





annual report 2015

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On the cover

This 360° view inside one of CQT's labs shows a setup built to study quantum matter. The red laser helps cool atoms close to -273°C. Atoms this cold no longer behave like particles but more like waves. The green laser controls the atoms for experiments to help us understand phenomena such as superconductivity and magnetism. This project is run by Kai Dieckmann's group. Photo Credit: Daniel K. L. Oi / CQT, National University of Singapore



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LETTER FROM THE DIRECTOR



Do you like assessments, writing progress reports, endless statistics on publications, impact factors and the like? Of course not. Nobody does, but, once you are given a licence to turn taxpayers' money into quantum technologies, it is only fair that you tell others what you did with that money. An International Review Panel convened in 2015 to assess CQT's first seven years of operation reported that it was "impressed". Needless to say, I knew we were doing well, but it is always nice to hear it from others, especially those who can offer impartial judgement and constructive criticism. The end result: CQT will continue to receive core funding through to 2022.

After hearing the good news, some of us went celebrating. I can only recall one CQTian, a beer-maker, quoting the Heineken Uncertainty Principle which says that "you can never be sure how many beers you had last night". Disclaimer: we are not sponsored by Heineken (some of us are partial to local Tiger) but if we were offered such sponsorship on good terms we would consider it.

Humour aside, while going through the review process I realised that the 2022 horizon, six years away, is almost another era in this rapidly moving field. So much progress has been made in the past six years (not necessarily in the directions we originally anticipated) that one can hardly speculate what will happen by then. Of course, I can stretch my imagination and suggest quantum random number generators in local casinos, island-wide quantum key distribution networks, quantum simulators which help to design new drugs, and super-precise atomic clocks leading to a super-accurate global positioning system. But the thing is, each year brings surprises.

Just this year our computers scientists surprised us, and the whole international community, by overturning a long-held belief that some forms of quantum computation can admit only quadratic speed-up. They showed that quartic speed-up is possible (see pp. 32–33). This can open new directions for research. How could we possibly have foreseen this development a few years ago? We could not. And there are other surprises as well. For example, we were genuinely surprised when we learned that the explosion that destroyed the Antares rocket carrying our payload did not destroy CQT's Small Photon-Entangling Quantum System (see p. 25). So, dear industrial partners and colleagues out there in the commercial world, if you are after truly robust quantum technology, look no further, talk to us!

happening.

"I knew we were doing well, but it is always nice to hear it from others, especially those who can offer impartial judgement and constructive criticism."

Talking about the commercial world, one of the major problems we will be facing in years to come is finding an optimal balance between basic and applied research. For some, basic research seems to be terribly inefficient and its practical results hard to predict. For others, myself included, it is the essence from which the practical applications of knowledge is drawn. Both sides have arguments. I believe CQT's strength is mostly in basic research, but we should certainly diversify our research and include more industry-related projects in our portfolio. I am glad to say that this is already

Even though I cannot tell you what exactly we will be working on six years from now, I do know that we will be doing something interesting. I can say this with some degree of certainty because I see genuine guality and potential in our team. I must stress that the team means not just academic researchers but literally everyone at CQT. This report will tell you more about our people and the many things they have achieved in 2015. I hope you will like it.

Artur Elient

About CQT

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CQT AT A GLANCE

The Centre for Quantum Technologies brings together quantum physicists and computer scientists to conduct interdisciplinary research into the foundations of quantum theory and the ways quantum physics enables new technologies. CQT was established in December 2007 as Singapore's inaugural Research Centre of Excellence with support from the National Research Foundation and Ministry of Education.



< CQT is hosted at the National University of Singapore (pictured). The Centre also has staff and facilities at Nanyang Technological University.

Budget overview 2015



In 2015 CQT researchers published more than 150 papers. The chart shows CQT's cumulative research output since the Centre was established.



CQT research covers a broad range of topics. We are developing tools to control the behaviour of individual particles of matter and light – atoms and photons. Harnessing quantum phenomena at this scale can enable technologies that you would think impossible – from incredibly precise clocks (see pp. 34–35) to the speeding up of computation (see pp. 32–33).



