annual report 2017

Centre for Quantum Technologies

CONTENTS

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LETTER FROM THE DIRECTOR

CQT is ten years old and still going strong. Well-wishers who gathered for our tenth anniversary offered both compliments and advice. "Wah, from zero to hero, lah" commented an old friend after visiting our labs. Ten years ago, he saw just empty rooms and dusty floors. "Don't stop, even at the top", quipped another high-ranking friend. I was not sure how to interpret this aspirational suggestion, so I just smiled and mumbled. After all, where is the top? The field of quantum technologies has expanded so much that no single institution can embrace the whole range of activities under this label. This said, we do have our niche. In 2017, like in years before, we've amassed quality publications and ingenious devices, so ticking all the boxes in our performance reviews. But there is more to our mission than just dry bibliometrics. This annual report offers a glimpse of the fascinating work behind the numbers.

To start with, we've built a vibrant research community (pp.20–21). We attract talented folk from all over the world to spend hours trapping ions or gazing at whiteboards covered with equations. Truth be told, we do more than welcome quantum nerds, we nurture them.

Our popular Generation Q Camp for pre-university students (pp.50–53) is designed to educate and inspire young minds. Our PhD and internship programmes draw some of the brightest students. And when they leave CQT with their hard-earned degrees, they do all kinds of interesting things, quantum and classical (pp.58–59).

Last year saw the usual buzz of experimental and theoretical activities. We welcomed Huanqian Loh and Travis Nicholson, our two new Principal Investigators (pp.40–41), and Charles Lim, a new CQT Fellow. Alexander Ling's group has been working hard on their new experimental marvel called SpooQySat (pp.45–49). Dimitris Angelakis' team paired with researchers at Google to work on quantum simulations (pp.32–35). Our study of the potential impact of quantum technology on Bitcoin made the news (pp.36–39) and our proposal for a quantum-safe standard for cryptography was accepted into a competition launched by the US National Institute of Standards and Technology. And we have not neglected basic research; Goh Koon Tong, a PhD student in Valerio Scarani's group, gives a nice review of work on quantum self-testing (pp. 42–44). This is just a small sample of what we're working on.

Even though still viewed as basic research, quantum technology is too important to be ignored by industry. Through interactions with research organisations, government and industry, we hope to create new intellectual property and new markets (pp.54–57). We also pay attention to explaining our research to the public at large (pp.74–75).

Thus, so far so good. How about the future? We have to both consolidate and innovate. Mr Quek Gim Pew, who became Chair of CQT's Governing Board in 2016, shares some of his thoughts on these issues in an interview (pp.15–17). Given his knowledge and experience, he is in a unique position to offer guidance from which we hope to benefit in years to come.

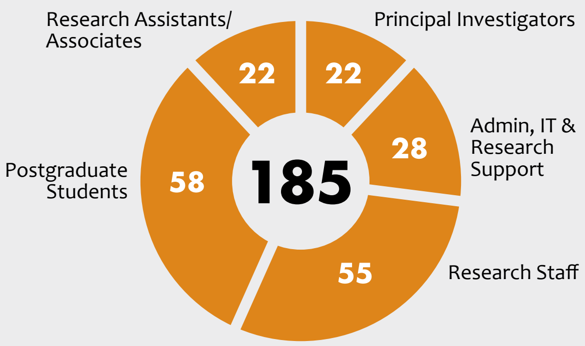
Last but not least, let me thank everyone who contributed to this report. I do hope you will find it both interesting and informative.

Artur Ekert

Photo: Tan Ngiap Heng 2007

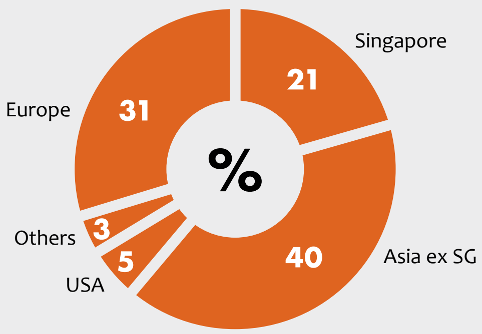
CQT AT A GLANCE

Headcount



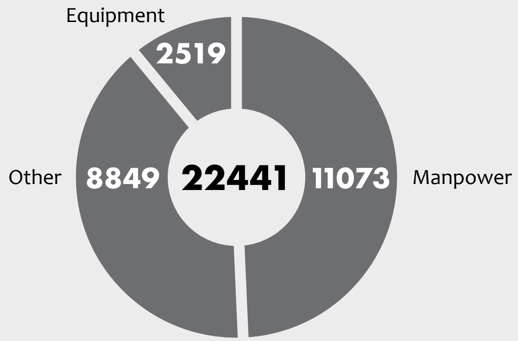
Count of CQT staff and students as of 31 December 2017. In addition, the Centre has 25 visiting staff.

Nationalities



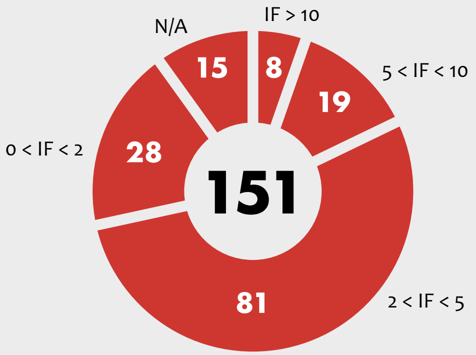
Nationalities of all research staff, admin staff and students employed in 2017.

Budget



Spending over the 2017 calendar year. Singapore $K. See p.79 for details.

Publications



Publications during 2017 by journal impact factor (IF).

The Centre for Quantum Technologies (CQT) is a national Research Centre of Excellence (RCE) in Singapore. It brings 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 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.

In 2017, CQT expanded on the NUS campus from its base in science block S15 into the adjacent block S14 (pictured), connected by a sky bridge. The renovated space accommodates two new experimental groups (see pp.40–41) and researchers contributing to the NUS–Singtel Cyber Security R&D Lab.

PEOPLE

Governing Board

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

Nicholas Bigelow
Professor of Optics, The Institute of Optics, University of Rochester

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

George Loh
Director (Programmes Directorate), National Research Foundation, Singapore

Tan Eng Chye
Deputy President (Academic Affairs) and Provost, National University of Singapore

Vincent Wu
Director, University Policy and Research, Academic Research Division, Higher Education Policy Division, Ministry of Education, Singapore

Chang Yew Kong
Chairman, Industry Advisory Committee (Information and Communications Technology), Singapore Institute of Technology

Ho Teck Hua
Tan Chin Tuan Centennial Professor and Deputy President (Research and Technology), National University of Singapore

Lui Pao Chuen
Advisor, National Research Foundation, Singapore

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

Scientific Advisory Board

Ignacio Cirac
Max-Planck-Institut für Quantenoptik

Atac Imamoglu
Institute of Quantum Electronics, ETH Zürich

Klaus Mølmer
Institute of Physics and Astronomy, University of Aarhus

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

The GB listing reflects members as of 31 December 2017. CQT thanks Serguei Beloussov, CEO of Acronis, who completed his term in November. We note there will be changes to the representatives of the National University of Singapore in 2018 as Tan Eng Chye becomes NUS President and Ho Teck Hua becomes Senior Deputy President and Provost.

Principal Investigators

Divesh Aggarwal
Computer Science

Other appointments: Assistant Professor, Department of Computer Science, National University of Singapore

Dimitris G. Angelakis
Theoretical Physics

Other appointments: Associate Professor, School of Electronic and Computer Engineering, Technical University of Crete, Greece

Murray Barrett
Experimental Physics

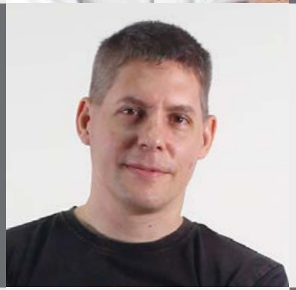
Other appointments: Associate Professor, Department of Physics, National University of Singapore

Kwek Leong Chuan
Theoretical Physics

Other appointments: Associate Professor, National Institute of Education and Deputy Director, Institute of Advanced Studies, Nanyang Technological University, Singapore

Kai Dieckmann
Experimental Physics

Other appointments: Associate Professor, Department of Physics, National University of Singapore



Rainer Dumke
Experimental Physics

Other appointments: Associate Professor, School of Physical & Mathematical Sciences, Nanyang Technological University, Singapore

Berge Englert
Theoretical Physics

Other appointments: Professor, Department of Physics, National University of Singapore

Joseph Fitzsimons
Computer Science

Other appointments: Assistant Professor, Engineering Product Development, Science and Math, Singapore University of Technology & Design

Rahul Jain
Computer Science

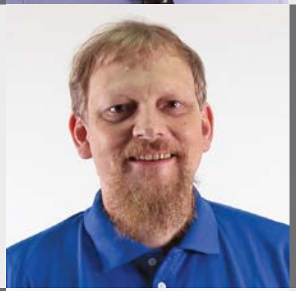
Other appointments: Associate Professor, Department of Computer Science, National University of Singapore

Dagomir Kaszlikowski
Theoretical Physics

Other appointments: Associate Professor, Department of Physics, National University of Singapore

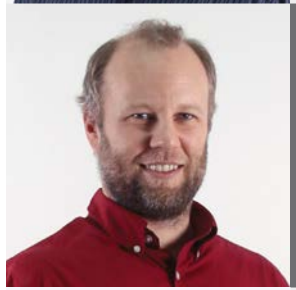
Hartmut Klauck
Computer Science

Other appointments: Assistant Professor, School of Physical & Mathematical Sciences, Nanyang Technological University, Singapore



Christian Kurtsiefer
Experimental Physics

Other appointments: Professor, Department of Physics, National University of Singapore



Troy Lee
Computer Science

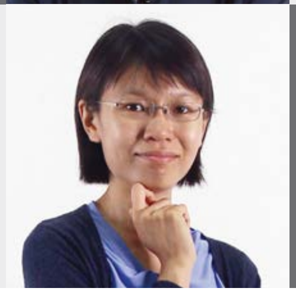
Other appointments: Associate Professor, School of Physical & Mathematical Sciences, Nanyang Technological University, Singapore

Wenhui Li
Experimental Physics

Other appointments: Assistant Professor, Department of Physics, National University of Singapore

Alexander Ling
Experimental Physics

Other appointments: Assistant Professor, Department of Physics, National University of Singapore



Loh Huanqian
Experimental Physics

Other appointments: President's Assistant Professor, Department of Physics, National University of Singapore

Principal Investigators

Dzmitry Matsukevich
Experimental Physics

Other appointments: Assistant Professor, Department of Physics, National University of Singapore

Manas Mukherjee
Experimental Physics

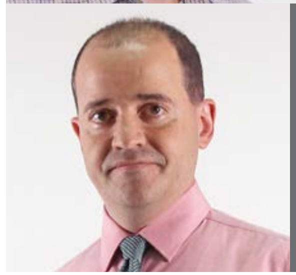
Other appointments: Assistant Professor, Department of Physics, National University of Singapore

Travis Nicholson
Experimental Physics

Other appointments: Assistant Professor, Department of Physics, National University of Singapore

Miklos Santha
Computer Science

Other appointments: Senior Researcher at CNRS in the Institut de Recherche en Informatique Fondamentale at the University Paris Diderot, France



Valerio Scarani
Theoretical Physics

Other appointments: Professor, Department of Physics, National University of Singapore

Vlatko Vedral
Theoretical Physics

Other appointments: Professor, Department of Physics, National University of Singapore and Professor, University of Oxford, UK

CQT Fellows

Benoit Gremaud
Theoretical Physics

Other appointments: Researcher at CNRS and Visiting Associate Professor, Department of Physics, National University of Singapore

Lim Ci Wen Charles
Theoretical Physics

Other appointments: Assistant Professor, Department of Electrical & Computer Engineering, National University of Singapore

Oh Choo Hiap
Theoretical Physics

Other appointments: Emeritus Professor, Department of Physics, National University of Singapore

Assistant Professor
Ng Hui Khoon

Research Assistant Professor
Mile Gu

Lee Kuan Yew Postdoctoral Fellows
Matthias Steiner
Tan Ting Rei

Senior Research Fellows
Alessandro Cere
James Grieve
Martin Kiffner
Gleb Maslennikov
Tan Si-Hui
Thibault Thomas Vogt

Research Fellows
Davit Aghamalyan
Kyle Arnold
Filip Auksztol
Bai Xueliang
Shrobona Bagchi
Tiago Batalhao
Robert Bedington
Cai Yu
Rakhitha Chandrasekara
Andy Chia
Dai Jibo
Michele Dall'Arno
Swarup Das
Debashis De Munshi
Tommaso Demarie
Kadir Durak
Tarun Dutta
Andrew Garner
Alexander Glaetzle
Christian Wolfgang Ernst Gross
Michal Hajdusek
Han Rui
Han Yunguang
Ho Shen Yong
Christoph Hufnagel
Md. Tanvirul Islam
Ravi Kumar
Sunil Kumar
Lam Mun Choong Mark
Le Phuc Thinh
Han-Hsuan Lin
Nana Liu
Liu Peiliang
Alexander Lohrmann
Juan Miguel Arrazola Mantilla
Debasis Mondal
Stefan Nimmrichter
Yingkai Ouyang
Sambit Bikas Pal
Chithrabhanu Perumangatt
Poh Hou Shun
Anupam Prakash
Mohamed Riadh Rebhi
Ansis Rosmanis
Arpan Roy
Junghee Ryu
Shabnam Safaei
Swagato Sanyal
Jamie William Jonathon Sikora
Tan Peng Kian
Jayne Thompson
Martin-Isbjörn Trappe
Maria Martinez Valado
Victor Manuel Bastidas Valencia
Antonios Varvitsiotis
Letizia Ventura
Wang Yukun
Naqueeb Ahmad Warsi
Wei Zhaohui
Wenhua Yan
Yu Deshui
Yu Wing Chi
Yum Dahyun
Zheng Yicong

Research Associates
Chng Mei Yuen, Brenda
Karthik Ilangovan
Yau Yong Sean

Research Assistants

Chau Thanh Tri
Chen Miaoqing
Chong Li Ming
Phua Sing Cheng Jasper
Kho Zhe Wei
Andrew Laugharn
Lei Yisheng
Lew Wai Cheong Lincoln
Li Weijun
Lim Zheng Jie Janet
Ng Kian Fong
Nguyen Hong Nhung
Nguyen Thi Phuc Tan
Robert Pisarczyk
Christine Lydia Satter
Shi Yicheng
Soe Moe Thar
Arian Stolk
Tan Senmao
Tan Yue Chuan
Tay Chun Mei
Varun Raj
Yuen Gin Hao

PhD Students

Anurag Anshu
Filip Auksztol
Phyo Bawse
Kishor Bharti
Naresh Goud Boddu
Ulrike Bornheimer
Sofia Botsi
Chai Jing Hao
Rakhitha Chandrasekara
Wilson Chin Yue Sum
Swarup Das
Aswin Alexander Eapen
Jaren Gan
Gan Koon Siang
Sanjib Ghosh
Goh Koon Tong
Kevin A. Gregory
Gu Yanwu
Roland Hablutzel
Han Jingshan
Tobias Florian Haug
Hermanni Heimonen
Alexander Hue
Rattakorn Kaewuam
Joshua Kettlewell
Srijita Kundu
Lam Mun Choong Mark
Alessandro Landra
Lee Jianwei
Len Yink Loong
Frederic Leroux
Lim Chin Chean
Liu Zheng
Maharshi Ray
Atul Mantri
Priyanka Mukhopadhyay
Ewan Munro
Debashis De Munshi
Nguyen Chi Huan
Wei Nie
Oon Fong En
Mikolaj Paraniak
Jung Jun Park
Ignatius William Primaatmaja
Erick Purwanto
Jiaan Qi
Alexandre Roulet
Seah Yi-Lin, Max
Stella Seah
See Tian Feng
Mathias Alexander Seidler
Shen Lijiong
Shi Yicheng
Angeline Shu Sze Yi
Sim Jun Yan
Suen Whei Yeap
Aarthi Sundaram
Tang Zhongkan Kamiyuki
Tang Zong Sheng
Jirawat Tangpanitanon
Thi Ha Kyaw
Francesca Tosto
Adrian Nugraha Utama
Noah Van Horne
Marek Wajs
Yang Anbang
Yang Siyi
Ye Luyao
Yu Xianquan
Aitor Villar Zafra
Zhang Zhiqiang
Zhao Liming
Zhao Zhikuan

Visiting Staff

Luigi Amico
Itai Arad
John Baez
George Batrouni
Chen Jingling
Tristan Farrow
Rosario Fazio
Dmitry Gavinsky
Peter Hanggi
Masahito Hayashi
David Hutchinson
Gabor Ivanyos
Dieter Jaksch
Antoine Joux
Pawel Kurzynski
Antia Lamas-Linares
Jose Ignacio Latorre
Chiara Marletto
Serge Massar
Christian Miniatura
Robert Taylor
Thomas Vidick
Sai Vinjanampathy
David Wilkowski
Yu Sixia

Research Affiliates

Iordanis Kerenidis
Lisa Raphals
Hoeteck Wee

Research Support

Cheng Too Kee Cliff
Bob Chia Zhi Neng
Mohammad Imran
Lian Chorng Wang
Dileej Radhakrishnan Nair
Ren Yaping
Teo Kok Seng
Akimov Volodymr

Administrative Staff

Artur Ekert (Director)
Lai Choy Heng (Deputy Director)
Kuldip Singh (Admin Director)
Chan Chui Theng
Giam Lay Enn Kelly
Jessie Ho
Jenny Hogan
Aki Honda
Valerie Hoon
Lim Ah Bee
Lim Fang Eng Jacky
Lim Mei Yin, Valerie
Lim Mui Lian Amell
Lim Siew Hoon
Lum Chune Yang
Resmi Poovathumkal Raju
Tan Ai Leng, Irene
Evon Tan
Tan Lay Hua
Toh Lee Yen, Yvonne
Yeo Kwan San Timothy

This listing includes all staff and students who worked at CQT during 2017, including those who left during the year. Names may appear twice when someone moved roles. It includes staff employed by the National University of Singapore (NUS), Nanyang Technological University (NTU) and Singapore University of Technology and Design (SUTD) who are part of CQT research groups. The PhD students listing includes students at CQT under the CQT PhD programme, other NUS graduate programmes, and from NTU and SUTD.

Alumni

Over the course of a decade, the Centre's alumni have grown into a crowd. More than 400 researchers, students and interns have been part of or affiliated with CQT since the Centre began. When CQTians leave, we ask if they'd like to stay in touch: departing colleagues who give us a way to contact them receive invites to our events. We also ask leaving staff and students what jobs they are going to next – the figures to the right are gathered from their answers.

