understanding of quantum technologies with companies and government agencies through oneon-one meetings. These conversations may seed future collaborations.

It falls within CQT's mission to do scientific outreach, engaging with the public and school students to explore the concepts of quantum physics and the potential impacts of quantum technologies.

## 250 Student visitors

We hosted both local and international students for visits, including 150 school students who came for lab tours during the NUS Physics Enrichment Camp, and 40 students who enrolled for CQT's own Q Camp offering a week's immersion in quantum technologies. Q Camp is organised and taught largely by the Centre's PhD students and postdocs.

![](_page_20_Picture_24.jpeg)

## 3 Cultural projects

We support science as culture, reaching new audiences through collaboration with the arts. In 2018. CQT contributed to an exhibition at Singapore's ArtScience Museum (see pp.25-26), was a partner for the theatre production 'Golden Record

![](_page_20_Picture_27.jpeg)

2.0' in the NUS Arts Festival and continued to run the Quantum Shorts competitions for quantum-inspired flash fiction and short films.

## 2 Public talks

CQT Principal Investigators were speakers at an 'ApéroScience' on quantum technologies organised by the office of the French Centre for Scientific Research (CNRS) in Singapore in January and at the Pint of Science Festival, held for the first time in Singapore in 2018, in May.

![](_page_20_Picture_31.jpeg)

#### OUTREACH

## 50+ Media mentions

CQT research or researchers were mentioned more than 50 times in media outlets during 2018. Significant coverage included a segment on quantum technologies in the hour-long documentary 'Singapore Reimagined' that aired on Channel News Asia, giving a stock-take of the country's smart nation initiative.

## 48k+ Online reach

Up-to-date information about CQT activities is shared through the Centre's website, social media and newsletters. The website received some 48,000 unique visitors during 2018, CQT's YouTube channel was watched for almost 3,000 hours, and the Centre has begun posting to LinkedIn as well as Facebook and Twitter, with a combined following across the platforms of 9,000 users.

![](_page_20_Picture_40.jpeg)

#### MONEY MATTERS

## Expenditure in 2018

	Manpower	Equipment	Other	Total
Core Funding	9,906,935	5,730,885	8,382,408	24,020,228
Competitive Grants	2,428,642	1,259,389	2,000,793	5,688,824
Total	12,335,576	6,990,274	10,383,201	29,709,052

#### 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 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 and Singapore University of Technology and Design receive additional support from their institutions.

#### **Competitive grants**

CQT researchers also compete for grant funding. In 2018, the Centre's active grants include awards from the Ministry of Education, the National Research Foundation and Agency for Science, Technology and Research, all in Singapore. Some CQT research is funded through the NUS-Singtel Cyber Security R&D Lab, a corporate research laboratory, and NUS competitive funds. International grants come from sources including the Foundational Questions Institute, the John Templeton Foundation and the Air Force Office of Scientific Research.

#### Thanks to our supporters

![](_page_21_Picture_8.jpeg)

![](_page_21_Picture_9.jpeg)

SINGAPORE UNIVERSITY OF

TECHNOLOGY AND DESIGN

![](_page_21_Picture_10.jpeg)

Q Upcoming events:

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

Q Jobs:

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

![](_page_21_Picture_17.jpeg)

![](_page_21_Picture_18.jpeg)

MajuLab

![](_page_22_Picture_0.jpeg)

![](_page_22_Picture_1.jpeg)

Centre for Ouantum Technologies

![](_page_22_Picture_3.jpeg)

Centre for Quantum Technologies

National University of Singapore S15-03-18 Science Drive 2 Singapore 117543