Explore more highlights of our published research on pages 24-29. Learn more at quantumlah.org/research

Equipment Manpower 2,007,648 9,841,471 5,951,837 Other Operating Expenditure

People

PRINCIPAL INVESTIGATORS



< Dzmitry Matsukevich **Experimental Physics**

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

Björn Hessmo 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



Rainer Dumke **Experimental Physics**

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



< Alexander Ling **Experimental Physics**

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

>



Kai Dieckmann **Experimental Physics**

>

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





< Christian Kurtsiefer **Experimental Physics**

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

Wenhui Li

Singapore





< Murray Barrett **Experimental Physics**

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

A "unique feature of the CQT PIs is the team spirit and the dynamism that is necessary for identifying and venturing into new experimental research directions"

International Review Panel, 2015

Experimental Physics

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



PRINCIPAL INVESTIGATORS



Dagomir Kaszlikowski >

Theoretical Physics

Other appointments:

Associate Professor,

Department of Physics,

National University of

Singapore

< Valerio Scarani **Theoretical Physics**

IA.XI

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



Theoretical Physics

Other appointments:

Associate Professor,

National Institute of

Education and Deputy

Director, Institute of

Advanced Studies, Nanyang

Technological University,

Stephanie Wehner Computer Science

Other appointments: Associate Professor, QuTech, Delft University of Technology



Berthold-Georg Englert > Theoretical Physics

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

Troy Lee

Singapore



Theoretical Physics

Other appointments:

Engineering, Technical

Assistant Professor, School

of Electronic and Computer

University of Crete, Greece

Rahul Jain

of Singapore



>

< Miklos Santha **Computer Science**

Other appointments: Senior Researcher at CNRS in the Laboratoire d'Informatique Algorithmique: Fondements et Applications at the University Paris Diderot, France

Computer Science

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



>



< Hartmut Klauck **Computer Science**

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

Computer Science

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



2 People

PhD Students Aarthi Meenakshi Sundaram Aitor Villar Zafra Alessandro Landra Alexandre Roulet Anurag Anshu Aram Mikaelyan Bharath Srivathsan Cai Yu Chai Jing Hao Chi Huan Nguyen Christian Gross Corsin Pfister Dai Jibo Debashis De Munshi Ding Shiqian Davit Aghamalyan Eduardo Javier Paez Barrios Ewan Munro Filip Auksztol Francesca Tosto Frederic Leroux Goh Koon Tong Gurpreet Kaur Gulati Han Jingshan Hermanni Heimonen Hu Yu-Xin Jaren Gan

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Supartha Podder Swarup Das Tang Zhongkan Kamiyuki Xavier Tarun Dutta Thi Ha Kyaw Ulrike Bornheimer Vamsi Krishna Devabathini Ved Prakash Victor Javier Huarcava Azanon Wei Nie Wilson Yue Sum Chin Wu Xingyao Ye Luyao Zhang Zhiqiang

Research Assistants

Andrew Bah Shen Jing Attila Pereszlenski Brigitta Septriani Do Thi Xuan Hung Elnur Hajiyev Ew Chee Howe Gan Koon Siang Guan Yilun Gupreet Kaur Gulati Kwong Chang Jian Lee Chern Hui Leong Xu Heng Victor Ley Li Yuan Musawwadah Mukhtar

Nelly Ng Huei Ying Nguyen Thi Phuc Tan Noah Van Horne Oon Fong En Pramod Mysore Srinivas **Ritayan Roy** Robert Pisarczyk Shalima Binta Manir Shi Yicheng Tan Peng Kian Tan Yue Chuan Thi Ha Kvaw Vindhiya Prakash Yau Yong Sean

Senior Research Fellows

Gleb Maslennikov Itai Arad Martin Rudolf Kiffner Noh Chang Suk Thibault Thomas Vogt Yu Sixia

Research Fellows

Alessandro Cere Andrew James Philip Garner Cai Yu Chia Andy Hsiao-Li Christoph Hufnagel Dai Jibo Guo Ruixiang Han Rui James Anthony Grieve Jamie William Jonathon Sikora Jean-Daniel Bancal Kadir Durak Kanhaiya Pandey Kyle Joseph Arnold Laura Mancinska Le Huy Nguyen Lee Changhyub Lee Su-Yong Loh Huangian Ma Ping Nang

Markus Debatin Markus Philipp Baden Maria Martinez Valado Michal Hajdusek Michele Dall'Arno Mischa Woods Mohamed Riadh Rebhi Nicholas Charles Lewty Poh Hou Shun **Robert Bedington** Sai Vinjanampathy Saptarishi Chaudhuri Shabnam Safaei Shang Jiangwei Tan Kok Chuan Bobby Jayne Elizabeth Donovan Thompson Tomos Harry Johnson Trappe Martin-Isbjoern Yu Deshui

Benny Joakim Andersson

Paul Constantine Condylis Pawel Krzysztof Kurzynski

Research Associates

Aarthi Lavanya Dhanapaul Cheng Too Kee Chng Mei Yuen, Brenda Truong-Dzuy Edward Truong-Cao

CQT Fellows

Oh Choo Hiap Benoit Gremaud

Ng Hui Khoon



Visiting Research Professors

Dieter Hans Jaksch Ghassan Georges Batrouni John Carlos Baez Joannes Theodorus Maria Walraven Jose Ignacio Latorre Luigi Amico Masahito Hayashi Miniatura Christian Pierre-Marie Rosario Fazio Thomas Francis Gallagher