PhD students

- By the end of 2017, 54 students had completed their PhDs under the CQT programme
- 44 students moved into another academic position, such as a postdoc role, after graduating
- 2 immediately took jobs in industry or government (others took industry jobs after working as a postdoc)
- 44 % of students took their next job in Singapore

Research Fellows

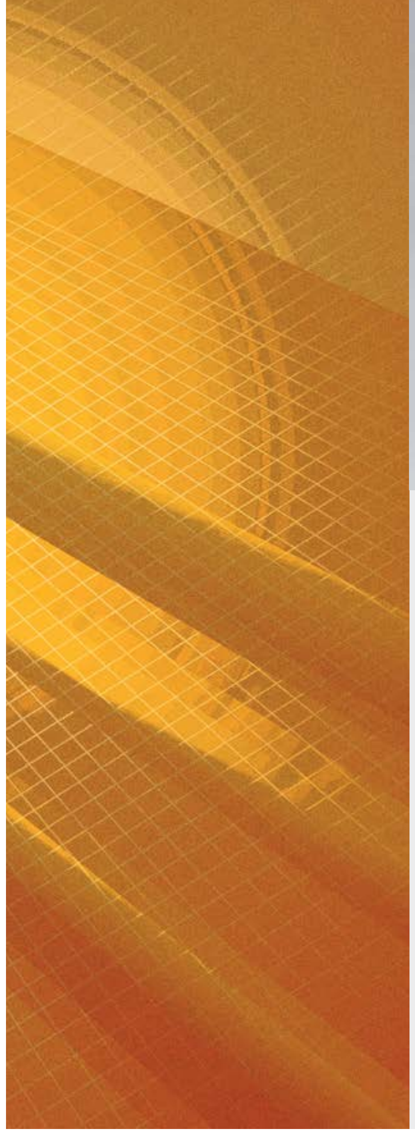
- CQT has around 130 former Research Fellows and Senior Research Fellows among its alumni
- At least 90 of these departing staff found another job in academia
- 10 alumni moved into science-related industry, with others taking jobs in areas including financial services, management consulting and telecommunications.

An alumnus' story

Paul Condylis was a Research Fellow in experimental groups in CQT for over six years. He joined a Singapore-based technology company called Jewel Paymentech in October 2017 as Lead Research Scientist. The company works on digital payments, delivering anti-fraud and compliance solutions. "I lead a team to develop deep learning and machine learning models to understand text documents, classify images, and identify fraudulent transactions," says Paul. He wanted to move into industry to have scope to climb a career ladder, and found the job with Jewel Paymentech through an advert on LinkedIn. "An experimental physicist must have a good understanding of data, statistics, data analysis, and computer programming, amongst other skills, which are the same skills that are required for a data science role. The grounding of a physics education gives you the ability to read and understand the current literature in AI, and then apply those techniques," says Paul. "Moving from experimental physics into data science and AI was easy due to the skills I acquired as a researcher".

Read about some of the Centre's alumni who have continued in research on pp.20–21 and find examples of graduates' career paths on pp.58–59.

PERSPECTIVES



In quantum technologies, tremendous potential

Mr Quek Gim Pew, Chief Defence Scientist at the Singapore Ministry of Defence, became Chair of CQT's Governing Board in November 2016. He shares his views one year into the job.

What do you do as CQT's Chair?

The Centre is well run, in the administration and the scientific research, so what is important for me is really to look at the bigger picture and the longer term. I have spent time over the past year trying to understand better the situation inside CQT, in the context of the National University of Singapore and at the national level. Going ahead, how best should we position CQT as a national research centre? How will we grow our resources and benefit the rest of the universities, economy and country as a whole? These are questions that are also very much in the mind of CQT's Director, Artur Ekert.

What are the directions you think the Centre should develop?
My sense is that, as Singapore is a small county with limited resources, there are a few things we should be clear about. I think without a solid foundation and deep expertise in the science, there is no basis for us to compete. I think we should firmly anchor ourselves in the science.

There are a few more things we should do. On the international level, if you look over the past year, I think you see a phenomenal increase in interest across the world, in the US, in Europe, and in China. So for us, I think a challenge is to continue to attract and maintain the talents that we have, and compete with all these places where they offer wonderful opportunities.

At the national level, today we are seeing pockets of quantum expertise and interest growing in other places, whether it's in other universities or in A*STAR. I think we should find a way to harness the collective resources that we have, to synergise what we have, to move forward as a nation. CQT is in a healthy position to play some form of leadership role in this.

Another thing that I've been trying to get a handle on is how to interest and attract our engineering folk. If we can bring in resources from outside, I think it can help us to move forward. This is the reason we have been working with the National Research Foundation (NRF) on the Quantum Engineering Programme.

How do you see engineering will play a role?
If you look at the current problem of building a quantum computer, the engineering challenge vs the theoretical physics problem is probably much, much higher, but the engineering challenges are not necessarily going to be solved by engineers that are trained in the conventional discipline.

I visited Christopher Monroe, who co-founded the quantum computing startup IonQ, in the US. The biggest takeaway I had from the visit was that while one can say the quantum computer is largely an engineering challenge, when you look at the groups in IonQ, you find that what they need are experimental physicists.

The other co-founder of IonQ, Jungsang Kim, shared his insight that if you look at the history of the transistor, the early days, again it was led largely by experimental physicists. You cannot expect engineers who are trained in vacuum tubes to come in and help to develop a transistor. That comes later, after a whole generation of engineers are trained in solid state physics. So while we are bringing engineering into the programme, we've got to bear in mind that the expertise required is quite unique and specific.

If we want to grow quantum engineering, we have to have a good balance. We should make sure that we bring in very strong experimental physicists. Over the course of the programme, we will hopefully train up and build up a whole generation of engineering expertise, and from there we can grow.

How did your trip to IonQ come about?
I was in Washington so I asked Artur, since I'm there, is there anybody that I could visit. It was exciting to talk to leaders in this field, see their contraptions, and to hear about their progress and share how things would evolve. We hope that we can explore ways for IonQ to partner the universities and companies here.

You mentioned last year that you would be asking Artur for a reading list...
He has given me a number of books to read. I keep up with reading popular science and reports too. I will ask Artur for his comments, and he will send me some of the papers behind the news. There are so many claims out there in the world about what is being done. I always find it important to make a check back with CQT to make sense of what is reality, what is myth and what is fiction. I also make a point that whenever I go overseas, I check with Artur if there is anyone nearby to chat with.

Do you do this for all the technology areas you monitor?
Not as much. Quantum technologies are a lot more difficult to appreciate and understand. One reason I agreed to take on the job in CQT was because of the potential growth of the exciting technology here. It is mind-boggling, but the potential is tremendous.

From this year, is there any quantum news that stood out to you?
Well, yes! – this issue about whether quantum computing will allow us to securely use the cloud (see p.31). In time to come, I think this would open up new opportunities. The big news over the past year has been quantum computers. The prospect of a quantum computer in whatever form is going to challenge a lot of what we are doing and what we are thinking today and change what is possible and what is not possible. I am thinking about how we position ourselves in these exciting developments.

How do you see basic and applied research co-existing?
We are seeing a maturing of the science, and we are getting practical devices into the commercial space. Even now, we are seeing CQT spinning off companies, such as S-Fifteen. The fact that we are able to secure Singtel, a very hard-nosed commercial company, to take a close look, says a lot about how mature this technology is.

For those individuals in CQT who have the entrepreneur bug, who would like to spin off, I would like to see how we can encourage and work within the university's constraints and support structures to let them succeed.

> "CQT has shown how you can tap very esoteric science and bring it all the way to applications, without losing focus on the science."

There is always an emphasis to see how investment in R&D translates into economic growth and into social growth. But the investment in research is much longer term, and the creation of NRF and the Research Centres of Excellence including CQT is a very strong endorsement of the need for Singapore to invest in basic sciences.

In turn, I think the fact that we have been able to make so much progress over 10–15 years is a very powerful endorsement that the decision taken then was the right decision. CQT has shown how you can tap very esoteric science and bring it all the way to applications, without losing focus on the science. This is the challenge that we must bear in mind. We must not drop one at the expense at the other.

When the Centre was founded in 2007, I was a bit surprised that Singapore was prepared to invest in quantum technologies, one of those things that is so far out into the future. We must be very thankful to them for their vision, for the leap of faith.

About the author
Quek Gim Pew was appointed Chief Defence Scientist of the Singapore Ministry of Defence in 2016. Before this, he was the Chief Executive Officer of DSO National Laboratories for over 12 years. Other appointments he held in the defence technology community include Director of R&D at the Ministry of Defence and the Deputy Chief Executive (Technology) DSTA. He also sits on various boards of organisations, institutions and directorship of companies.

Peer review

Every year, the Centre is reviewed by its Scientific Advisory Board, comprising experts in quantum technologies from around the world.

In 2017, the SAB timed their visit for December, to coincide with CQT's tenth anniversary celebrations. The members of the SAB (see p.7) spent a week at CQT, meeting with Principal Investigators (PIs), research staff, students, visitors, senior staff, the Director and the Centre's Governing Board.

They conduct this peer review to offer feedback on the Centre's operations and science, submitting a report that summarises their findings (see box *The SAB says*) and makes recommendations. The recommendations fall in two parts: first a review of how the Centre responded to the SAB's recommendations of the previous year, then new sets of recommendations. Here we share some of the outcomes.

How we improved

A previous recommendation of the Board was that CQT should offer more advanced courses for graduates. The SAB noted that "Substantial steps were taken to address our recommendation". Courses included two lecture series coordinated by PIs but co-taught by Research Fellows – one on quantum information and cryptography, and another on convex optimisation and quantum information.

Among the new recommendations was that this initiative be expanded. "We suggest that the postdocs are given the opportunity to teach courses if they want to do so. Experience in teaching may be very valuable in their academic job search," the SAB wrote in its report.

Other past recommendations that concerned keeping an eye on the quality and number of student applications, maintaining a substantial visitor programme, and exposing students and postdocs to career opportunities in industry were also considered resolved.

What's still to do

Other areas still need our attention. The SAB had recommended in 2016 that CQT should consider new hires to bridge quantum computer science with many body physics or post-quantum cryptography, and to recruit scientists in the area of experimental solid state computing. These recommendations are reiterated in the 2017 recommendations.

CQT's experimental activities are strongest in atomic, molecular and optical (AMO) physics. The SAB observes in its report that "a research group working on solid state qubits and devices would also be in a position to interact with the AMO groups. Given the existing spectrum of expertise and interest, CQT has the potential to become a world leader in investigation of hybrid quantum systems".

Among the new recommendations, the SAB also suggested initiating an annual retreat for the Centre's PIs to encourage collaboration and strengthen discussions on long-term strategy. The members write "experience both at CQT and elsewhere shows that it is difficult to make up time for casual science discussions which typically incubate future collaborations". A retreat could be an opportunity that helps "PIs maintain close working relationships and brainstorm for new ideas together in order to develop long term visions for the center."

The week of the SAB visit is a period of intense scientific discussion, fuelled by coffee in the Centre's Quantum Cafe.

To bring the SAB up to speed on CQT's scientific achievements, each group presents a few posters on its latest results.

The SAB says

"The Center is well established. It is producing good science, with several highlights. Visible steps towards developing technology and making connections to local companies have been taken, which have resulted in the establishment of the first start-up company as well as a joint project with Singtel. CQT is offering excellent training for its PhD students, postdoctoral researchers, and research assistants. Furthermore, the Center is very visible through publications, presentations at conferences, a flow of guests, and the organization of conferences. It is conducting an excellent communications and outreach program with impact in Singapore and internationally."

Rise of the quantum island

Back in 2004, even before CQT was founded, the popular science magazine *New Scientist* ran a short piece on the quantum research happening in Singapore. They referred to it being the 'rise of the quantum island'. More than ever before, the country is living up to this promise.

CQT is a focal point of quantum research in Singapore, but it's not the only place it's happening. The quantum wave has spread, with research groups in other parts of the National University of Singapore, and at Singapore's other universities and research organisations, working on the topic.

In the wider world, the community is growing too. China in 2017 announced that it would build a $10 billion quantum research centre, Europe has committed €1 billion to a quantum flagship initiative launching in 2018, and the UK has a £270 million programme underway. There is also investment in industry – big tech companies are racing to develop quantum computers – and a plethora of start-ups. In March 2017, *The Economist* put quantum technologies on its cover.

It's a bright moment for quantum R&D. The local impact is that CQT researchers have new opportunities to collaborate and build partnerships. At the same time, CQT-trained researchers find new jobs they have the expertise to fill.

Quantum networks

In 2016, CQT became a founding member of the NUS–Singtel Cyber Security R&D Lab, a corporate laboratory supported by the National Research Foundation (NRF). CQT is contributing expertise on quantum-safe communication. It's a sign of the maturing of the local market for quantum technologies, and discussions to establish further partnerships are underway. Meanwhile, the Centre's researchers are already involved in joint projects with scientists across Singapore.

These collaborations have included projects between the groups of CQT's Berge Englert and Leonid Krivitsky at the Data Science Institute (DSI) of the Agency for Science Technology and Research (A*STAR).

Berge's group worked with Leonid's on methods to measure quantum states. A PhD graduate from Berge's team who'd worked on the project joined A*STAR after graduating. Also at DSI is another CQT PhD graduate, Victor Leong, hired as a Scientist.

"I was looking for a place where I could effectively apply the skills and knowledge gained throughout my PhD training. Interest in quantum technologies is rapidly growing at A*STAR and research efforts in these areas are being ramped up, so there are numerous opportunities to get things going," says Victor.

Indeed, in 2017, Leonid started a new collaboration with CQT's Murray Barrett as co-PI, funded by an A*STAR grant, to develop optical devices for coherent wavelength conversion of single photons emitted by trapped ions.

A benefit to such projects is being in close proximity. "It is easy to pop by to borrow lab stuff, or to simply meet people to discuss our current experiments and trade useful ideas," says Victor.

Back in NUS, Alexander Ling's group has collaborations with researchers in the NUS Centre for Advanced 2D Materials (CA2DM) and in the NUS Faculty of Engineering (FoE). The work with CA2DM has involved fabrication of novel, tunable waveguides (see p.26). In 2016, his group was inspired by a proposal from the group of Mankei Tsang in FoE for a super-resolution imaging technique, performing one of the first experiments in the world to demonstrate the new technique.

Further collaborations with colleagues in NUS FoE are getting underway. In 2017, the faculty recruited Charles Lim, an expert in the theory of quantum cryptography (read about one of his research results on p.29), as an Assistant Professor in the Department of Electrical & Computer Engineering. Charles got into the quantum field during his time as a physics undergraduate in NUS, when he did his final year project with CQT's Valerio Scarani in 2009. He now holds a co-appointment as a CQT Fellow.

A CQT diaspora

Other former members of CQT are helping to seed quantum communities, too. Former CQT Research Fellows Dario Poletti and Tomasz Paterek are both now Assistant Professors in Singapore universities. Dario is at the Singapore University of Technology and Design, and Tomasz at the Nanyang Technological University (NTU). Also at NTU is Mile Gu, who joined the university's School of Physical and Mathematical Sciences and the Complexity Institute after winning an NRF Fellowship in 2016. Mile retains an affiliation with CQT as a Research Assistant Professor in the CQT group of Vlatko Vedral.

Tomasz continues to collaborate with his CQT colleagues, resulting in co-authored papers on topics including quantum biology, the foundations of quantum mechanics and the statistics of quantum walks. Although originally from Poland, Tomasz wanted to stay in Singapore. "Once you're here it is hard to move out and leave the convenient organisation of many things," he says.

Singaporean Ng Hui Khoon, who has been affiliated with CQT since 2009, took a position at Yale-NUS College in 2013 as an Assistant Professor. She has a 25% appointment with CQT in the group of Berge Englert. "The joint affiliation has been very useful in providing a rich research environment for my own research group," says Hui Khoon.

And the benefits go both ways. Hui Khoon brings expertise in quantum error correction and fault tolerance, which are essential to proposals for universal quantum computers. "These are exciting times for quantum computing. We, meaning CQT and related institutes in Singapore, are well-placed to participate in it and even lead the Asian efforts," says Hui Khoon.

A thriving research community, with diverse expertise and wide networks of collaboration, is what will make Singapore not only a quantum island, but also a competitor in the quantum world.

NEWS

News in brief

CQT hosts Singapore's Deputy Prime Minister

Singapore's Deputy Prime Minister Mr Teo Chee Hean toured CQT on 26 September with a delegation from the National Research Foundation (NRF), Ministry of Education and Ministry of Finance. He also visited the Centre for Advanced 2D Materials, which neighbours CQT on the NUS campus. Professor Tan Chorh Chuan, President of the National University of Singapore, hosted the visit with CQT's Deputy Director Lai Choy Heng, Principal Investigators and staff. DPM Teo visited in his capacity as Chairman of NRF. CQT research projects highlighted during the visit included participation in the NUS–Singtel Cyber Security R&D Laboratory (pictured above) and an atomic clock being designed with the goal of being the world's most accurate.

PI cited for high citations

CQT Principal Investigator Vlatko Vedral was named a 2017 Highly Cited Researcher by Clarivate Analytics in November. Clarivate says: "Ranking in the top 1% by citations for field and publication year in Web of Science, Highly Cited Researchers are leading the way in solving the world's biggest challenges". Vlatko's research interests are in quantum information and the foundations of quantum physics. He has published research on topics including quantum thermodynamics, quantum biology and quantum gravity.

Celebrating CQT graduates

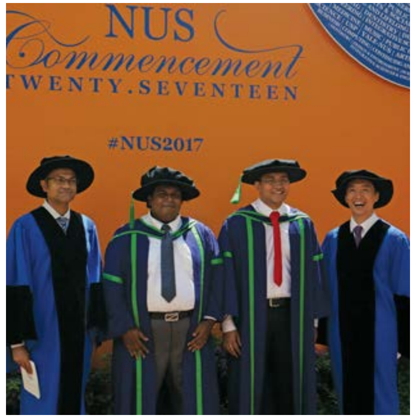
In 2017, eleven students in the CQT programme completed their PhD. Each has made a novel contribution to the sum of human knowledge – and acquired learning and skills that they are now ready to bring into the next stage of their careers. "It's a fantastic time to be working in quantum technologies," says CQT Director Artur Ekert. "Governments continue to see the value in supporting research in our field. At the same time, companies are expanding their quantum programs and we're seeing new startups. CQT's graduates will have many opportunities." Read more about CQT's graduate programme and graduating students on pp.58–61.

Boost for early-career CQT scientist

CQT Senior Research Fellow James Grieve was selected to take part in two prestigious conferences in 2017. In January, he was a participant in the Global Young Scientists Summit 2017 organised by Singapore's National Research Foundation for the "the world's outstanding PhDs and post-doctoral fellows under the age of 35". He also won a place at the Commonwealth Science Conference 2017, an event organised by the UK's Royal Society and NRF, in June. James has been working at CQT on quantum optics in the group of Alexander Ling since 2012.