Visiting Research Associate Professors

Antia Lamas Linares David Paul Maxime Wilkowski David Andrew Wilson Hutchinson Gabor Ivanyos Visiting Senior Research Fellows

Dmitry Gavinsky Mile Gu Thomas Georges Pierre Vidick Venkatesh Srinivasan

Visiting Research Fellow

Tristan Farrow

Research
Assistant
ProfessorsLKY
Postdoctoral
FellowJoseph FitzsimonsMatthias Steiner

Joseph Fitzsimons Tomasz Paterek

Research Support

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Administrative Staff

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Lim Mei Yin, Valerie Lim Mui Lian, Amell Mashitah Bte Mohammad Moasi Norima Bte Mohamat Sarnon Poovathumkal Raju Resmi Tan Ai Leng, Irene Tan Hui Min Evon Tan Lay Hua Valerie Hoon Yeo Kwan San Timothy

ALUMNI

The CQT research community is constantly renewing itself as students graduate and postdocs move on. By the end of 2015, the Centre had 223 academic alumni. The data presented here are collected from 97 responses to a survey of our former CQTians.

Top ten destinations





Type of job



Read interviews with some recent graduates of our PhD programme on pages 40–41.

GOVERNING BOARD

Lam Chuan Leong (Chairman)

- Senior Fellow, Lee Kuan Yew School of Public Policy, National University of Singapore
- Director, ST Electronics (Info-Software) Systems Pte Ltd
- Serguei Beloussov
- CEO, Acronis
- Senior Founding Partner, Quantum Wave Capital
- Founding Partner, Runa Capital
- Chairman of the Board and Chief Architect, Parallels
- Chairman of the Board of Trustees, Russian Quantum Centre

Nicholas Bigelow

• Professor of Optics, The Institute of Optics, University of Rochester

Chang Yew Kong

• President, ST Electronics Software Systems Group

Artur Ekert

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

Ho Teck Hua

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

John Lim

• Divisional Director, Higher Education Policy Division and Divisional Director, Higher Education Operations Division, Ministry of Education

Lee May Gee (Alternate member)

• Deputy Director (Higher Education), Ministry of Education

George Loh

• Director, Physical Sciences & Engineering Directorate. National Research Foundation

Lui Pao Chuen

• Advisor, National Research Foundation

Tan Eng Chye

• Deputy President (Academic Affairs) and Provost, National University of Singapore

Tan Geok Leng

• Executive Director, Science and Engineering Research Council, A*STAR

Changes to the Governing Board in January 2015

Ho Teck Hua replaced Barry Halliwell, Tan Chin Tuan Centennial Professor and Senior Advisor to the President, NUS

SCIENTIFIC ADVISORY BOARD

Ignacio Cirac

• Director, Head of Theory Division, Max-Planck Institute of Quantum Optics

Atac Imamoglu

• Head of Research, Quantum Photonics Group, Institute of Quantum Electronics, ETH Zurich

Gerard Milburn

• Director, Centre for Engineered Quantum Systems, University of Queensland

Michele Mosca

Deputy Director and Co-founder, Institute . of Quantum Computing, University of Waterloo

Christophe Salomon

• Research Director, Laboratoire Kastler Brossel, CNRS

Umesh Vazirani

• Director, Berkeley Quantum Computation Center (BQIC), Computer Science Division, College of Engineering, UC Berkeley

Jun Ye

• JILA and NIST Fellow, University of Colorado and National Institute of Standards and Technology



∧ The SAB makes an annual visit to CQT to talk science. Here Gerard Milburn (right) is in conversation with CQT Principal Investigator Berge Englert (left).



DECIDING **OUR FUTURE**

CQT went through two reviews in 2015

An International Review Panel (IRP) convened in 2015 to assess CQT's first seven years of operation reported that it was "impressed". The IRP conducted an external evaluation of the Centre arranged by Singapore's Ministry of Education (MOE) "to provide a critical assessment of CQT's performance, strategic relevance and future potential."

The IRP's report (see box below) formed one input to the Academic Research Council that advises on the spending of Singapore's research budget. We were pleased to learn following the meeting of this council that CQT will continue to receive core funding through to 2022. Initial grants to the Centre were to fund its first ten years of operation, until the end of 2017.

Objective Perspective

At the invitation of Singapore's Ministry of Education, eminent scientists joined an International Review Panel (IRP) to help assess the performance of CQT. The members of the IRP received a selfassessment report from the Centre and spent four days in Singapore in April for meetings with staff and stakeholders. The IRP was asked to focus first and foremost on assessing CQT's quality of research and organisation, followed by its success in talent development.

The panel summarized its report as follows: "The International Review Panel has been impressed by the achievements of the Centre for Quantum Technologies. In a short time span, it has attracted world-

class researchers, both senior and junior, established a strong relationship with local Universities and built the requisite infrastructure to support the Centre. These elements culminated in making a strong scientific impact in the international community and built a reputation of excellence for Singapore."

Considering the Centre's long term potential, the IRP wrote "Quantum" science is an unusually dynamic field with frequent ground-breaking developments on both sides, theory and experiment. CQT has emerged as a major player in this field, with a potential to influence its future trajectory."

Details of the support to come from the Centre's major stakeholders - MOE, the National Research Foundation (NRF) Singapore and our host university, the National University of Singapore - will be confirmed in 2016.

As well as welcoming the IRP in April, the Centre hosted its Scientific Advisory Board in July. The scientists on the board made strategic recommendations for changes that could strengthen CQT (see box to right).

We are grateful to the many people involved in organising and carrying out these assessments for their careful help in shaping CQT's future.

Members of the IRP, 2015

Raymond Laflamme (Chair) Director, Institute of Quantum Computing, University of Waterloo

Gerd Leuchs Director, Max Planck Institute for the Science of Light

Andrew Yao Dean, Institute for Interdisciplinary Information Sciences, Tsinghua University

Observer: Nicholas Bigelow Rochester

On Doctors' Advice

The members of CQT's Scientific Advisory Board (SAB) made their annual visit to the Centre in July. In a report submitted to CQT's Governing Board and Principal Investigators, the SAB writes "As the Centre had completed a major external review just prior to the meeting of the SAB, we have taken this opportunity to take a more strategic view of the Centre's research program and general operations."

The report outlines the big picture, noting that CQT "is now planning for the next phase of operation beyond 2017... The Centre should continue to seek targets of opportunity to ensure that it remains a global leader in fundamental quantum science."

The report also presents a set of recommendations for the Centre spanning funding, staffing and facilities. These include the suggestions that "every PI has at least one external grant, either held individually or in collaboration with another PI" and that "the Centre establish an internal PhD research workshop run by the PhD students themselves. This should include an event to encourage experimental students to visit other laboratories."

Atac Imamoglu

(Ex-officio Member, CQT SAB) Head of Institute for Quantum Electronics, ETH Zurich

(Representative of MOE's Academic Research Council, CQT GB) Lee A. DuBridge Professor of Physics & Optics, University of

NEWS IN BRIEF

What we did this year...

Applauded our two APS Fellows

Two of CQT's founding members, Professors Oh Choo Hiap and Berge Englert, were elected Fellows of the American Physical Society in 2015. The society has some 51,000 members around the world, with fellowship limited to no more than 0.5% of this number. Choo Hiap (pictured right) was cited "For vital contributions to the development of physics teaching and research in Singapore, especially establishing its leading position in research in quantum technology, and for important personal contributions to this field." Berge (left) was cited "For distinctive theoretical contributions to the foundations, interpretation, and applications of quantum mechanics."



Got inspired at the theatre

The CQT writer's residency of Singaporean playwright Eleanor Wong culminated in March in two evenings of performance at Centre 42 theatre. Drawing inspiration from ideas and themes in the quantum world to inform and illumine ordinary life, *Initial Conditions* was presented as a staged reading by Cake Theatrical Productions with support from Centre 42. The piece will become part of a larger meditation on love and relationships in a changing world. Eleanor gathered material for her work over four months in 2014 through meetings with scientists, lab visits and attending talks.

The Quantum Immersion writer's residency is supported by Singapore's National Arts Council. CQT welcomed Tania De Rozario as the Centre's writer-inresidence for 2015 in September.



Photo Credit: Tuckys Photography

Co-organised a UK-Singapore Quantum Symposium

The Symposium held 26–27 March at NUS brought together leading researchers in quantum technologies from the UK and Singapore. Both countries have made longterm investments in quantum tech: Singapore in CQT and the UK in the 2013 announcement of a national Quantum Technologies Programme worth £270 million. The meeting's goals were to foster the exchange of ideas and spark collaborations. The event was organised by CQT and the British High Commission's Science and Innovation team.

Exhibited all over town

There were many opportunities for the public to meet us this year. CQT's research in quantum cryptography was featured in the NUS exhibition "Building Our Nation through Science and Technology" on campus and in shopping malls. We also took hands-on setups to Xperiment, the opening event of the Singapore Science Festival. Held at VivoCity mall, the three-day event is estimated to have attracted 35,000 people.

Last but not least, CQT organised a one-day showcase at Singapore's ArtScience museum in December, offering seven zones of exhibits including experiments and film screenings. Some 400 people visited. "Even my 5 year old enjoyed it. The presenters did a good job explaining on her level," wrote one visitor on their feedback form.