Quantum Shorts on screen

"It was funny and fab". "Mind boggling and sets you thinking." "It was really unique to learn through the films." These are comments from visitors to the Quantum Shorts event organised by CQT with Singapore's ArtScience Museum in February. It was a screening over four days of ten short films inspired by quantum physics. The ten films were finalists in CQT's Quantum Shorts film festival, run with media partners *Nature* and *Scientific American*, and international scientific partners and screening partners. The ultimate winner was a film called *Novae* (by Thomas Vanz, pictured). Quantum Shorts is an annual competition for creative works with quantum themes – it returned in September 2017 with a call for flash fiction.



A conference that's Asian – and global

The 17th Asian Quantum Information Science (AQIS) conference came to the National University of Singapore 4–8 September, drawing over 100 researchers from the region and beyond. Although it has always been held in Asia, AQIS has developed a strong reputation among the international quantum information community and draws participants from around the world. The programme included eight invited talks, two invited tutorial talks, 46 contributed talks and 88 posters. The tutorial talks were given by Peter Høyer from the University of Calgary on "Quantum walks" and by Charles Bennett from IBM Research on "Forging the culture of quantum information science".

Complexity workshop brings fields together

The Workshop on Interdisciplinary Frontiers of Quantum and Complexity Science was held in January in Singapore as part of a project supported by the John Templeton Foundation. "At the outset, complexity and quantum science appear quite different. One commonly deals with networks of interacting systems on the macroscopic scale, while the other describes matter at the quantum mechanical level. Yet both fields seek to understand nature by studying how it fundamentally processes information," says Mile Gu, a project leader and meeting co-organiser. He is an Assistant Professor at the Nanyang Technological University and Research Assistant Professor at CQT. Some 45 scientists attended the event, which also featured a public talk at the Science Centre Singapore. Videos of all talks are online.

Director wins public honour

CQT's Director Artur Ekert was presented with the Public Administration Medal (Silver) in Singapore's National Day Awards on 9 August. He is one of 90 recipients of the Medal in 2017. It is presented for "outstanding efficiency, competence and industry". On the news, Artur said "I am glad that our joint effort to make Singapore a quantum island is noticed and recognised."

Collaborations in dance and music

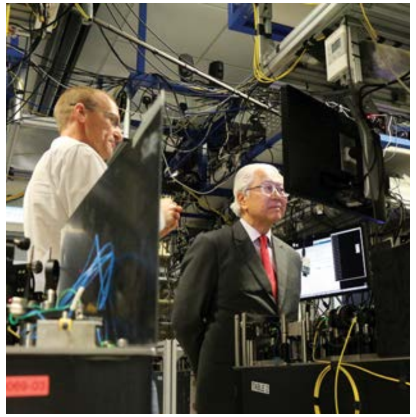
CQT was a creative partner for the NUS Arts Festival 2017: Brave New Worlds, continuing an association begun in 2016. The festival, held over two weeks in March, had an audience of some 10,000 people. CQT collaborated with NUS Indian Dance on *Sambhavna*, a full-length work that considered the movement of dancers (pictured on a visit to CQT) as particles, as well as taking a philosophical and historical look at the intersection of science and arts. CQT also supported the inclusion in the festival programme of *The Quantum Music Project* with LP Duo and Dragan Novkovic, an EU-funded collaboration of physicists, musicians and engineers. CQT researchers Vlatko Vedral and Andrew Garner are involved in the project. (Photo: Back Alley Creations)

We are 10

On 7 December 2017, CQT celebrated its tenth birthday. To mark the occasion, we held a two-day conference featuring distinguished invited speakers, contributed talks by alumni and posters from our community. The event followed a year-long survey of CQT's research achievements through colloquia delivered by CQT Principal Investigators. These talks, providing an introduction to some of CQT's major research directions, are available to watch on the Centre's YouTube channel. We also had artists from local company IdeaInk create sketchnotes of the talks. See pictures on pp.70–73.

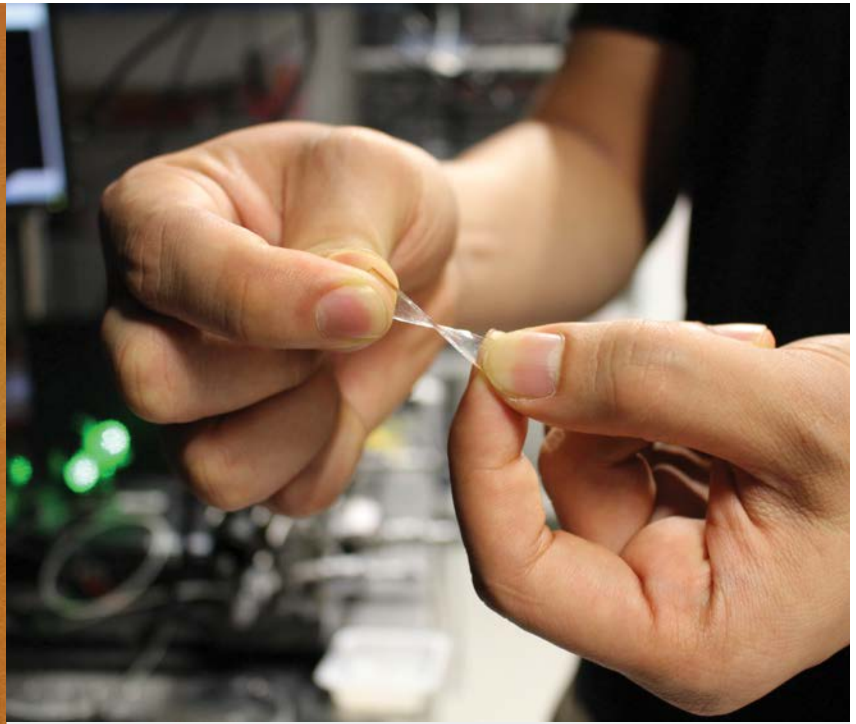
Former President Dr Tony Tan visits

Dr Tony Tan Keng Yam, President of Singapore 2011–2017, was instrumental in the founding of CQT. He was Chairman of Singapore's National Research Foundation when it created the Research Centres of Excellence programme, under which CQT was the first centre established. Dr Tan visited CQT on 10 November to see the progress made in the decade since. He was hosted by CQT's Director Artur Ekert. Speaking to CQTians at the end of his visit, he said "Under the direction of Artur and the senior management, all of you have made a great contribution to Singapore. I congratulate the CQT and all of you, and I hope you have many interesting problems to work with in the coming years."



NEWS

Science updates



Stretchy waveguides

CQT researchers have started building optical devices from an unexpected material: a polymer like that used to seal the edges of sinks. A big advantage is being able to tune the devices' behaviour by simply stretching or bending the flexible material.

"This research started out sounding like crazy talk and yet it worked," says Alexander Ling, the group's Principal Investigator. The team demonstrated a tunable beamsplitter created from polydimethyl siloxane (PDMS).

It offers a new approach to building integrated optical systems, for example for feeding light into optical fibers or for miniaturising lab experiments. Other groups had built waveguides in PDMS before, but without using the flexibility for tunability. The project was carried out with collaborators at the NUS Centre for Advanced 2D Materials and Graphene Research Centre.

Applied Physics Letters **111**, 211106 (2017)

When communication exceeds information

CQT PhD student Anurag Anshu collaborated in work presented at one of the world's top conferences in computer science. The work concerns how much communication it takes to complete certain tasks, compared to how much information the tasks involve. This relates to the idea of compression. Compressing a picture, for example, maintains the file's information content while minimising the communication needed to transmit it.

A few years ago, computer scientists discovered a task with an unexpected property: the task required very little information but took lots of communication to complete. "It's like the antithesis of what computer scientists want," says Anurag. He and his collaborators investigated whether similar tasks could exist with quantum communication, when bits can be entangled or exist in superposition. They found that even with such quantum powers there exist tasks that take exponentially more communication than information to complete. This shows a limit to what kind of message compression is possible in the quantum world.

STOC 2017 Proceedings of the 49th Annual ACM SIGACT Symposium on Theory of Computing DOI:10.1145/3055399.3055401 (2017)

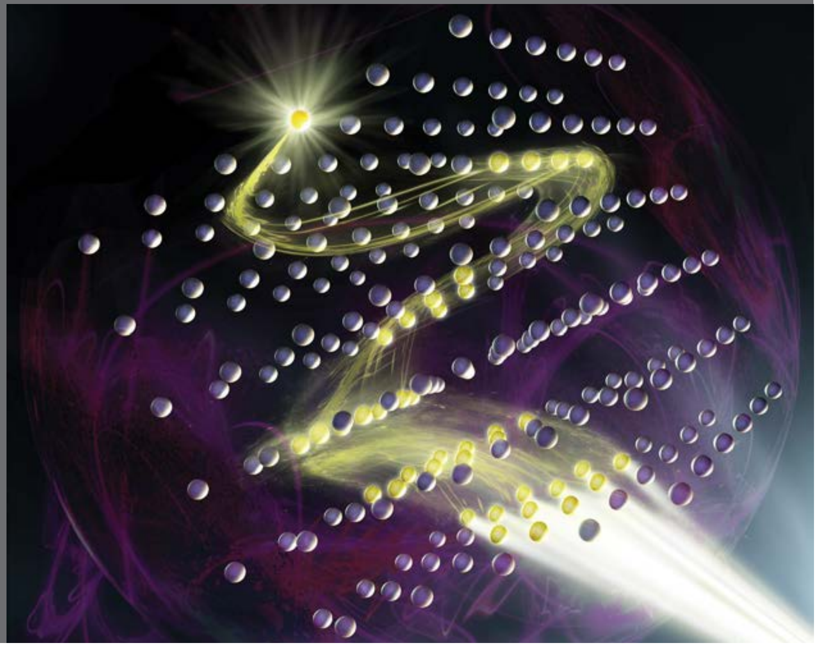
Spin lens for quantum information

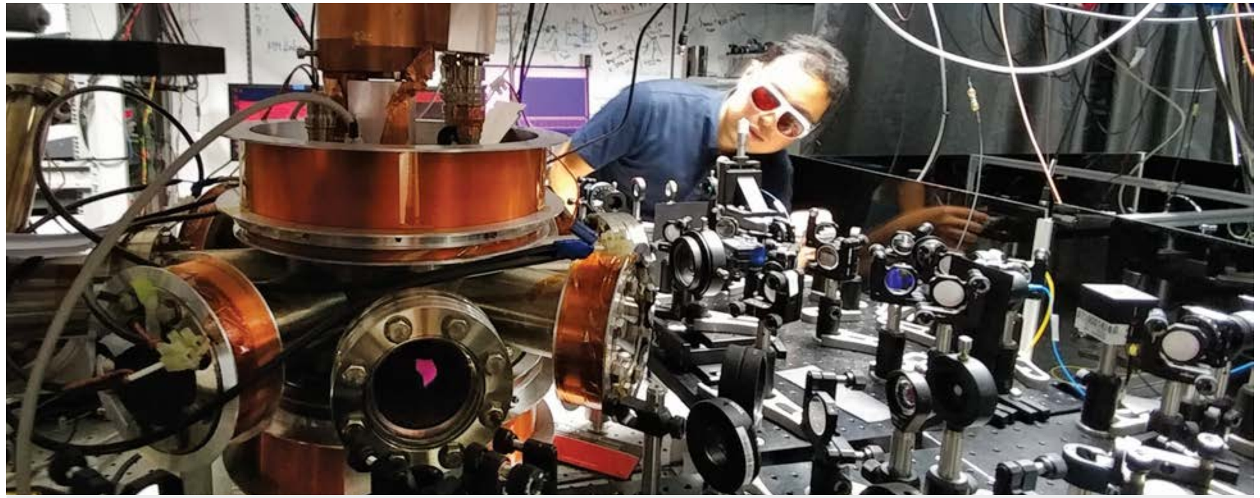
An international team including CQT Research Fellow Alexander Glaetzle proposed a scheme to help transfer information from light to matter, with potential applications in quantum networks and computing.

The team's innovation is showing how a cloud of atoms can work as a 'lens', focusing a light-induced excitation from a single photon into one or few atoms in the system. "Ultimately, the goal is to map photonic qubits with high efficiency onto single atoms, such that the well-developed quantum computing toolbox with single and two-qubit gates becomes available" says Alexander.

The physicists present several variants of their lenses, including multifocal ones, where a single delocalised spin excitation is transformed into a state with entanglement between excitations at spatially separated focal points. They simulate how these 'quantum spin lenses' could be implemented in arrays of Rydberg atoms, which are atoms in a highly excited state.

Physical Review X 7, 031049 (2017)





Barium qubit promising for telecoms

CQT Principal Investigator Manas Mukherjee and his team have built a barium ion quantum bit (qubit) that has fast operation speeds close to telecoms wavelengths. These qubits could be engineered into future quantum repeaters or other network elements that may integrate with existing optical fibre networks.

Barium ions interact with infrared light of wavelength 1762nm, which is just outside the telecom U-band. The team measured a barium ion flipping between its '0' and '1' states some 250,000 times per second, or 250 kHz. Previously the best performing barium qubit managed only 50kHz. The team credits new laser systems for their achievement. They designed their experiment to use diode lasers at 1762nm that have only become available in the past few years. Previous experiments used noisier fibre lasers. Another advantage of the all-diode design is that it could be miniaturised.

Journal of the Optical Society of America B **34**, 1632 (2017)

Quantum replicants to win on efficiency

"Humans have long been fascinated with the idea of replicating nature through machines" says CQT's Mile Gu. He is no exception: with collaborators, he investigated 'input-output processes', assessing the mathematical framework used to describe arbitrary devices that make future decisions based on stimuli received from the environment.

In almost all cases, the team found, a quantum device is more efficient than a classical device. That's because classical devices have to store more past information than is necessary to simulate the future. Co-author Jayne Thompson explains: "Classical systems always have a definitive reality. They need to retain enough information to respond correctly to each future stimulus. By engineering a quantum device so that different inputs are like different quantum measurements, we can replicate the same behaviour without retaining a complete description of how to respond to each individual question."

npj Quantum Information **3**, 6 (2017)

Record speed for QKD

Quantum key distribution (QKD) is a technique to exchange encryption keys for secure communication – but current QKD systems suffer from low secret key rates. It's enough to protect an organisation's most sensitive data, but demand could outstrip supply if the organisation wants to use QKD for all its data traffic. CQT Fellow Charles Lim and his collaborators demonstrated a QKD protocol that achieves a record speed of 26.2 megabits per second over the equivalent of 20km of optical fibre.

The trick to the team's success was using higher-dimensional quantum bits to distribute secret keys. The team adapt the 'prepare and measure' protocol. Secret bits are encoded in the arrival time of single photons, while measurements of the complementary phase states reveal any information leakage. "Our techniques have resolved some of the major challenges for high-dimensional QKD systems based on time-bin encoding, and could potentially be used for image and video encryption, as well as data transfer involving large encrypted databases," says Charles, who is also an Assistant Professor in the NUS Department of Electrical and Computer Engineering.

Science Advances
DOI:10.1126sciadv.1701491 (2017)

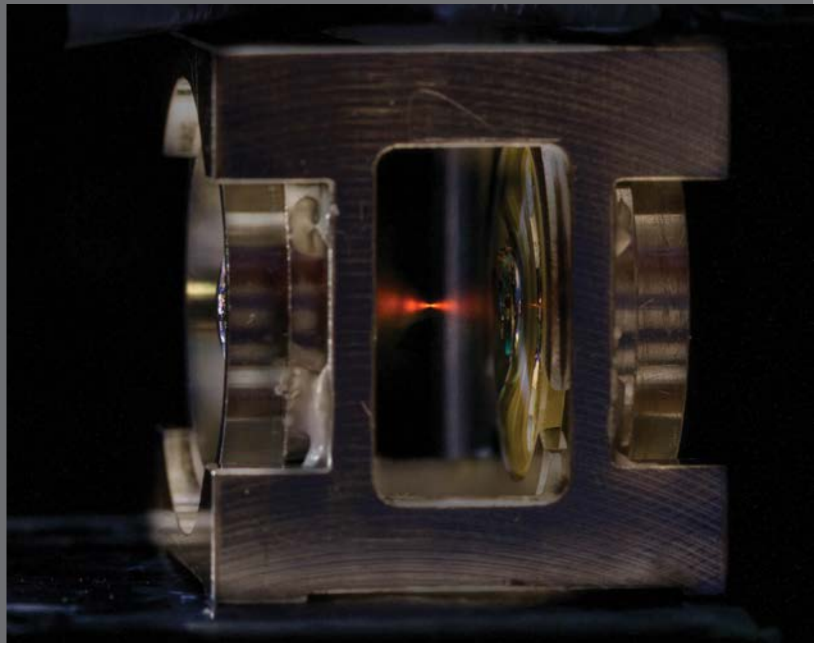
Lens trick doubles odds for interaction

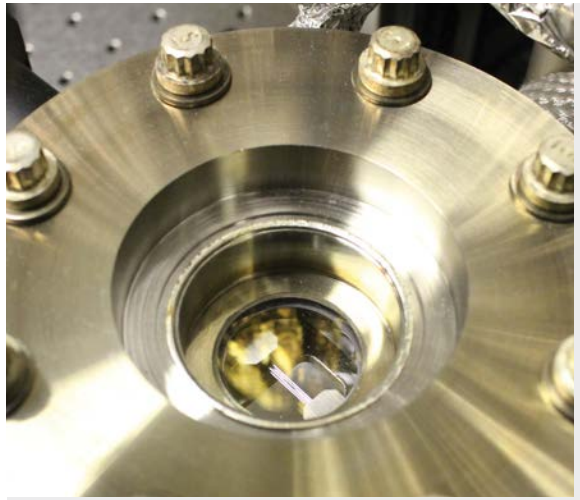
It's not easy to bounce a single particle of light off a single atom that is less than a billionth of a metre wide. However, researchers at CQT found a way to double the odds of success, an innovation that might be useful in quantum computing and metrology.

CQT's Wilson Chin Yue Sum, Matthias Steiner and Christian Kurtsiefer compared how much light a single Rubidium atom scatters when the light comes from just one direction, versus when it comes from two. When the atom was sandwiched at the focal point between two strongly-focusing lenses, it scattered red photons twice as effectively as when light came through just one lens. This double-lens configuration is borrowed from a super-resolution imaging technique known as 4Pi microscopy.

With this setup, the atom changed not only the photons' direction but also their spacing, which is evidence of nonlinear interaction. Nonlinear effects are crucial for processing information stored in light.