Awarded film prizes

The Quantum Shorts contest that launched in 2014 reached its conclusion in April, with prizes awarded to a handful of quantum-inspired movies under three minutes long. Top prize went to UK-based artists Ruth Jarman and Joe Gerhardt, known as Semiconductor, for a visualization of data captured during a geomagnetic storm in the Earth's upper atmosphere. Judge Charlotte Stoddart, head of Multimedia at *Nature*, said "20Hz is a beautiful and mesmerising film." *Nature* and *Scientific American* were media partners for the 2014 contest. We launched a new Quantum Shorts contest for flash fiction in September, teaming up with quantum centres around the world as scientific partners.





Congratulated our young innovator

CQT's Joe Fitzsimons, who does research on the theory of quantum computing, was one of ten scientists and entrepreneurs selected for the 2016 MIT Technology Review's 'Innovators Under 35 Asia' list. He is best known for being a co-inventor of blind quantum computing, a protocol to delegate a computation to a remote quantum computer while keeping the description of the computation hidden from the device executing it.

Joe is a Research Assistant Professor with CQT and an Assistant Professor at the Singapore University of Technology and Design. He was awarded a National Research Foundation Fellowship in 2013.

Hosted the International Conference on Laser Spectroscopy

Some 240 scientists, students and exhibitors from 25 countries came to Singapore for ICOLS 2015, a prestigious biennial conference in atomic, molecular and optical physics. The conference was held 28 June to 3 July at the Shangri-La Rasa Resort on Sentosa island. "We had great talks on topics ranging from a new quantum authentication protocol to the extreme precision of atomic clocks and research on optical activation of neurons. The ambience of the venue was also very nice," said Kai Dieckmann, CQT Principal Investigator and chair of the organising committee.

The next major international conference to be hosted by CQT is the 13th International Conference on Quantum Computing, Measurement and Communication, to be held at NUS University Town 4–8 July 2016.



Graduated PhD students

Eight CQT PhD students were formally awarded their doctoral degrees at the NUS commencement ceremony on 9 July. "It has been, and continues to be, a privilege to have all these talented young people in our PhD@CQT programme," says Berge Englert, head of CQT's Academic Committee. Including this year's cohort, CQT has seen a total of 25 students graduate since its programme was established in 2007.

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Launched Generation Q Camp

Thirteen students from eight Singapore junior colleges attended Generation Q Camp, an ntensive three-day workshop at CQT in June. Organiser Jamie Sikora, a Research Fellow, said "I wanted to introduce young students to the exciting worlds of quantum physics, advanced mathematics and cryptography. The goal of the camp is to give a quick glimpse of quantum cryptography, explain why it's secure, and how such devices are being built today." One participant said the camp nad "made quantum mechanics much more appealing and exciting to me".

SCIENCE UPDATES

Highlights of our published research....

Photons shape up

CQT's quantum mechanics demonstrated an elegant trick to shape photons to be more easily absorbed by atoms (Physical Review *Letters* **113**, 163601). The technique could be used in devices that shuttle information between photons and atoms and back again. Christian Kurtsiefer and his team first created a pair of correlated photons, then engineered the shape of one by operating on the other. Their goal was a photon of exponentially rising brightness. A cold cloud of Rubidium atoms (pictured) create the photons.



Boost for interactive proofs

A big question for researchers in quantum computing is, where does quantum physics give an advantage? CQT researcher Joe Fitzsimons and his collaborator have added to the list with a "multiprover interactive proof system" that gains power by exploiting entanglement. The findings were presented at conferences in 2015 (preprint at arXiv:1409.0260).

An interactive proof is when the verifier can question a more powerful but untrustworthy 'prover'. Computer scientists know that you can check a wider range of proofs with access to this kind of help than you can without, and that if you add more provers you can do better still. The discovery that you can verify even more from entangled provers was, however, unexpected because people had thought provers might use entanglement to cheat.

Experiment survives rocket explos

CQT's first satellite payload - a quantum photon source - survived being in a rocket that failed on launch, disintegrating in a giant ball of fire. "We don't know how the device survived the explosion, but this has validated the years of careful design that was put into the project," CQT researcher Alexander Ling told the Straits Times newspaper, which covered the news in August. The device was a first generation of the Small Photon-Entangling Quantum System (SPEQS), intended to test technology for a global quantum communication network.

The group will not reuse the recovered device but have written up the post-explosion test results for publication (preprint at arXiv:1512.08834). They also have new generations of the device ready for the next attempt to reach orbit.



Two mysteries become one

Wave-particle duality and uncertainty have been fundamental concepts in quantum physics since the early 1900s - now we know they are different manifestations of the same thing. This is thanks to work by an international team led by Stephanie Wehner (Nature Communications 5, 5814).

The quantum uncertainty principle sets a limit on how precisely you can know certain pairs of a particle's properties at once. Stephanie's team found that knowledge about the wave versus particle behaviour of a system is constrained in exactly the same way. They used the language of entropic uncertainty relations to make the connection.