Nature Communications **8**, 1200 (2017)





Cross-Kerr nonlinearity in ions

"We have a very clean demonstration of an effect that people have been thinking about in optics for decades," says CQT's Dzmitry Matsukevich, who led research resulting in two papers in *Physical Review Letters*. One was featured as an Editor's Suggestion.

In optics, the Kerr effect is a change in the speed of light in a material because of the material's interaction with the light's electric field. The cross-Kerr nonlinearity arises when one light pulse affects the propagation of a second pulse. The CQT group saw an analogous effect between the two modes of vibration of two or three cold, trapped Ytterbium ions. The modes are axial and radial – vibrations along or out from a line. The group showed that vibrations in one mode can excite vibrations, phonons, in the second – a behaviour known as parametric oscillation. With the setup tuned differently, the team could also measure frequency shifts in one mode to count the number of phonons in the second. The technique offers new tools for experiments in quantum thermodynamics and quantum computing.

Physical Review Letters **119**, 150404 (2017)
Physical Review Letters **119**, 193602 (2017)

Qubit, qutrit, ququart

The dimension of a quantum system tells you how much information the system can store. A quantum bit, or qubit, has states equated with '0' and '1'. A qutrit is a three dimensional system with states '0', '1' and '2'. A ququart has four dimensions.

Accurate measurement is important for proper implementation of quantum communication and quantum computing protocols, but it turns out, said CQT's Valerio Scarani, that "there is a conceptual problem in how dimension witnesses are defined". The CQT team found that dimension witnesses cannot distinguish between a group of systems of low dimension and a truly, irreducibly, high-dimensional state. You could think of it like trying to assess a vehicle by counting wheels. The old witnesses couldn't tell two two-wheeled motorbikes apart from a four-wheeled truck. Having pointed out the problem, the team also proposed a witness that can detect irreducible dimension four.

Physical Review Letters **119**, 080401 (2017)

Cat protection

A thought experiment puts Schrodinger's cat into a superposition of alive and dead. According to work by CQT's Victor Bastidas and Dimitris Angelakis with collaborators in Germany, shaking it could keep it there.

The finding – which applies to cat states of atoms, spins and optomechanical resonators – is thanks to new maths for describing the interaction of a driven quantum system with its environment. The team found a way to simplify the equations describing the state, the environment and the driving potential.

Typically you expect a quantum state to 'decohere' when it's in contact with the environment – the information leaking out through interactions, until the quantum superposition is lost. Unexpectedly, these simplified equations show there exists an external driving potential that keeps the quantum state fixed, even as it interacts with the environment. Protecting quantum states in this way could be useful in quantum devices.

Physical Review Letters **117**, 250401 (2016)

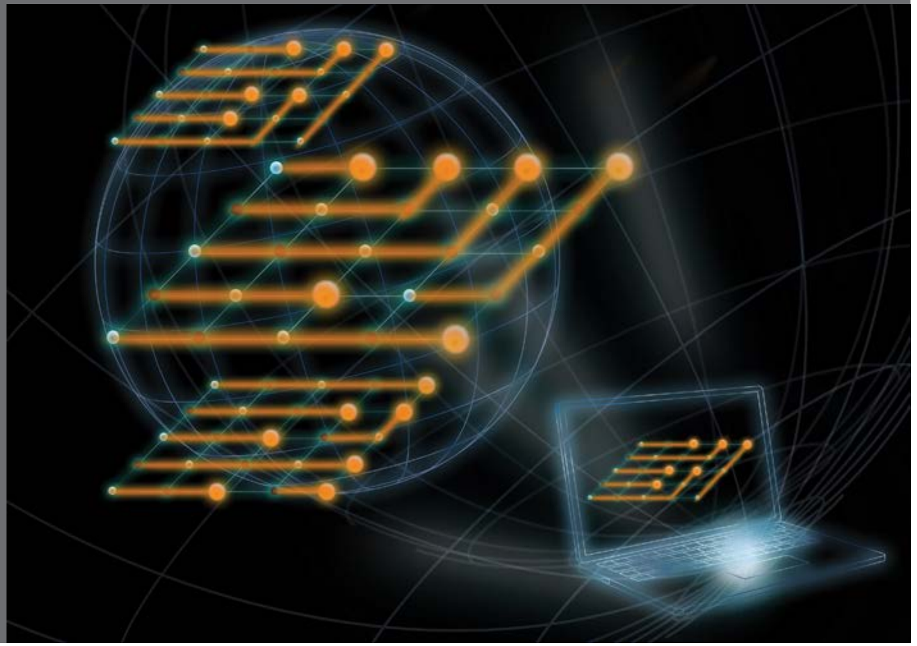
Security over the cloud

"Quantum computers became famous in the '90s with the discovery that they could break some classical cryptography schemes – but maybe quantum computing will instead be known for making the future of cloud computing secure," says Atul Mantri, a PhD student with CQT Principal Investigator Joseph Fitzsimons.

The researchers and their collaborators have proposed a way you could use a quantum computer securely, even over the internet. The technique could hide both your data and program from the computer itself. Researchers had previously shown that users who can make or measure quantum bits could disguise a computation performed on a remote quantum computer. Work in 2017 by Joseph, Atul and their collaborators extends that power to those who can only send classical bits – like someone using a quantum computer over the internet.

The scheme applies to a form of quantum computing driven by measurements. The hope for security comes from the quantum computer not knowing which steps of the measurement sequence do what: whether the measurements are inputs, operations or outputs. If the owner of the quantum computer tries to reverse engineer the sequence, this ambiguity leads to many possible interpretations of what calculation was done. The true calculation could be hidden among the many, like a needle in a haystack. "The set of all possible computations is exponentially large – that's one of the things we prove in the paper – and therefore the chance of guessing the real computation is exponentially small," says Joseph.

Physical Review X **7**, 031004



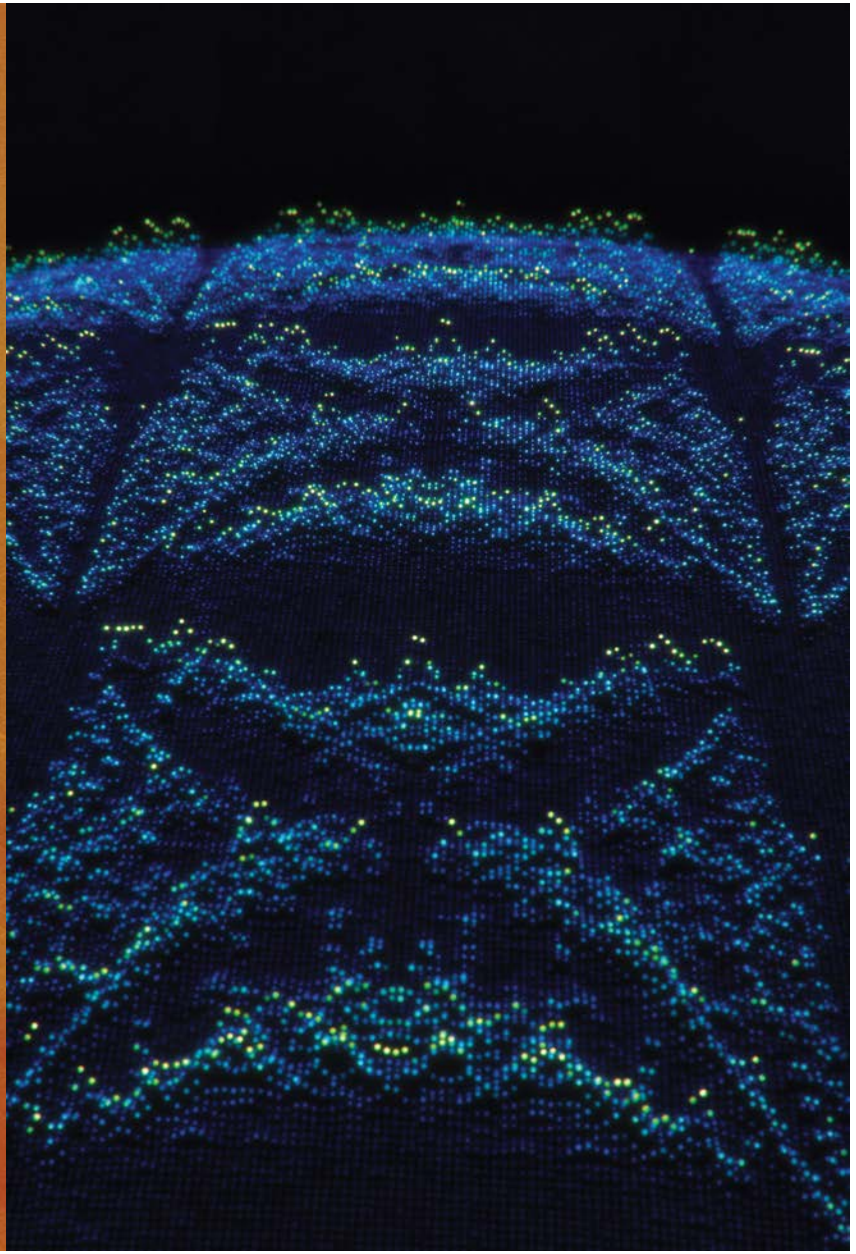


Image: Visual Science/Google

Quantum simulation on a superconducting chip

Dimitris Angelakis describes his collaboration with Google's quantum computing team, which led to a paper in Science

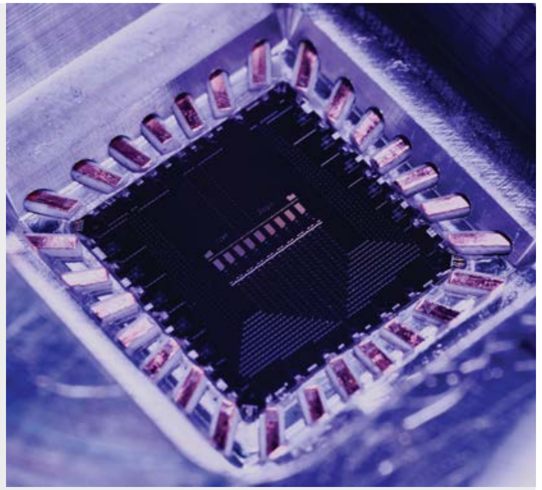


Photo: Erik Lucero, Google

When I submitted a proposal to join CQT back in 2010, the idea was to study what we can do with interacting photons for quantum simulations. This year, in collaboration with the scientists at Google building quantum chips, we've realised a simulation that sets a benchmark for the field.

Using a chain of nine superconducting quantum bits (qubits), we simulated the surprising and beautiful pattern of the 'Hofstadter butterfly', a fractal structure first predicted in 1976 to describe the behaviour of electrons.

We also studied the complex phenomenon of 'many-body localisation'. This is a quantum phase transition – akin to the phase change that happens when water freezes into ice – that determines whether materials are conductors or insulators.

My group members Jirawat Tangpanitanon, Victor Bastidas, and I collaborated with the group led by John Martinis at Google and the University of California, Santa Barbara (UCSB) to realise these experiments. The results were published 1 December in *Science*[1]. The simulated butterfly was reported by media including Singapore's *The Straits Times*.

How it all began

Ten years ago, people were already familiar with the idea of using atoms or ions to simulate physical problems, for example in material science, that may be hard to solve computationally. For example, today's computers struggle to calculate why some materials are insulators while others are conductors or superconductors.

The Nobel Laureate Richard Feynman had grasped this problem since the 1980s, suggesting that we could use a more controllable and perhaps artificial quantum system – a 'quantum computer' or 'quantum simulator' to study these systems.

The idea of using photons for a quantum simulator is newer. It was only in 2007 that I published the first paper proposing this approach. Initially, my plan at CQT was to build a theoretical framework to understand what is possible, but at the same time we tried to reach out to experimentalists to test our ideas.

Left: These quantum butterflies emerged from simulations performed on Google's quantum chop. They map how electron energy levels in a material would split and shift as an applied magnetic field gets stronger. A single, measured butterfly is multiplied here for artistic effect. The colour-coding of the dots comes from experimental data and shows the location of the energy levels. Energy increases in the forward direction and magnetic field increases along the horizontal axis. Top on this page: The picture is a photograph of a superconducting chip (area of entire chip: 1 cm^2) consisting of nine qubits in a 1D array. Microwave pulses are applied to control the states of the qubits and their interaction and control the dynamics in the system.

This took time. The first successful experiment for our group was in 2014 with collaborators in Germany. We've had to learn from attempts that didn't work – sometimes experiments were not tunable to the regime we needed – and find ways to adapt.

In 2015, I was invited to participate in a two-month programme at the Kavli Institute of Theoretical Physics at UCSB dedicated to this new field I helped to create, now known as Many-Body Physics with Light. The institute holds these focussed programmes to bring together people in hot topics. There is one talk per day with the rest of the time for interaction and collaboration. Jirawat and See Tian Feng, another of my PhD students, came with me.

In the last week of the programme, we met Pedram Roushan, who is a quantum electronics engineer with Google. We went through the early papers on simulations with photons to see what we might be able to do with Google's superconducting qubits. We had the idea to look at many-body localisation – and Jirawat started to look into the details (see box *A PhD contribution*). Later, Victor joined the project too.

As theorists, we participated by developing the proposal for the experiment and crunching the numbers on what we'd expect to see. We spoke or swapped emails frequently, sometimes every day. Pedram would help us with the time difference by talking at midnight his time from his lab. In the middle of 2016, we all met again at a conference I had organised in Greece on 'Quantum Simulation and Many-Body Physics with Light'. That's when we really nailed our plans.

Capturing the butterfly

Hofstadter's butterfly first appeared in calculations of electrons moving though a material in a magnetic field. The butterfly maps the splits and shifts of the electron's energy levels with changes in the field strength. We worked out how to simulate this by hitting the qubits on Google's chip with one photon at a time.

In the simulation, the photons take the role of the electrons while gates on the qubits provide an analogue of the magnetic field.

Our method is like hitting a bell. The sound it makes is a superposition of all the basic harmonics. By hitting it in different positions a few times and listening long enough, one can resolve the hidden notes. We do the same with the quantum chip, hitting it with photons and then following their evolution in time. The technique maps the energy levels of the photons stored in the nine qubits.

To study many-body localisation, we needed to hit the qubits with two photons simultaneously. We also needed the qubits to be disorderly, which we can get by programming some randomness into their properties.

It was predicted in the 1950s that disorder in a material could block the movement of particles through it. That's called localisation. If the particles can interact with each other, the problem becomes 'many-body' – and much harder to model.

In the localised phase, photons should get stuck in certain areas of the qubit chain. Quantum computers may one day exploit this effect to protect stored quantum information.

To carry out the experiments, Pedram had to tune the parameters on Google's 9-qubit chip. We didn't hear from him for a while, and then suddenly he sent data. We ran the experiment a few times, running different parameters, getting better data.

We found precursors of many-body localisation by applying our spectroscopy technique to different regimes of disorder and interaction. For just two photons in nine qubits, a conventional computer could simulate the behaviour we expect – these predictions were in good agreement with our results. But if we had a few more qubits – and there are already chips with some 20 qubits, and promises of 50 – the problem would become intractable for classical machines. That's when quantum simulators will come into their own.

This work feels like a culmination of my scientific existence in CQT, in the sense that it delivers on the proposal I first put forward ten years ago. We're thinking about what comes next. We have some interesting ideas for simulations of problems from physics, material science and biology. We are also looking at other areas like applications of quantum approaches in machine learning and big data. It's exciting to see the huge range of applicability of quantum simulators.

[1] P. Roushan *et al*, Spectroscopic signatures of localization with interacting photons in superconducting qubits, *Science* **358**, 1175 (2017)

About the author
Dimitris is a Principal Investigator at CQT and Associate Professor at the Technical University of Crete, Greece. His group works in quantum technologies with a focus in implementations of quantum computation and quantum simulation with quantum optical systems.

A PhD contribution

By Jirawat Tangpanitanon

To be an author on a *Science* paper, I am standing on the shoulders of giants. My supervisor Dimitris Angelakis has spent 15 years building his expertise in this field. I was a third year PhD student when we started this project, and this is only my second paper.

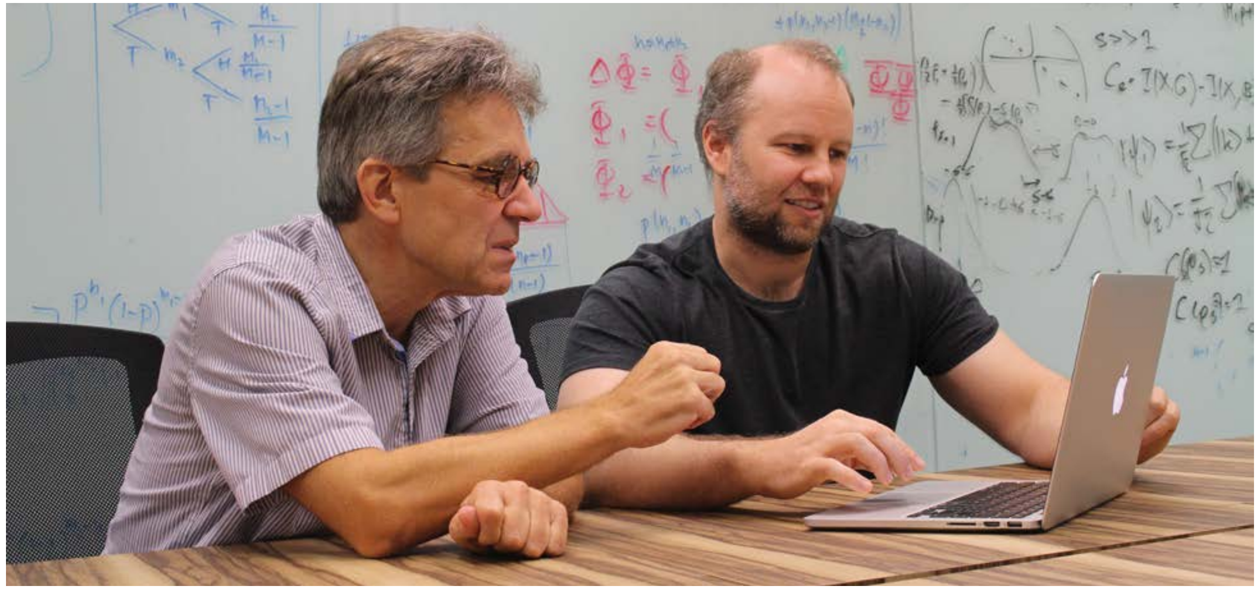
Dimitris and our collaborator Pedram Roushan at Google know very well how a system of superconducting qubits works – how the energy levels look and what kind of things you can control. Based on this knowledge, they could tell it would be possible to realise the Hofstadter butterfly, but they weren't sure how to practically do it. They decided to try and asked me to figure it out.

Since I came to CQT, I have done a lot of work in Dimitris' group on quantum simulations. That familiarity helped me to come up with ideas. I was walking in Kent Ridge park when I realised how to do the measurements. The theory of the tool itself, any undergraduate should be able to understand.

It's nice as a theorist to collaborate in an experiment. I spent time writing notes to explain the ideas and even doing some data analysis. The kind of measurement we did in the paper needed the good control that Google has over its qubits.

Since the paper came out, I've had lots of invitations from my home country, Thailand, to give talks. I hope that a centre like CQT will exist in Thailand someday.

Jirawat (left) is a PhD student under the supervision of Dimitris (right) and a co-author on the result.



Crypto vs quantum computers

CQT's computer scientists are looking at the potential impact of quantum computers on cybersecurity – from communication to currency. Troy Lee explains

The excitement surrounding quantum computers is palpable. It's clearest in the growing interest of industry in the quantum space. In November 2017, IBM announced a 50 qubit quantum computer, and Google promises to be not far behind. Startups doing quantum hardware and software number in the dozens. Major Chinese tech companies such as Alibaba and Tencent are starting their own quantum computing research labs.

One area that will certainly be affected by the development of quantum computers is cryptography. Shor's quantum algorithm to efficiently solve the factoring and discrete logarithm problems can break RSA and elliptic curve cryptography, two key protocols that are used to secure the internet and financial transactions. Together with other computer scientists at CQT, I am looking into further impacts of quantum computers on cryptography, and how to develop quantum safe cryptographic schemes.

While quantum computers large enough to break today's cryptographic protocols are still some ways away, the US governmental agency NIST is already preparing a standard for quantum safe cryptography, with a call for proposals that ended in late 2017 (see box *Securing the future* on p.39). One proposal was submitted by CQT's very own Divesh Aggarwal, Anupam Prakash, and Miklos Santha and their collaborator.

We also turned our attention to another hot topic of 2017, the decentralised 'cryptocurrency' Bitcoin. Largely driven by its rise in price – the price of bitcoin rose over thirteenfold during the course of the year – Bitcoin has risen to global prominence. The entire space of cryptocurrencies has seen an explosion of interest. There are now nearly 1400 different coins listed at coinmarketcap.com, with total market valuation of over 700 billion dollars.

What will be the impact of quantum computers on Bitcoin? This was a question that had already shown up on Bitcoin forums, and the Bitcoin community was roughly aware of certain attacks that could be made by a quantum computer. No very precise or quantitative study had been made, however, which is what Divesh, Miklos and I tried to do in the paper "Quantum attacks on Bitcoin, and how to prevent them"[1], together with our Australian-based collaborators Marco Tomamichel and Gavin Brennen.

Basics of Bitcoin

Before getting to our results, let me give a brief overview of how the Bitcoin protocol works. There are two key ideas: digital signatures and the proof-of-work.

A digital signature is a cryptographic primitive that imitates the ideal functionality of a handwritten signature – Alice's signature on a message authenticates that Alice created the message because no other person can replicate Alice's signature. For a digital signature this is done through Alice creating a public and secret key pair. The public key represents Alice's identity, and can be known globally. The secret key, on the other hand, should be known only to Alice. The public key can be computed from the secret key; computing the secret key from the public key, however, is a computationally hard problem that is infeasible to solve in practice.

A digital signature can be thought of as a form of a zero-knowledge proof, a cool idea from theoretical computer science developed in the mid 1980s. A zero-knowledge proof is a way for Alice to prove that she knows the solution to a problem without giving away any information about the solution itself. In digitally signing a message, Alice proves that she knows the secret key corresponding to her public key, without revealing any information about the secret key. Anyone who knows Alice's public key can verify whether or not the message was signed correctly.

At a high level, a transaction in Bitcoin is simply a message, for example, "I, Alice, send 3 bitcoins that I own to Bob". Now you can see the need for the functionality of a digital signature – Alice needs a way to authenticate that she is sending this message. Otherwise, Bob himself could send a message saying that Alice was sending him 3 bitcoins, thereby stealing her coins.

We also need a mechanism to protect Bob in this scenario from what is known as a double spending attack. Alice could try to spend the same bitcoins multiple times, for example sending them to Bob and also to Charlie.

Preventing a double spending attack is where the proof-of work comes in. All messages encoding bitcoin transactions are recorded in a ledger. This ledger consists of a chain of blocks, each block being a list of transactions. The ledger is the definitive account of all bitcoin transactions that have taken place, thus it is important that everyone agrees on the contents of the ledger. Achieving this consensus is the most difficult problem in creating a decentralized currency.

Bitcoin achieves this consensus by means of a proof-of-work. New blocks are added to the chain by so-called miners who compete to decide who has the right to create a new block by solving a computational search problem. The difficulty of this search

Left: Miklos Santha (left) and Troy Lee (right), Principal Investigators at CQT, are consulting for cryptocurrency provider Hcash on the quantum security of cryptocurrencies.

problem is adjusted so that a solution is found by the network every 10 minutes on average. Once a miner solves the search problem, he broadcasts the newly created block to the rest of the network. In compensation for his effort, the winning miner receives a reward in bitcoin.

A difficulty arises when two miners solve the search problem in the same moment and broadcast different new blocks to the network. In this case, there is a fork in the chain, and an uncertainty about which is the true history of bitcoin transactions. The rule in Bitcoin is that the true history is given by the longest chain.

The purpose of the proof-of-work is so that no one miner can dominate the creation of blocks, i.e. be able to win the search competition more than 50% of the time. This makes it very unlikely that any individual could rewrite bitcoin history in their favour by unilaterally creating the longest chain. To win the search competition more than 50% of the time would require an enormous investment in computing power – at the current difficulty level, it would require spending more than one billion USD on specialised computational hardware.

Mining is safer than signatures

Our first finding on the impact of quantum computers on Bitcoin was quite surprising to me. As the proof-of-work is a search problem, a quantum computer can use Grover's algorithm to perform this search with quadratically fewer search queries than needed classically. This seems like it would lead to quantum dominance in Bitcoin mining.

However, the profits from mining Bitcoin have led to an arms race of ever more sophisticated mining hardware. Current specialized mining devices, called ASICs can perform 14 trillion search queries per second.

On the other hand, the maximum gate speeds of near term quantum devices are projected to be at most 100 million operations per second. This massive gap in speed essentially negates the quantum speedup achieved by Grover's algorithm. Thus quantum computers do not represent a security threat to the Bitcoin proof-of-work in the near future.

For the signature scheme used by Bitcoin, however, the story is different. Bitcoin uses an elliptic curve signature scheme, which has security based on the hardness of the discrete logarithm problem over an elliptic curve group. On a sufficiently large quantum computer, Shor's quantum algorithm can be used to solve this problem, and could compute the secret key corresponding to a given public key very quickly.

The key qualification here is 'large enough'. To run Shor's discrete logarithm algorithm on a 256-bit number (as used in Bitcoin) would require about 2000 logical qubits. Once error-correction is taken into account, however, we estimate that a realistic figure for the number of qubits needed is more like 500,000. Even assuming optimistically that the number of qubits in quantum computers will be able to double every nine months, quantum computers able to break the elliptic curve signature scheme of Bitcoin are still at least a decade away.

About the author

Troy is a Principal Investigator at the Centre for Quantum Technologies and an Associate Professor at the Nanyang Technological University. He is one of the leaders of CQT's computer science group. He holds a fellowship from Singapore's National Research Foundation.

A testing ground

Still, it is never too early to start planning for the protocol succession needed with the rise of quantum computing technology. Several cryptocurrencies are already taking this into account and deploying a quantum safe signature scheme.

Miklos and I, together with our Australian-based coauthors Marco and Gavin have been consulting for one of these coins, called Hcash. We have been advising them on the various types of signature schemes that are belived to be quantum safe. Hcash has implemented two quantum safe signature schemes in a test coin, a lattice based signature scheme and a hash based signature scheme. These features are scheduled to be launched into the main Hcash coin in the second quarter of 2018.

I find this to be a very interesting testing ground. While the NIST decisions are still years away, cryptocurrencies are already testing post-quantum cryptography in practice with billions of dollars at stake.

[1] https://arxiv.org/abs/1710.10377

Securing the future

The US National Institute of Standards and Technology (NIST) has begun a process to define 'post-quantum' standards for cryptography. In 2016, the agency launched a year-long call for proposals for cryptographic protocols resistant to attack by quantum computer.

Among the 69 submissions accepted into round one of the competition is 'Mersenne-756839', from CQT researchers Divesh Aggarwal, Miklos Santha and Anupam Prakash, with collaborator Antoine Joux at the UPMC University of Paris.

The team invented a new key encapsulation mechanism, which is convertible into an encryption system. The security of their proposal is based on arithmetic modulo Mersenne numbers – numbers of the form $p = 2^n-1$, where n is a prime. NIST asked for a concrete choice of parameters that achieve a desired security. The team's proposal uses the Mersenne prime 2^n-1, where $n = 756839$.

It will take three to five years of analysis before NIST reports its findings, and then a further two years for the agency to have ready draft standards. The agency does not expect to pick a winner, but to identify several algorithms as "good choices".

The goal is to recommend approaches for quantum-resistant encryption early enough to protect data that needs long-term security, overlapping with the possible timeline for the arrival of large-scale quantum computers.

All of the first round proposals have been made public for review. Divesh or Antoine will also present the team's proposal at a workshop NIST is organising in April 2018 in Florida. "This will be followed by an open discussion of the proposal's merits and demerits," says Divesh.

New kids on the block

Loh Huanqian (left) and Travis Nicholson (right) are setting up new experiments in cold molecules and Rydberg atoms, respectively, in these labs 1 and 2. Both new Principal Investigators are recruiting postdocs and PhD students to join their groups.

In September 2017, Loh Huanqian and Travis Nicholson joined CQT as Principal Investigators. They are establishing two new research groups in atomic physics, building experiments from scratch in newly renovated lab space.

For both PIs, the first steps towards their scientific goals (see box *Two directions*) have been to equip their labs, with purchases from optical tables to office chairs, and to recruit postdocs and PhD students. Openings are listed at www.quantumlah.org/about/joinus.php.

Huanqian did her PhD at JILA in the United States, a joint institute of the National Institute of Standards and Technology (NIST) and University of Colorado Boulder. There she worked on measurements of the electron electric dipole moment in the group of Nobel laureate Eric Cornell. Travis did his PhD in the group of Jun Ye, a physicist at NIST. His PhD thesis demonstrated the most accurate atomic clock on Earth, which won't gain or lose a second in 15 billion years.

Huanqian is a Singaporean and was previously a CQT research fellow. She worked in the group of Dzmitry Matsukevich on molecular ions, and then in the group of Martin Zwierlein at the Masachusetts Institute of Technology on ultracold molecules.

These experiences have provided the inspiration for her present work as an NUS President's Assistant Professor. "Right now quantum control of molecules is at a very exciting phase in the atomic physics community, and it means a lot to me to be able to pursue this big frontier back home," she says. Huanqian has been awarded a Fellowship from the Singapore National Research Foundation.

Travis, an American also appointed as an Assistant Professor in the NUS Department of Physics, arrived after completing a postdoc at the MIT-Harvard Center for Ultracold Atoms. There he worked with Mikhail Lukin and Vladan Vuletic on slow light. Having experienced two physics frontier centres in the US, he found CQT offered a similarly attractive set up. "There's only a handful of honest-to-goodness centres in the world that have several experimental groups doing this kind of physics and doing it well. It's wonderful to be in such an intellectually vibrant environment," he says.

Two directions

The Loh group

Huanqian's group aims to perform quantum state engineering at the single-molecule level, to explore new phenomena in quantum physics and chemistry. Cold molecules in well defined quantum states offer a clean, tunable way to simulate interesting materials like superconductors. Like quantum legos, they can also be used to assemble dream materials not necessarily found in nature but which could have highly desirable properties.

The Nicholson group

Travis's group is interested in using Rydberg dressing of strontium in optical lattices to achieve squeezed states and quantum logic. Ultracold strontium in lattices is the basis for the world's best atomic clocks. Meanwhile ultracold atoms in Rydberg states have realized high-fidelity quantum gates. The goal is to combine these two approaches to achieve a novel, high-fidelity quantum logic scheme.

Self-testing

Goh Koon Tong describes his work in the CQT group of Valerio Scarani on the fingerprinting of quantum states – a technique that allows devices to be 'self-testing'

A musky stench fills the air. The door is cordoned off and the carpet beneath is soaked with blood. You are in the middle of a crime scene. As a forensic investigator, your task is to identify the murderer. You scour the room for any possible clue. You pray that the culprit's fingerprints can be found.

Fingerprints are unique to individuals and provide evidence of that person's presence. It turns out that quantum states have fingerprints too. We don't need these fingerprints to catch quantum criminals, but we think they can be helpful for quantum technologies. This is thanks to the idea of 'self-testing'.

Self-testing boasts the possibility of checking the serviceability of devices without requiring any knowledge of their underlying mechanism. Different devices will use different quantum states. Looking for the state's fingerprint will tell you if the device can do its job.

This article's author Koon Tong writes at the whiteboard during a group discussion with (from left to right) Li Xinhui, Han Yunguang, Cai Yu, Valerio Scarani and Lee Zhi Xian.

This is perfect if you're the customer for a state-of-the-art device that you cannot open or understand. You may have bought the device from a company you're not sure you trust, or know that the device will self-destruct if you try to look inside.

In the group of Valerio Scarani at CQT, we have discovered how to measure fingerprints of new classes of quantum states, widening the possible range of self-testing devices.

Bell's theorem

Let's begin the story from its origin: Bell's theorem. Just less than a century ago, Albert Einstein, Boris Podolsky and Nathan Rosen dubbed quantum theory "incomplete" because it does not fulfill the principle of local realism.

Locality refers to the belief that physical objects that are spatially separated do not interact instantaneously. Realism refers to the belief that values of physical quantities are predetermined prior to the act of measurement on them. The description from quantum physics of particles in a shared, 'entangled' state was not compatible with these seemingly common-sense beliefs. However, discrediting a theory based on personal beliefs rather than experimentation is not scientific.

Three decades later, the physicist John Bell proposed a way to make an experimental test of local realism. Bell considered measurements on two spatially separated systems. He showed that quantum theory predicts a value for some combination of results on entangled systems that exceeds the maximum value allowed by the local realism principle. Hence, local realism is falsifiable by what is now known as a Bell test. The mathematical relation that bounds the value of an observable imposed by local realism is known as Bell's inequality.

The violation of Bell's inequality was first demonstrated in the 1980s, but it was only two years ago that experiments truly 'loophole-free' confirmed the results. This dealt a final blow to the remnants of the local-realistic loyalists. It sounds like the perfect ending – except this is not the end of our story, instead it is the beginning.

Black box devices

We're at the dawn of commercial quantum technologies. It is only a matter of time until we can buy a range of quantum devices off the shelf, from communication tools to measurement devices and computers. When a customer buys a quantum device, how do they know if it is doing what it is supposed to do? How do we know if a quantum computer is churning out the correct solution? How do we know if a quantum cryptographic device produces secure encryption keys?

A Bell test could be a first step. Entanglement is a prerequisite to violation of Bell inequality and hence, Bell violation certifies entanglement. Entanglement is an ingredient for protocols in quantum computing, communication and measurement. Yet, such statements are often too weak to test a quantum device. We don't just need to know that a device is making quantum states with entanglement, we want to know exactly what that quantum state is.

Conventional tests of quantum states require assumptions to be made about the devices making and measuring them, but these assumptions may be unwarranted. We also run into a slippery slope problem: if we trust that part of the device is fully functional, then why not trust others? If we trust that the device works, then what is the point of the test?

Such concerns have created growing interest in the quantum information community in device-independent certification – the idea of running tests that make no assumption about the device itself. The appeal is that we draw conclusions based solely on observations and physical laws, from looking at the statistics of measurement results. This approach is also known as self-testing.

Self-testing

If one digs deep into the literature, the origin of self-testing can be traced as far back as 1987. That year, Boris Tsirelson, Stephen Summers and Reinhard Werner noticed that certain observed statistics could only be achieved by a particular quantum state. However, this observation was left as a brief comment obscured in their works. Five years later, Sandu Popescu and Daniel Rohrlich published a paper that is fully dedicated to this problem but it remained a subject of academic curiosity. It took another decade before Dominic Mayers and Andrew Yao coined the term "self-testing" for schemes that test quantum devices relying only on the observed statistics.

One can think of these statistics as the unique classical fingerprints of the quantum state. No matter how elusive the quantum state is, it will inevitably leave behind its fingerprints.

To begin with, physicists could only identify fingerprints for the maximally entangled qubits state (or the 'singlet state'). No one knew if self-testing was a phenomenon that is exclusive to the singlet state. I'm part of a team of researchers led by Valerio that has discovered how to check the fingerprints of many other quantum states.

The team's initial effort revealed the fingerprints of many bipartite and tripartite quantum states. Notably, we collaborated with Miguel Navascués, then at the University of Bristol, to produce a blueprint for the self-testing of all pure bipartite entangled qubits states and all bipartite maximally entangled states.

Inspired by this progress, the team continued looking for fingerprints. Working alongside Caltech's Andrea Coladangelo, we found the fingerprints of all pure bipartite entangled states[1]. This explosion of known self-testable quantum states suggests that self-testing is a common feature of quantum theory itself.

Into the real world

So far, so good, but formulating a technique to verify quantum devices in theory is meaningless unless it's feasible.

A first step towards making self-testing practical is to show that it's robust against the noise intrinsic to experiments. Robust self-testing gives meaningful and non-trivial bounds on the 'closeness' between the measured states and the ideal quantum state amidst small experimental imperfections.

The good news is that all known self-testing proofs can be shown to be robust. However, there are still obstacles. The most glaring problem is that self-testing relies on observed statistics, which will deviate from the ideal. Moreover, for self-testing schemes based on Bell inequality violations, due to statistical fluctuations, the estimated violations may even exceed its quantum theoretical maximum, rendering any existing theoretical analysis invalid.

Recent works address such problems and offer partial solutions[2,3].

Currently in CQT, Valerio's team is coming together with the experimental team led by Alexander Ling to check the fingerprints of entangled photon states created in the lab. Future quantum devices may be certified thanks to today's efforts to push the boundary of scientific knowledge.

[1] A. Coladangelo, K. T. Goh, and V. Scarani, All pure bipartite entangled states can be self-tested, *Nature Communications* **8** 15484 (2017)

[2] M. O. Renou, D. Rosset, A. Martin, and N. Gisin, On the inequivalence of the CH and CHSH inequalities due to finite statistics, *J. Phys. A: Math. Theor*. **50** 255301 (2017)

[3] P.-S. Lin, D. Rosset, Y. Zhang, J.-D. Bancal, and Y.-C. Liang, Device-independent Point Estimation from Finite Data, arXiv:1705.09245 (2017)

About the author

Koon Tong is a final year PhD student at the Centre for Quantum Technologies under the supervision of Principal Investigator Valerio Scarani. His research area revolves around correlations that can only be obtained from quantum systems.