Introducing the quantacell

"The authors hope that this article will inspire Tesla Motors to start developing quantum batteries for their vehicles". That small note comes at the end of a theoretical paper by CQT's Sai Vinjamapathy and co-authors proposing that quantum batteries could charge faster than classical ones (New Journal of Physics 17, 075015).

The imagined battery is made from an array of particles, each of which can be 'charged' by absorbing energy to go from a lower to a higher energy state. The researchers find that the time it takes to charge N particles can scale as 1/N – in other words, the bigger the battery, the faster it charges. The speed-up is possible because entanglement is created between the particles. The best you'd expect without entanglement is a constant charging time.

Computing with time travel

A message sent back in time could help us to perform currently intractable computations - even if that message is never read, according to work by CQT's Mile Gu (*npj Quantum Information* **1**, 15007) and his collaborators. Researchers had previously found that messages sent into the past along closed timelike curves could gain computational power, but physicists dislike closed timelike curves because they violate causality. The classic example is that someone could travel back in time and kill their grandfather, negating their own existence. The team's new scheme sidesteps this issue by using open timelike curves that don't allow any interaction with the past. They showed that there is still a gain in computational power as long as the time-travelling particle is entangled with one kept in the present.



Calling on entanglement witnesses

In a collaboration with Singapore's Data Storage Institute, Berge Englert's group demonstrated an improved scheme for detecting entanglement, which is the property of two particles existing in a shared state. Entanglement is an essential ingredient for quantum protocols in communication and computation, making an ability to test for it important.

Previously it was thought that you would need as many as 15 witness measurements to be sure that two qubits were entangled. The new scheme needs at most six measurements and a mean of only 2.5, when the witnesses are chosen carefully (Physical Review Letters 113, 170402). The tests were performed on photon pairs, assuming the source produces identical pairs each time.



Precision with Barium

Manas Mukherjee's group at CQT measured properties of Barium ions with record precision (Physical Review A 91, 040501). The results are relevant to the search for physics beyond the Standard Model because Barium is a strong candidate for studies of parity violation.

The team measured transition probabilities and branching fractions for $^{138}Ba^+$ from an excited *p*-state to lower energy s and d states. Their findings were in agreement with but up to six times more precise than the previous best experimental results. The data constrains theoretical predictions which vary because they depend on simplifying assumptions.



The second laws of quantum thermodynamics

The second law of thermodynamics says that entropy will increase, describing things as diverse as the cooling of a cup of coffee, the efficiency of engines and the heat death of the Universe. Now researchers including CQT's Stephanie Wehner have shown that the classical second law has a family of cousins operating at smaller scales (PNAS 112, 3275). The discovery of these second laws of quantum thermodynamics will be important to understanding the behaviour of quantum systems and nanomachines. The new laws converge to the traditional one when applied to large systems.

Extreme quantum weirdness

CQT researchers observed the most extreme guantum weirdness ever measured in the lab. The precision measurement of entanglement in photon pairs by Christian Kurtsiefer's group pushed close to Tsirelson's bound - the quantum limit for the Bell test they performed. The achievement is evidence for the validity of quantum physics and will bolster confidence in schemes for quantum cryptography and quantum computing designed to exploit this phenomenon. Coauthored with a theorist from the University of Seville in Spain, the paper (Physical Review Letters 115, 180408) reports that the measurement also rules out a proposed extension to quantum theory.



Majoranon simulation

An experiment brought into virtual existence an impossible particle known as a "Majoranon" (Optica 4, 454). The work involving CQT theorist Dimitris Angelakis was proof-ofprinciple that quantum simulation techniques can explore the boundaries of known physics. Dimitris' team had earlier proposed a way to simulate the famous Majorana equation, which has two solutions representing different types of particles. One solution is thought to describe neutrinos, chargeless particles that interact so weakly with matter that you don't notice the billions of them streaming through you every minute. The other solution is the 'Majoranon', presumed not to exist because it would violate the law of charge conservation. This forbidden physics was possible in the simulation, however, performed in Germany with light in a waveguide chip.

6

CAPTURING VALUE FROM FUNDAMENTAL RESEARCH

CQT can offer technology, advice and skilled manpower to local business and government writes Alexander Ling, who leads the Centre's outreach to industry

In 2015, researchers from CQT held a record number of meetings with representatives from industry and government agencies. We hosted delegations in our laboratories and participated in events such as the "R&D Showcase to Large Local Enterprises (LLEs)" organised by Singapore's National Research Foundation in July.

With growing global interest in the commercial potential of quantum technologies, from the precision sensors of today to the quantum computers of the future, we see CQT having an important local role to play. We aim to deliver value from our research in three ways: through innovation, by providing advice and as a source of skilled people.