Image: Measuring the fingerprint of quantum states, captured here in an artist's impression, could help to guard against errors and defective devices in quantum technologies.

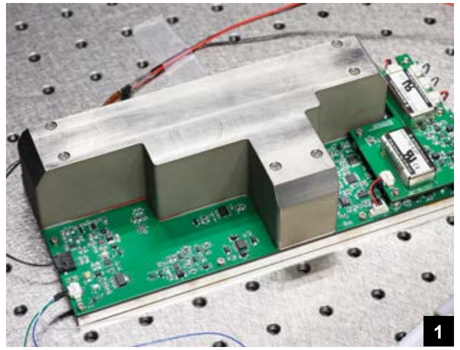
Made at CQT: quantum satellites

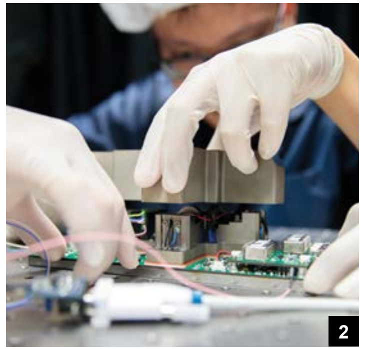
See behind the scenes as Alexander Ling's group prepares to launch a second quantum Cubesat

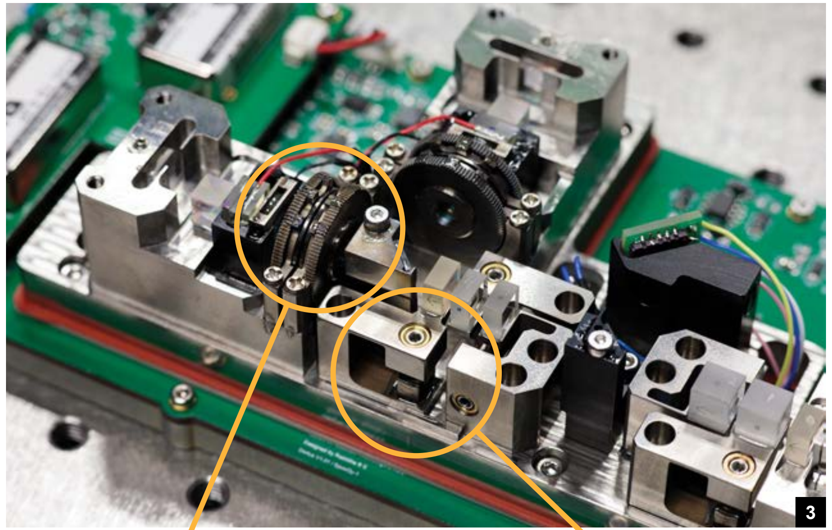
Above Earth, there's a shoebox-sized satellite called Galassia making 90-minute orbits. Inside that satellite runs a quantum light source built at CQT. That first step towards technology for a global quantum network, taken in 2015, should soon be followed by another: the launch in 2018 of CQT's SpooQySat.

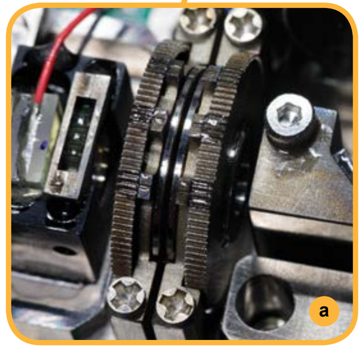
The group of CQT Principal Investigator Alexander Ling has pioneered the development of small, rugged and low-power sources of entangled light particles for quantum communication via satellites in orbit. The work of the multidisciplinary team was photographed for this story.

PhD students Aitor Villar Zafra (left) and Tang Zhongkan Kamiyuki (centre), with Research Fellow Rakhitha Chandrasekhara (right) assemble a quantum light source for space. Aitor has a background in communications engineering, Zhongkan in physics and Rakhitha in electrical enginering.





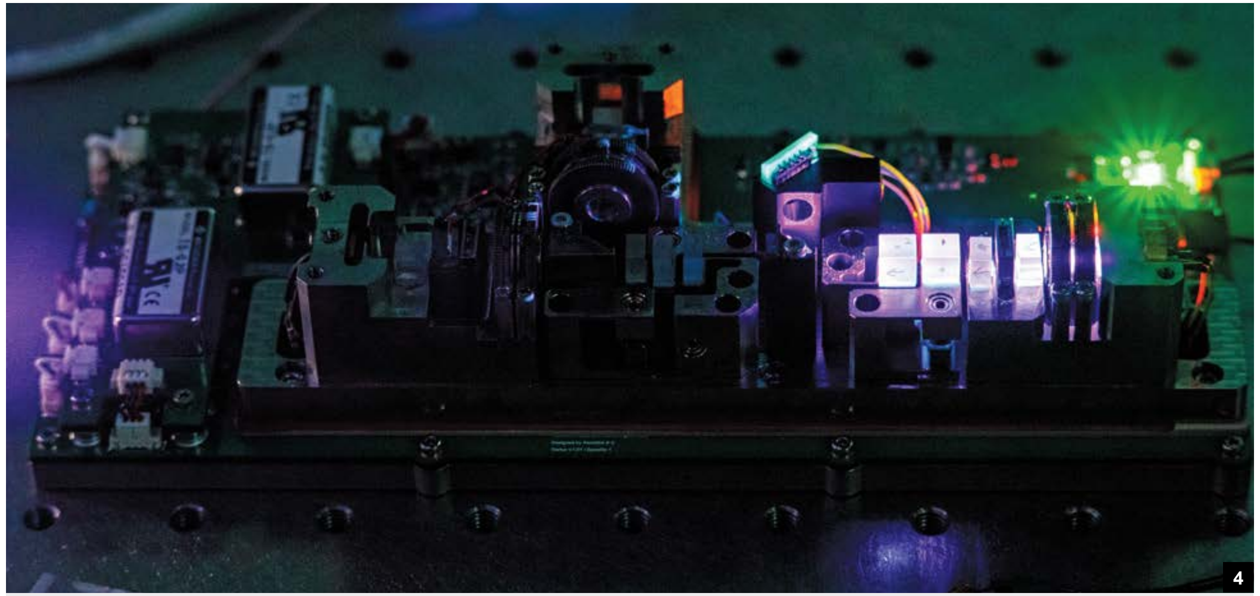




1 The team designed the small photon-entangling quantum system (SPEQS) to fly inside a Cubesat, a standard form of nanosatellite that is relatively inexpensive to build and launch. Entangled photons allow secure communication and, in the long term, can network quantum computers. In this device, however, light stays on board. The creation and measurement of entangled photon pairs all happens within the metal box, controlled by electronics on a printed circuit board.

2 The components that create the quantum light are protected within a casing machined from titanium. The team are careful to handle the device in a clean environment, to avoid dirt or grease that might affect its operation in space.

3 Inside SPEQS is a complex array of optical devices and alignment mechanisms. Entangled photons are created through a process known as 'spontaneous parametric-down conversion', which happens as laser light shining in from the bottom right of the device passes through the visible blocks of crystal. This material is beta-barium borate (BBO). A photon passing through BBO sometimes get turned into two photons of lower energy. The succession of crystals ensures such pairs emerge entangled. In SPEQS, entangled photons are directed for measurement in the two branches of the device to the upper left. The laser beam and components must be finely aligned for this to work. The alignment must also survive vibrations during a rocket launch and temperature changes as the satellite swings through hot sun and cold shadow. Close-ups show how the CQT team tackled the challenge.



a Wheels notched with 72 ridges rotate a prism that moves the direction of the beam, to aim it squarely into the detector. The wheels, like other titanium components in SPEQs, were machined to CQT's design by companies in SIngapore that support the aerospace industry.

Sitting to the left of the wheels, at the end of the red wire, are liquid crystal polarisation rotators that orient the photons before they go into the detector. The team have invented a control scheme based on tracking the capacitance of these devices that avoids the temperature sensitivity of their usual settings.

b Five interlocking flexure stages nested in a compact footprint give precise tuning of the position of the BBO crystals. These are adjusted using a screw **c** with a thread too fine to see with the naked human eye. Each steel screw's tip rests on a hard saphire plate.

4 The team are taking data on the performance of SPEQS in the lab – measuring the rate of entangled pair production and quality of the entanglement – to benchmark against the performance of the device when it is in orbit. Compared to the first device launched on Galassia, this SPEQS should be brighter and show entanglement. These stages

| THE STRAITS TIMES | SATURDAY, JUNE 17, 2017 |

Communications privacy in the quantum era

Alexander Ling

For The Straits Times

China's satellite Micius blasting off from a launch centre in Gansu province last year. Micius is now able to send out pairs of photons that share a special correlation called quantum entanglement. PHOTO: AGENCE FRANCE-PRESSE

China's satellite Micius is making news for connecting two ground stations 1,200km apart at a rate of one signal per second. That won't sound impressive – it's a lot slower than broadband – but this satellite is transmitting an extraordinary signal. It's a harbinger of the future for cyber security.

On Thursday in the journal Science, the Micius team reported that the 600kg satellite, orbiting 500km above Earth, has distributed pairs of light particles to the two receivers. Most satellites beam out bright signals, made up of large numbers of light particles (known as photons), to make sure their messages reach the ground. This satellite sends out individual photons. Moreover, the satellite sends out pairs of photons that share a special correlation called quantum entanglement. This property is a vital ingredient in emerging technologies for computing and encryption.

There has long been a scientific consensus that entanglement distribution from satellites should be possible. My team at the Centre of Quantum Technologies had demonstrated, in December 2015, a source of photon pairs in space on board the 2kg Galassia spacecraft built by the National University of Singapore (NUS). Galassia was not equipped with telescopes to distribute photons, and so the recent report is the first demonstration of photon pair distribution from space to ground. It's a great technological feat – and it's encouraging for groups around the world working on entanglement-based technology.

In the long term, we may look to quantum satellites to connect a global network of quantum computers. In the near term, we may need them to protect our privacy from such machines.

The past few years have seen dramatic progress in the development of quantum computers. These machines accelerate problem-solving for some types of mathematical sequences by exploiting phenomena such as entanglement. Very basic quantum computers are already available on the cloud – IBM launched one last year to the public, which it upgraded last month to have 16 quantum bits. Other big industry players such as Google, Microsoft and Intel, and aggressive deep-technology start-ups, are also readying the technology for commercial applications.

Quantum computers should bring benefits in areas such as optimisation and drug simulation, but it is also an established fact that they can crack today's common encryption systems. Concern is growing that malicious actors may be recording encrypted data in anticipation of quantum computers. This is a particular challenge for those tasked with maintaining long-term data privacy, from government communications to personal health data.

This has spurred interest in encryption techniques that are "quantum-safe". There are two approaches – a search for mathematical problems that will remain difficult for a quantum computer, and the more novel approach of developing quantum hardware for encryption. Scientists and mathematicians in Singapore are working on both, engaged in the worldwide effort to develop the encryption eco-system of the future.

The search for problems that can resist a quantum computer is a tricky proposition since the technology is still maturing. It is likely that we have not yet uncovered the full potential of quantum computing. Nevertheless, some of my colleagues at NUS are working in this area and they are not alone. The National Institute of Standards and Technology in the United States is organising a competition to identify quantum-resistant problems.

The second approach uses hardware to enhance an encryption scheme we already know to be immune to quantum computers, in which the communicating parties lock and unlock their data using the same key. The key is simply a string of random numbers. The key lacks mathematical structure for the quantum computers to analyse, blunting their advantage. The challenge is to distribute the keys. In today's crypto environment, we use complex mathematical sequences that are vulnerable to quantum computers.

Quantum Key Distribution (QKD) offers an alternative. In QKD, the communicating parties share photons that are encoded with randomness. An advanced form of QKD achieves this with quantum entanglement. Any eavesdropping attempt on the photon stream disturbs the encoding, giving rise to detectable errors. QKD is a peerless technology in forcing an eavesdropper to leave behind tell-tale signs.

Singapore has deep expertise in entanglement technology. Researchers at the Centre for Quantum Technologies pioneered the development of entanglement-based key distribution. Scientists from the centre are collaborating with the NUS-Singtel Cyber Security Research & Development Laboratory to prepare local optical fibre for QKD technology, aimed at securing critical infrastructure and sensitive communications. Singapore's size and rich fibre connections make it an ideal environment for this project.

The situation changes if we need to connect distant parts of the globe, for example Singapore to New York. If we use optical fibres, the photons would have to travel through thousands of kilometres of glass, and will ultimately be lost. That's when we look to satellites.

My team is focused on making instruments that fit on small spacecraft such as Galassia. These smaller satellites are commercially attractive, and could enable a constellation of spacecraft to enhance service quality. This is a community effort. We are working with the University of New South Wales-Canberra to investigate inter-satellite QKD and are engaging with university and industry teams around the world to improve the technology. By working together, we will be able to ensure continued communications privacy even when the technology landscape changes rapidly.

stopinion@sph.com.sg

• Alexander Ling is a principal investigator at the Centre for Quantum Technologies, associate professor at the National University of Singapore, and also a theme leader at the NUS-Singtel Cyber Security Research & Development Laboratory.

of the team's roadmap are funded by Singapore's National Research Foundation. The team are exploring funding options and partnerships for later stages that will involve sending signals satellite-to-satellite or satellite-to-ground. The team will carry out range-testing experiments supported by the Air Force Office of Scientific Research.

5 There are projects in other parts of the world to build quantum satellites too. Alexander wrote about the bigger, picture for *The Straits Times* in June 2017, after publication of the first results from the Chinese satellite Micius, a 600kg satellite launched in 2016. The Micius team followed the first distribution of entangled photons from space to ground with an encrypted video call between China and Europe that used Micius as a trusted relay to share quantum keys. Canada is funding development of a quantum satellite called QEYSSat and Europe has numerous proposals to do quantum key distribution from spacecraft in low Earth and geostationary orbits.

6 Meanwhile, CQT has built in-house the 4kg SpooQySat, held in the picture by satellite expert and CQT Senior Research Fellow Robert Bedington. Cubesats are built from units measuring 10cm along each edge. SpooQySat is made of three such cubes. The SPEQs device slots vertically in the body, with the power supply and communications hardware housed in the top unit. The satellite will have a skin of solar panels.

Providing the satellite makes it through rigorous pre-launch testing, SpooQySat should lift off with the Japanese Space Agency (JAXA) in the second half of 2018. It will join the cargo in a rocket taking supplies to the ISS. SpooQySat will be delivered to the ISS too.

7 When it is time for the satellite to be deployed, an ISS astronaut will pack SpooQySat into a spring-loaded ejector, like that pictured. This will be transferred through an air lock in the Japanese Experiment Module to the outside of the space station. A robotic arm developed by JAXA will pick up the package, aim and fire – shooting the satellite into its predetermined orbit. All being well, SpooQySat will turn on and send back data for 6 to 12 months before it descends into Earth's atmosphere and burns up.

Helping youth make a quantum leap

CQT's summer camp for junior college students is popular enough to have a waiting list. Jamie Sikora introduces Generation Q Camp

Four years ago, I sat down with CQT's outreach team with the intention of creating a summer camp for young students. We wanted to offer a place for pre-university students to see the new developments in the exciting world of quantum.

The final years of school are a pivotal time for young students. Soon, they will have to start making decisions concerning the direction they would like to steer their careers. It is an invaluable resource for these students being able to talk to people who already went down the road they are thinking of taking.

What's more, it looks like quantum technologies could be an exciting route to pick. In 2017, China demonstrated a quantum communications satellite and Google said it was close to having a quantum computer that could do something beyond the reach of all today's machines. Here in Singapore, CQT has been funded since 2007 to do research in quantum technologies and is now building partnerships with companies like Singtel.

When designing the camp, we had ambitious goals in mind. The first was to educate and inspire young minds eager to learn cutting edge science. There are many misconceptions out there about exactly what 'quantum' is all about, so what better than to learn straight from the experts themselves! We wanted to open our doors to show what is going on in our building.

In 2017, 45 students from 14 different schools registered to take part in Generation Q Camp. They were taught by CQT researchers and PhD students.

Secondly, we wanted to give back to the community that allows for our centre to exist. Some people think that academics are social hermits, hoarding their ideas. They may have preconceptions about physicists from watching the socially-awkward characters on the sitcom The Big Bang Theory. This would be a chance to show that the opposite is true, that we enjoy sharing and discussing ideas.

Our third goal was to make sure that the camp was super fun for everyone involved. We decided to have no assignments or examinations, and we made camp t-shirts for everyone!

Teaching quantum physics

Singapore's schools do famously well in teaching students maths and science – the country ranks first in the world in standardised tests by the intergovernmental Organisation for Economic Co-operation and Development. Still, we wondered if it would be possible to teach our advanced topics in maths, physics, and computer science to students aged around 17–19, in their Junior College (JC) years.

The first "Generation Q Camp" in 2015 was a three-day workshop. We had thirteen participants that year. The students found it engaging – one said the "whole camp is simply amazing and enriching"– so we immediately made plans to run the summer camp again in June 2016.

> *"When we asked the students to describe the camp in a single word, responses included SUPERFUNANDNERDY"*

In 2016, we had a volunteer from the Ministry of Education come to give us some advice. Yang Yarong is a Curriculum Resource Development Officer in physics. She attended the lectures and gave us really helpful feedback on how to make sure the jump from JC to the camp was seamless, with tips on how to improve the structure of the course. The biggest challenge was coordinating with all the volunteers to make a unified curriculum.

By June 2017, we had a waiting list for a five-day camp with over 40 students taking part and more than 20 volunteers from CQT running the event. Our team of graduate students, postdocs, professors and administrative staff helped to teach and take care of the students during their time at CQT.

The camp mixed hand-written lectures, hands-on experiments, and visits to see laboratories performing modern experiments. The students got a glimpse of what world-class physicists get to do all day. When asked to describe the camp in a single word, some responses we received were: "Eye-opening", "Fun!", "Boombastic", "Enriching", "Enlightening", "Life-changing", and a personal favourite, "SUPERFUNANDNERDY".

The human factor

It was particularly nice to see the students making friends from other schools. There are quite a few Junior Colleges in Singapore. To give a fair chance to students from all schools to take part, we set a limit on how many students from each school we accepted. By the end of our most recent camp, many students were hanging out in large groups to discuss science, play board games, and enjoy each other's company.

I think I speak for all the volunteers when I say it was a rewarding experience for us as well. It was a pleasure to interact with young scientists and to take up the challenge of conceptualising quantum mechanics without relying on all the background mathematics.

Many of the graduate students were teaching for the first time and they did a fantastic job delivering interesting and creative lectures and activities, such as a scavenger hunt with encrypted clues. After a demonstration of superconducting qubits, we had a surprise treat of liquid-nitrogen frozen marshmallows and ice-cream – a highlight of the camp!

Afterwards, you could spot some of the students doing attachments with CQT. It's obvious that for these students, one week of advanced physics was not enough. Some of them have even contributed to future summer camps by writing chapters in the lecture notes. It's great we could give a jump start to those determined to keep studying maths and physics.

Having now finished my postdoc at CQT, I leave the future of Generation Q Camp in the capable, more youthful, hands of the CQT PhD student committee. The committee currently consists of Hermanni Heimonen, Mathias Seidler, Srijita Kundu, and Kishor Bharti. Find out Hermanni's perspective in the box *Looking to the future*.

I am excited to see how the camp evolves and I'm confident it will continue to be a great success. I wish every success to the Q Camp students too. I'm sure I'll see some of them making great contributions in science and technology in the future.

About the author

Jamie was a postdoc with the Centre for Quantum Technologies from 2014 to 2017. He received his PhD in quantum information at the University of Waterloo, Ontario, Canada, then spent two years as a postdoc at the Université Paris Diderot, France, before joining CQT. In 2017, he moved back to Ontario for a postdoc position at the Perimeter Institute for Theoretical Physics.

Looking to the future

By Hermanni Heimonen

Jamie may have left CQT, but Generation Q Camp is here to stay.

I've had the opportunity to work on Q Camp for two years as a co-organiser. It's a bit of a cliché, but I've noticed for myself that to explain something to someone, I have to understand the material much better. I was studying for my PhD qualifying exam when I first lectured for the students in 2016 so the teaching experience was particularly helpful.

I gave a talk about 'How (not) to build a quantum computer' – covering the basics of what a computer is and what makes the quantum part. The 'not' was there because different people are trying different ways of building quantum computers, and we still don't really know which will work best.

A week before my first talk, IBM put a five-qubit quantum computer on their cloud. A few weeks before this year's camp, IBM put out a 16-qubit quantum computer – so I'm just waiting for next year! It would be interesting to have the students get hands-on with the IBM machine, but it will take some thinking because quantum algorithms is one of the hardest topics we teach.

The camp has really improved over the years from us learning how to fit lectures and activities together and by hearing the students' feedback. It's clear the students are engaged from the amount of questions they ask and how difficult those questions can be.

As the responsibility for the camp shifts to new hands, with me and the other members of the PhD committee taking over, we hope to continue the curriculum development. When Q Camp returns in 2018, I want to see more practical demonstrations and experiments for the students. Also, our liquid nitrogen cookbook needs new recipes!

Hermanni is a graduate student at CQT, studying for a PhD in theoretical quantum physics.

A demonstration of a 'superconducting quantum interference device' required liquid nitrogen. We used the leftover liquid, which is colder than -196°C, to make ice cream.

INDUSTRY
COLLABORATION

A show for cybersecurity

CQT exhibited at GovWare 2017, the cornerstone event of Singapore International Cyber Week

The Centre for Quantum Technologies brought experts and devices to the GovWare conference, 19–21 September 2017. Held during Singapore International Cyber Week, this event is aimed at "technology leaders, industry professionals, policy-makers and innovators".

Delegates at GovWare came from both business and government. Thanks to the Centre's presence in the exhibition hall, these cybersecurity professionals and government end-users had the opportunity to learn about the risks and opportunities of the quantum era.

"GovWare was the right platform to share the relevance of CQT research to the cybersecurity industry. We communicated the point about quantum computing posing threats to RSA and cybersecurity and shared about quantum-safe solutions, which were not widely known even among industry professionals. Hopefully this awareness will help the community better prepare for advances in quantum technologies," says Lum Chune Yang, Head of Strategic Development for CQT's industry relations team.

The Centre's research in this area spans the study of the quantum security of current encryption schemes, the proposal of new protocols (pp.36–39) and the development of hardware.

Representatives from some 60 different organisations talked to CQT staff at the event or stopped by the Centre's booth. The CQT industry team's objectives are to inform, engage and create with external parties. While exhibiting contributes to informing industry about quantum technologies, the Centre offers training and consulting for organisations looking for deeper learning. There are also possibilities for research collaborations.

One of the displays at CQT's GovWare booth highlighted the Centre's collaboration with Singtel, Asia's leading communications group. CQT is working with Singtel in the NUS–Singtel Cyber Security R&D Lab to develop quantum communication technology for Singapore's fibre networks. We showcased a device built in-house that will measure how quantum signals are affected by the environment as they travel through fibre (see box *On the exhibition floor* p.56).

Other devices on display included:

- A compact source of entangled photon-pairs, with output coupled to fibres. Such photons can be used for key distribution and timing synchronization
- A satellite designed to test technology for quantum key distribution over cross-continental distances (pp.45–49)
- A fast quantum random number generator
- An ion trap, ion-trap chip and superconducting circuit which could contain quantum bits (qubits) for quantum computing

Check CQT's website for news of events where the team will be exhibiting in 2018 and beyond.

On the exhibition floor

CQT's Janet Lim was one of the researchers at the Centre's stand at GovWare. In this Q&A, she describes the experience

What are you working on at CQT?

I'm a research assistant in Professor Christian Kurtsiefer's group, working in the NUS–Singtel Cyber Security R&D Lab. We are working towards implementation of quantum key distribution (QKD) on the Singtel fibre network, to offer a new level of communication security. QKD at telecom wavelengths (1260nm to 1625nm) has the potential for fast deployment on the current infrastructure. Currently, my team and I are working on the characterisation of the Singtel fibres.

What made you interested in quantum technologies?

I joined Prof. Christian's group during my undergraduate years because I was interested in photonics – it meant that I could get my hands on lasers! After learning more from the people around me, I became interested in quantum technologies.

What was your role at the GovWare exhibition?

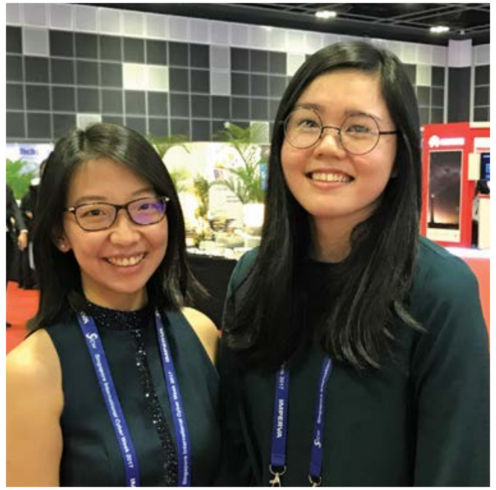
As an exhibitor, I mainly spent time explaining to visitors what my team is working on. We had transported a polarimeter setup to the exhibition. We built this to understand how the polarisation of light coming out of Singtel fibres may be affected by environmental factors, which our QKD system will need to compensate for. I had conversations with engineers, researchers from other research centres, and students.

What kind of questions were you asked?

The most common was "What is quantum physics and how is it incorporated in cyber security?". The most surprising was "Is this project about increasing the efficiency and speed of Singtel's optical fibres?". Our work is about security rather than speed.

What type of job do you hope to do in the future?

Initially I was thinking of going into teaching, but my experience in this Singtel project has opened my worldview. It's exciting to see the potential synergy that exists between quantum research and industry, which could bring tangible benefit to the economy and society. I am leaning towards a job in the general direction of quantum physics, exploring ways to contribute outside of the lab.



CQT's Janet Lim (right) pictured at the GovWare exhibition with Amelia Tan Peiyu, Project Principal Investigator, Singtel

Be informed

CQT offers workshops and seminars to inform organisations about quantum technologies. The Centre's industry team and researchers have delivered three such workshops to companies and government agencies so far, with more to come.

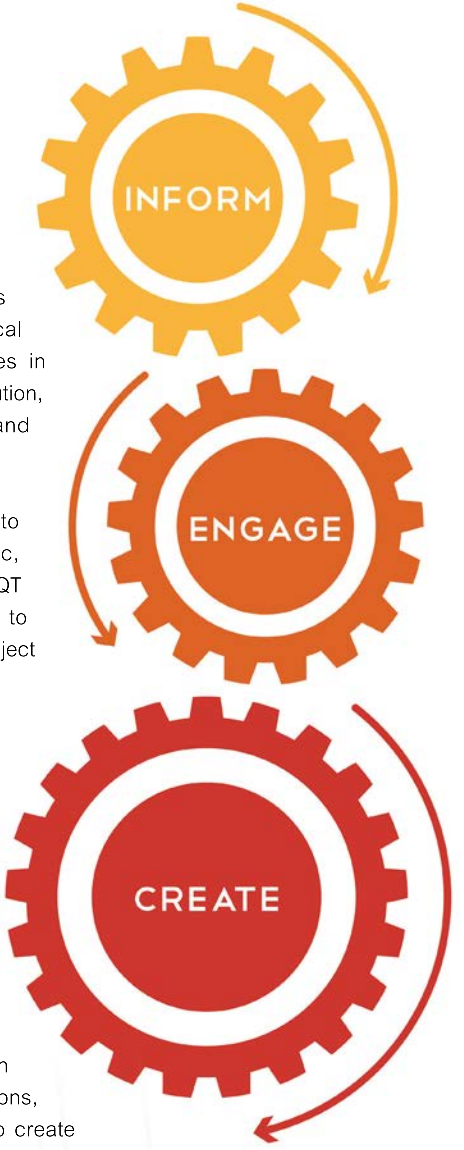
These workshops can help companies understand the potential impact of quantum technologies on their businesses or assist government agencies in planning and preparing for technology changes on the horizon. Topics could include the basics of quantum information processing, quantum computing technology and its applications, quantum-safe communication and quantum sensing, just to name a few.

These workshops can also be customised to meet specific interests of the organisations, and designed at an appropriate technical level to suit the requirements and objectives of the workshop. Hands-on demos, lab tours and brainstorming sessions can also be incorporated to augment the workshops to give a practical feel to the participants' experience.

In 2018, for example, the Centre plans to deliver a three-hour workshop at the Internet of Things (IoT) Asia conference, happening 22–23 March at Singapore EXPO. The workshop would be for up to 30 conference delegates and would cover basic ideas of quantum information processing and its implications for cryptography, as well as real, accessible and practical applications of quantum technologies in industry, including secure key distribution, randomness generation, sensing and atomic clocks.

For organisations that would like to address a clear and specific topic, arrangements can also be made for CQT researchers with relevant expertise to consult with the organisations on a project basis over a period of time.

CQT's strategy to realise the promise of quantum technologies has three themes: to inform, to engage and to create. Companies already informed about quantum technologies are invited to engage the Centre or its spin-offs for discussion on collaboration opportunities. Quantum technologies is an emerging field, with many opportunities for innovation. Through interactions with research organisations, government and industry, we hope to create intellectual property, products and services, and new markets.



Contact us at industry@quantumlah.org for information or with enquiries.

What can you do with a PhD?

A PhD can be a pathway to becoming a scientist. It's a period of mentorship and training in a research group, during which a student deepens their knowledge, grows independence and works towards a novel piece of research.

The skills acquired during this process can be applied in careers outside science, too. CQT PhD students are good at problem-solving, adept with numbers and motivated self-learners. Depending on their projects, students may also have become good at coding, electronics or mechanical design.

In past annual reports, we have followed students into new jobs at Apple, DBS Bank and Mindef in Singapore and postdoc positions around the world. This year, we find out what two of the Centre's most recent graduates, Debashis De Munshi and Aarthi Sundaram, are doing now.

Aarthi (pictured above) completed her PhD in computer science at CQT in 2017, supervised by Miklos Santha. Her research involved work on quantum algorithms and the mathematical complexity of problems. She is now a Hartree Postdoctoral Fellow at the Joint Center for Quantum Information and Computer Science (QuICS) in the United States. The centre is a

partnership between the University of Maryland and the National Institute of Standards and Technology. QuICS offers two-year Hartree Fellowships to exceptional candidates interested in quantum information science and quantum computing.

Debashis did his PhD in the experimental laboratory of CQT's Manas Mukherjee, building and running experiments on trapped barium ions. He then worked briefly as a postdoc in the Centre before accepting a job with KLA Tencor, a multinational company that develops inspection and metrology technologies for the semiconductor and nanoelectronics industries. His leaning towards industry was apparent even earlier, as he filed a patent application and developed ideas for businesses during his PhD. Debashis joined KLA Tencor's Singapore facility in September 2017 as Systems Engineer (manufacturing). He is pictured (right) dressed for work in a Class 100 cleanroom.

Aarthi Sundaram

How did you choose where to do your postdoc?

A key factor was the portfolio of research. Clearly, it is helpful to join a place that has research interests aligned with your own. Additionally, it's good if there is a good variety of research being conducted within a dynamic group. That gives you the chance, as an early stage researcher, to be exposed to new ideas and techniques and to expand your own interest profile. QuICS seems to tick both those boxes for me.

How are you finding it so far?

I'm excited about exploring a new part of the world both personally and professionally. I am exploring certain areas of research which I have not worked in previously. An added bonus is Washington DC being a cultural hub in the US along with its free museums and a lot of activities on offer.

What do you miss from Singapore?

Shorter flights to visit family, the great variety of delicious tropical fruit juices and longer daylight hours during the winter months! On a more serious note, I miss the people I had a chance to interact and work with in CQT and the friends I made during the five years I spent in Singapore.

What are your plans for the future?

As of now, my long term plan is to remain in academia and research. As a rapidly growing research area, the opportunities in quantum information seem to be increasing too. So, I am keeping my options open on wherever opportunities may open up.

Debashis De Munshi

What does your job involve?

The machines we build are extremely complex. Think of a lab at CQT: a whole room of equipment and electronics carefully tuned by researchers. Now imagine taking everything, bundling it into a box of size 4m×4m×4m, and requiring that it work at the push of a button. That's what these machines are like.

Manufacturing these systems is not an automated process. It requires manual work, almost like the way that we as PhD students built our systems. My job is to troubleshoot issues during manufacturing and to suggest and perform design changes.

Why did you want to move into this area/industry?

I was interested to embrace the challenges of commercial technological developments.

What skills or knowledge from your training in science are relevant to this role?

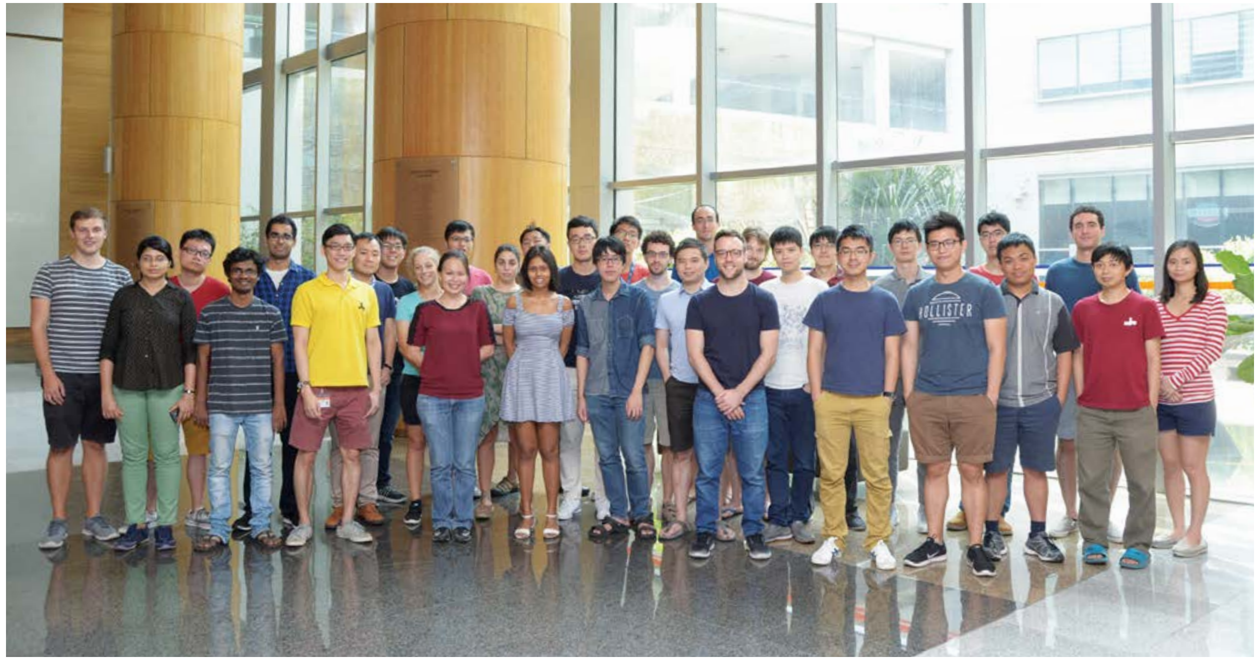
As a scientist, one learns how to solve problems. That's what I did during my PhD and that is what I am doing now. It is surprising how easily the concepts of problem solving can be transferred from one field of work to another.

How are you finding the job?

It is challenging not only technically, but also in terms of operations management. As a manufacturing systems engineer, I work with cross-functional teams having widely different technical expertise and operational objectives.

What is the most interesting thing you've learnt?

What has fascinated me the most in the last few months is how complex a commercial system can be. Some of these systems rival the complexity of some of the labs of CQT.



Earn a PhD at CQT

We welcome students from all over the world to do research in quantum technologies

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 step into the dynamic field of quantum technologies. We have opportunities in experimental and theoretical physics and in computer science.

In 2017, there were more than 70 students supervised at CQT. The CQT PhD programme provides 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. Find more information on the student programme and a description of how to apply at www.quantumlah.org.

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.