As an advisor

As quantum devices reach technological maturity, industry is becoming more interested in how they work. Here CQT plays an important advisory role. CQT can keep local stakeholders informed about how guantum technology can impact their operations. This includes knowing, for example, how the prospect of a quantum computer threatens public key encryption systems, or about the cutting-edge capabilities of single-photon detectors. We are preparing to give workshops on high-interest topics.

As a source of manpower

CQT trains its researchers and students to a high standard. We have created a core of people who could staff future technology businesses. To encourage innovation, businesses need to employ active problemsolvers - and there's no doubt that doing research at CQT develops such skills. Giving decision makers a first-hand look at our facilities and research outcomes makes clear what our graduates can do.



As an innovator

CQT is exploring how to commercialise some of its own technological innovations. Because CQT is primarily a basic science organisation we are looking to license our ideas or build partnerships to make this happen. We hope to see joint projects emerging from our ongoing conversations in the next few years. We will also support any researchers who want to strike out on their own to form start-ups through the University's enterprise programmes.

products.

work.

their experiments.

Businesses or agencies interested in collaborating with CQT or learning more about CQT research can contact Alexander Ling at cqtalej@nus.edu.sg

CQT benefits from doing outreach to industry too. We are gaining new perspectives on how to frame our research questions and deeper insight into the problems industry and agencies want to solve. Our meetings are often a two-way exchange of ideas.

Open conversation may be the way we discover value in the 'collateral outcomes of fundamental research. To build experiments that push the forefront of human knowledge, scientists often invent new technologies to help. These technologies are not the goal of the research but side-

In one presentation we gave about CQT technology for secure communication, for example, we described how we distribute a key using entangled photon pairs born within a few femtoseconds of each other. Our visitors were interested in whether the photon timing could be used to provide time-keeping without relying on an external service like the global positioning system (GPS). The idea had struck us too, and we could point our visitors to a CQT paper about how this might

We don't know yet if this idea will be pursued commercially, but there is precedent for collateral discoveries to become big successes. A famous example is the world wide web, first created by scientists at the particle physics laboratory CERN to manage information about

6

A RECORD QUANTUM SPEED-UP

CQT Principal Investigators Troy Lee and Miklos Santha overturned a longheld belief about what quantum algorithms can achieve

This year CQT computer scientists and their collaborators busted a hypothetical ceiling on quantum speed-ups, the theoretical speediness of a quantum versus a classical program in solving a problem.

It was big news in the community. The results were greeted as a "breakthrough" on the widely-read blog Shtetl-Optimized by computer scientist Scott Aaronson at the Massachusetts Institute of Technology. He wrote "The highest compliment one researcher can pay another is, 'I wish I'd found that myself.' And I do, of course, but having missed it, I'm thrilled that at least I get to be alive for it and blog about it. Huge congratulations to the authors!"

Double powered

Whereas the previous best quantum advantage for 'total functions' was the quadratic speed-up of Grover's algorithm - for searching unsorted databases – the new speed-up is that squared: it's quartic. The new 'super Grover' algorithm does not solve any particular real-world problem, but its existence raises the possibility that a super-quadratic quantum speed-up is possible for useful functions.

The results appear in the preprintⁱ "Separations in Query Complexity Based on Pointer Functions" by Andris Ambainis, Kaspars Balodis, Alexander Belov and Juris Smotrovs from the University of Latvia and Trov Lee and Miklos Santha from CQT. The work was also selected for a plenary talk at the 19th Conference on Quantum Information Processing (QIP) held in Canada in January 2016 and will be presented at the 48th Annual Symposium on the Theory of Computing (STOC) in the US in June 2016.

Query complexity is a measure of how much one needs to know about the input of a function to determine the output. It comes in different flavours depending on what constraints you apply to how you access the input - including whether you can guery in a guantum way - and if you must know the output with certainty or just with high probability.

Grover's algorithm famously has quantum guery complexity that is a power of two better than that of the classical query complexity.



Written $D(f) \sim Q(f)^2$, it translates to a quadratically faster run-time for the quantum algorithm.

The guadratic separation of Grover's algorithm has remained the best known separation for total functions since the algorithm was described in 1996, despite intensive search for something better. Given this situation, researchers thought Grover's might have hit a limit. "It was really quite a deeply held belief in the community that a quadratic separation was the best possible," says Troy, who is also faculty at Nanyang Technological University. But the team's work uprooted this belief, showing a function for which the quantum query complexity is a power of four better: $D(f) \sim Q(f)^4$.

One of the promises of quantum computing is that we can solve

described a function with a record power-of-four quantum speed up, overturning a long-held belief that you couldn't do better

problems faster, but how much faster? CQT researchers have

An important point is that the speed-up record is only for total functions - ones that accept any input. There's another famous quantum algorithm, Shor's algorithm for factoring, which has an exponential speed-up. However, Shor's is a partial function, meaning that it is defined only for some inputs.