Congratulations to our graduates of 2017

Rakhitha Chandrasekara
A Cubesat Compatible Electronics Platform For Miniaturized Single Photon Pair Sources
Supervised by Alexander Ling
CQT PhD Programme

Christian Gross
Atomic 2S1/2 to 3P3/2 Transition for Production and Investigation of A Fermionic Lithium Quantum Gas
Supervised by Kai Dieckmann
CQT PhD Programme

Corsin Pfister
Decoherence Estimation in Quantum Theory and Beyond
Supervised by Stephanie Wehner
CQT PhD Programme

Debashis De Munshi
Precision Measurements to Explore Underlying Geometries and Interactions in a Trapped Ba+ Ion
Supervised by Manas Mukherjee
CQT PhD Programme

Lam Mun Choong, Mark
Molecular Spectroscopy of Ultracold 6LI40K Molecules
Supervised by Kai Dieckmann
CQT PhD Programme

Sambit Bikas Pal
Molecular Spectroscopy of Ultracold 6Lithium – 40Potassium Molecules: Towards Stirap Transfer to Absolute Ground State
Supervised by Kai Dieckmann
CQT PhD Programme

Supartha Podder
Exploring Different Models of Query Complexity and Communication Complexity
Supervised by Hartmut Klauck
CQT PhD Programme

Swarup Das
Application of Precision Measurements with Trapped Ion and Development of a Planar Surface Ion Trap Setup
Supervised by Manas Mukherjee
CQT PhD Programme

Tarun Dutta
Precision Measurement to Study Strongly Correlated Systems – From a Single Ion to Phonons in an Ion Chain
Supervised by Manas Mukherjee
CQT PhD Programme

Wei Nie
Gauge Fields and Geometric Phases in Periodic Systems
Supervised by Kwek Leong Chuan
CQT PhD Programme

Wu Xingyao
Self-Testing: Walking on the Boundary of the Quantum Set
Supervised by Valerio Scarani
CQT PhD Programme

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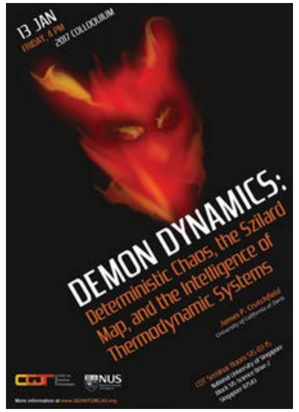
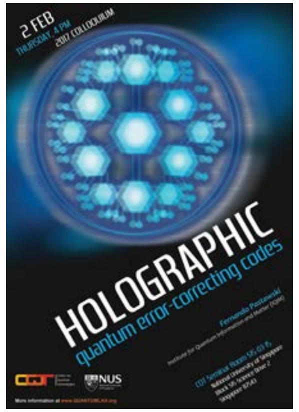
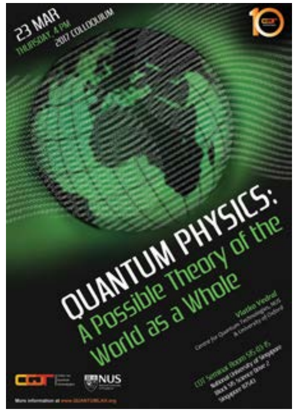
EVENTS

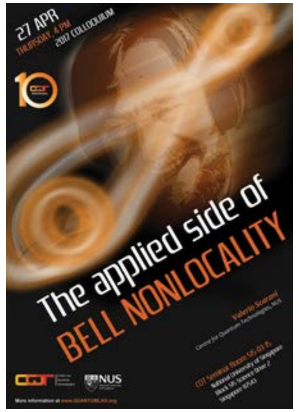
Conferences & Workshops in 2017

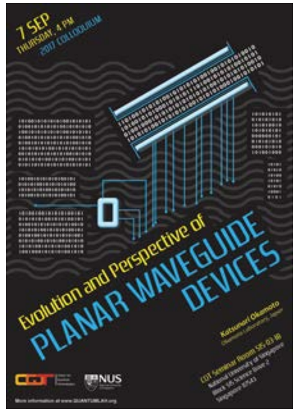
8 – 12 January	International Frontiers of Quantum and Complexity Science	Hotel Fort Canning, Singapore
15 – 17 February	From a single particle to many-body quantum physics and its application	Park Alexandra Hotel, Singapore
18 March	Mini-Workshop on Post-Quantum Cryptanalysis	SPMS, NTU, Singapore
4 – 8 September	17th Asian Quantum Information Science Conference	Shaw Foundation Alumni House, NUS, Singapore
7 – 8 December	CQT10 Conference	NUSS Guild House, NUS, Singapore

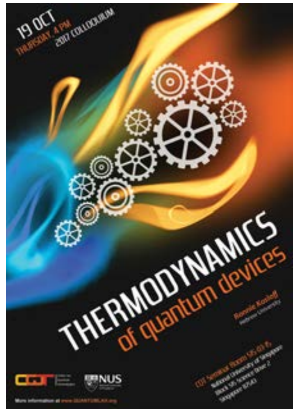


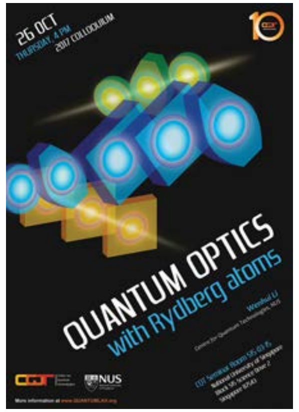


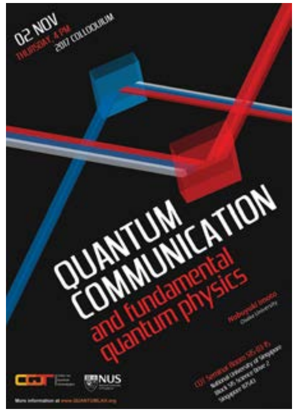


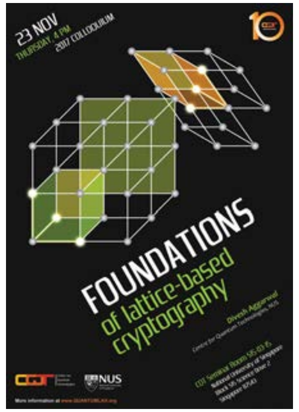












CQT'S 10TH ANNIVERSARY

In December 2017, CQT celebrated its tenth birthday. We marked the occasion with special scientific events.

Over 7–8 December, we hosted a two-day conference that brought together members of CQT, some of the Centre's alumni and distinguished speakers. Here we present some photos from the event.

Leading up to this event throughout the year, the Centre's Principal Investigators presented colloquia that gave a snapshot of the Centre's current research. Enjoy overleaf some snippets from live-drawn sketches by local company Idea Ink that summarise each talk. The videos and full sketch-notes can be found online.

CQT10 conference speakers

Quantum simulation with classical and quantum computers
Ignacio Cirac
Max-Planck-Institut für Quantenoptik

Rigorous RG: a provably efficient algorithm for simulating 1D quantum systems
Umesh Vazirani
UC Berkeley

Quantum Computing with Trapped Atomic Ions
Christopher Monroe
JQI, QuICS, and University of Maryland

The neutron as a quantum particle and wave
Charles Clark
National Institute of Standards and Technology and Joint Quantum Institute

Jerome Cardano: The Quantum Astrologer
Michael Brooks
Freelance Writer

Contributed talks from CQT alumni

Priyam Das
Martial Ducloy
Cord Mueller
Kavan Modi
Ritayan Roy
Marcelo Santos
Wu Xingyao
Yong Siah Teo

1 Ignacio, a member of the Centre's Scientific Advisory Board (SAB) since 2007, opened the day's events.

2 Umesh, also a long-serving member of CQT's SAB, spoke about a new classical algorithm for simulating quantum systems.

3 Christopher, as well as holding academic appointments, is co-founder of the quantum computing start-up IonQ.

4 Artur poses with Charles and a graphic recording of Charles and Charles' talk on the physics of neutrons.

5 CQT students chat with Michael, who spoke about his popular science book on the Renaissance mathematician Jerome Cardano.

6 The CQT10 conference was held at the NUSS Guild House with lunch served in its bright lobby – a chance for friends old and new to mingle.

7 Oh Choo Hiap (second from left), now an NUS Emeritus Professor and CQT Fellow, helped to establish quantum research in Singapore, leading to the Centre's founding.

8 Nicholas Bigelow from the University of Rochester, New York, (left) joined the conference. He is a member of CQT's Governing Board.

9 Former Ministry of Education officers Benny Lee and Perry Lim – in the white shirts, to the left and right of Artur, respectively – helped to draft the policies for CQT when it was founded.

10 It was our birthday, so we had cake. What may not be obvious in the picture is that the 1 and 0 on top of the cake are qubits in superposition. Whether they appear as 1 or 0 depends on the viewing angle.

11 Artists from Idea Ink, a graphic recording company in Singapore, took notes in cartoon form on each of the conference talks.

12 There's always more to learn. We closed our conference with a poster session of results from CQTians and colleagues.

Colloquia by CQT PIs

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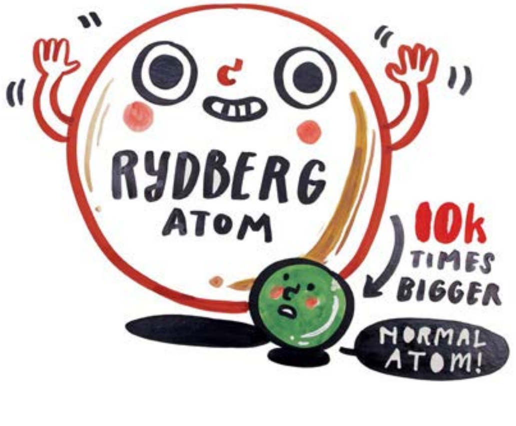
Find more details of the talks, videos and the complete sketch-notes at www.quantumlah.org/events/colloquia.php

5

6



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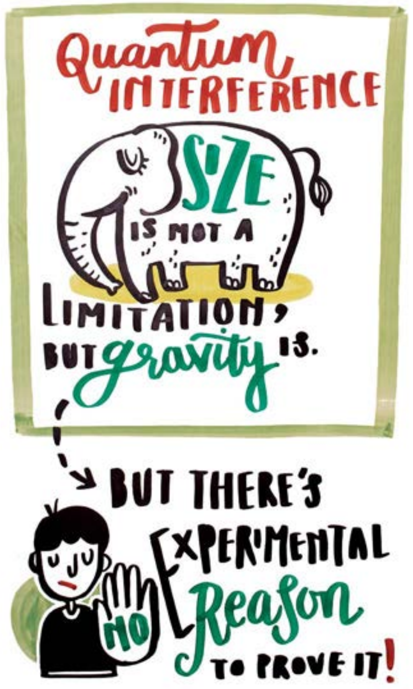

1 **Quantum simulations with strongly interacting photons: Merging condensed matter with quantum optics for quantum technologies**
Dimitris Angelakis

2 **Foundations of lattice-based cryptography**
Divesh Aggarwal

3 **What do the data tell us?**
Berge Englert

4 **Secure quantum computation**
Joe Fitzsimons

5 **The applied side of Bell nonlocality**
Valerio Scarani

6 **Quantum optics with Rydberg atoms**
Wenhui Li

7 **Quantum physics: A possible theory of the world as a whole**
Vlatko Vedral

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OUTREACH

CQT online

The Centre's website at www.quantumlah.org offers news, event lists and links to group research pages. The site had over 70,000 users in 2017, with more than 400,000 page views. It relaunched in December 2017 with a new, mobile-friendly design.

CQT's YouTube channel hosts scientific talks, interviews and short films. It has 700 subscribers and has accumulated over 100 days of 'watch time' in the calendar year.

The Centre is also active on Facebook (3.1k followers), Twitter (2.6k followers) and LinkedIn (1.4k followers) and offers an e-newsletter (600 subscribers).

In the news

There were more than 50 news stories in 2017 that mentioned CQT or CQT research. Highlights include:

- Singapore newspaper *The Straits Times* featured the results of a collaboration between Dimitris Angelakis' group and scientists at Google as a picture story under the heading 'Beautiful Science'. The results (see pp.32–35) were also covered in media including the *Asian Scientist*, *ScienceDaily* and on Greek television.
- There was a flurry of news about the publication of first results in June 2017 from the satellite Micius, launched by China to demonstrate quantum communication from orbit. CQT's Alexander Ling, who also works on quantum satellites (see pp.45–49) was interviewed by media including *Science*, *Discover* and the *BBC News*. He wrote an opinion piece on the news for Singapore's *The Straits Times*.
- *BBC News* also quoted CQT Director Artur Ekert on China's quantum satellite. Artur invented the entanglement-based protocol for quantum cryptography in the '90s. He told the *BBC* "when I proposed the scheme, I did not expect it to be elevated to such heights."
- *The Economist* published a special package of features on quantum technologies in March 2017 titled 'Quantum leaps: a mind-bending technology goes mainstream'. CQT's Vlatko Vedral was among the scientists interviewed.

Schools outreach

We're keen to support and encourage young students' interest in science. This year the Centre hosted more than 200 students – from high schools, junior colleges and undergraduate programmes – across different events.

- 45 students participated in CQT's Generation Q Camp (see pp.50–53), spending a week in the Centre for classes and activities.
- Supporting events organised by the NUS Department of Physics, we offered lab visits to around 150 students taking part in a Physics Enrichment Camp and 50 students and teachers competing in the International Young Physicists Tournament.
- CQT participated in the NUS Faculty of Science Open House, offering an introductory talk and guided lab tours.

Public outreach

We aim to make our research accessible through the materials we share online and to spark curiosity and conversation about the subject through our public engagement activities.

- CQT has run the Quantum Shorts competitions since 2012 as an annual celebration of short films and fiction inspired by quantum physics. The 2016 call for films wrapped up in 2017 with screenings of the ten finalists, selected from over 200 entries, in four countries at prestigious venues. The venues included Singapore's ArtScience Museum (see p.23). The 2017 call for fiction closed in December with some 400 entries, with winners to be announced in 2018.
- The Centre was a partner in the NUS Arts Festival 2017 with collaborations in dance and music (see p.25). Research Fellow Andrew Garner, a partner in the Quantum Music project wrote for the NUS *Artzone* magazine "I believe the task faced by scientists and artists is the same: to observe a facet of reality, distil its essence, and communicate this insight to others. Hence, there is much to gain through dialogue between artists and scientists."
- The Centre offered a public lecture in partnership with Singapore Science Centre by visiting physicist Howard Wiseman. Over 100 people registered for the talk 'Are we Living in The Matrix' – also available to watch on CQT's YouTube channel.

Outreach ambassadors

The centre's outreach team is supported by research staff and students in delivering these activities. Special thanks to our outreach ambassadors of 2017: Andrew Garner, Roland Hablutzel, Hermanni Heimonen, Alexander Hue Jun Hao, Mathias Seidler, Jamie Sikora, Suen Whei Yeap and Jirawat Tangpanitanon

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MONEY MATTERS

Expenditure in 2017

	Manpower	Other	Equipment	Total
Core	8,199,903	6,544,903	1,181,120	**15,925,926**
External Grants	2,716,501	2,289,673	1,152,833	**6,159,007**
NUS–Singtel Cyber Security R&D Lab–Theme 4	156,889	14,599	185,422	**356,910**
Total	**11,073,293**	**8,849,175**	**2,519,375**	**22,441,843**

Stakeholder Support

CQT's operations are supported by its stakeholders through direct funding and other contributions. Singapore's National Research Foundation and Ministry of Education awarded $195 million in core funding for the Centre's first ten years. Following the Centre's international review in 2015, CQT is receiving a further $100 million in follow-on-funding for the period 2017–2022.

CQT is an autonomous research centre hosted by the National University of Singapore. It also has staff at the Nanyang Technological University and the Singapore University of Technology and Design. Support from the universities includes provision of building space, administrative staff and contributions to PI salaries.

External Grants

CQT Principal Investigators and Research Fellows have received a number of local and international grants for their work. In 2017, the Centre's active grants include awards from the Ministry of Education, the National Research Foundation and the Agency for Science, Technology and Research, all in Singapore. International grants come from the Foundational Questions Institute, the John Templeton Foundation and the Air Force Office of Scientific Research.

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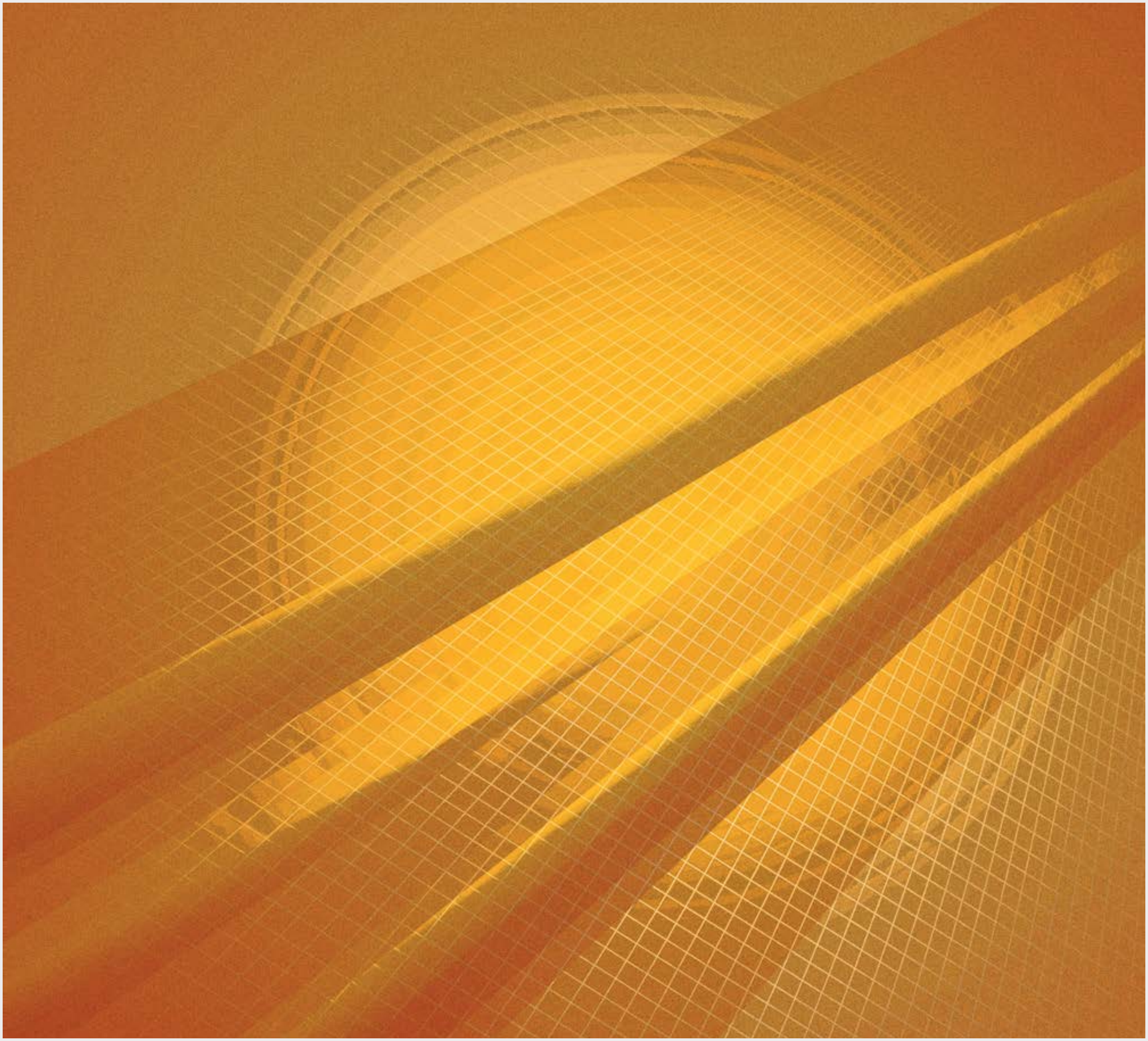

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