Complexity relationships

everything, work on this" Troy Lee

than quadratic for total functions.

"It was

like drop



The researchers also set new records for the relationships between deterministic and randomised zero-error query complexity (refuting a conjecture that had stood since 1986), and zero-error and bounded-error randomized query complexities. Scott Aaronson and his coauthors have since built on these results, presenting findings including a super-quadratic separation between quantum and randomized query complexitiesⁱⁱ at QIP 2016.

CQT's team initially set out to understand a paperⁱⁱⁱ which improved on earlier results by Miklos, also at the French national research organisation CNRS. "So he was of course interested to see what they had done and see if he could improve it further," explains Troy. The new work involves variants of a function defined in that paper.

Troy and Miklos began working to extend the result with co-author Alexander Belov, who was spending two months at CQT. When Alexander returned to Latvia, he brought in colleagues there. As soon as the team spotted the implications for quantum query complexity, "it was like drop everything, work on this," says Troy. "It was extremely fast. The whole paper took maybe two weeks to write."

(i) Preprint at http://eccc.hpi-web.de/report/2015/098/ (ii) Preprint at http://arxiv.org/abs/1511.01937 (iii) Preprint at http://eccc.hpi-web.de/report/2015/050/ **Projects in focus**

6

TIME KEEPERS

Murray Barrett's group at CQT aims to build the world's best atomic clock



 \wedge This is the lab where the work will happen. Murray (right) is pictured with group member Kyle Arnold.

For most of us, knowing the time to within a few minutes is precise enough. But physicists like CQT Principal Investigator Murray Barrett want to be able to measure time in billionths of a billionth of a second.

Murray's group has proposed a novel scheme for building an atomic clock that could better today's best time-keepers. It's about more than pushing limits. "New generation clocks will inevitably play a crucial role in tomorrow's technology," Murray says.

Atomic clocks are already behind a surprising amount of modern technology, from creating Global Positioning System signals to

synchronizing internet traffic. By international agreement, the second is even defined in terms of a resonance frequency of Caesium atoms at 9,192,631,770Hz.

But the Caesium standard at microwave frequency lags the state of the art. An optical atomic clock based on neutral Strontium atoms currently holds the record for being the world's most accurate and stable clock. Located at JILA, a joint institute of the University of Colorado Boulder and the US National Institute of Standards and Technology, it measures seconds with an accuracy of 10⁻¹⁸ and is so stable that it would neither gain nor lose a second in 15 billion years about the age of the Universe.

Clocks this precise can detect gravity warping time. Einstein's general relativity predicts that clocks tick faster in a weaker gravitational field. "Our performance means that we can measure the gravitational shift when you raise the clock just 2 centimeters on the Earth's surface," JILA's Jun Ye told media in 2015. Ye is a member of CQT's Scientific Advisorv Board.

With just a little more improvement in performance, atomic clocks could be used for mapping the Earth's shape, known as 'relativistic geodesy', with applications in Earth systems modelling, monitoring and mineral and oil exploration. Ultimately the second could end up being redefined, too.

Looking to Lutetium

Murray's group wants to use an optical transition in Lutetium ions not previously considered a clock candidate - to develop this next generation of technology. The scheme relies on a novel idea he has dubbed 'hyperfine averaging'.

In an atomic clock, it's the oscillations of the laser that define the tick-tock for counting time. The role of the atoms is being a stable frequency reference. The laser is tuned to match the energy gap of an atomic transition from a lower to a higher energy level. To keep

that transition frequency as constant as possible, the atoms must be protected from external influences such as magnetic and electric fields that can shift the atom's energy levels. Previous atomic clocks have been based on transitions between energy levels with zero orbital



∧ The energy levels of Lu⁺ make it a strong clock

adapted from ref (i).

candidate when hyperfine averaging is applied to the ¹S₁ -> ³D₁ transition. The scheme to the right shows the

hyperfine splitting for this transition in ¹⁷⁶Lu⁺. Figure

Lu⁺ ions could work in a lattice because they have 'negative polarisability'. Researchers including Nobel Prize winner David Wineland observed as long ago as 1998 that this property leads to the existence of a 'magic frequency' where the frequency shift caused by the ions' motion cancels the shift in energy levels caused by the field.

project.

angular momentum (J=0) which are intrinsically resistant to external fields. Murray realised that you can instead create an effective J=0 level by averaging over a set of transitions between multiple hyperfine levelsⁱ. This hyperfine averaging means you can consider atomic transitions that were previously ruled out.

Murray zoomed in on Lutetium because it fulfills the criteria for hyperfine averaging to work, that the atom have a nuclear magnetic moment greater than the transition states' orbital angular momentum He had also spotted a promising clock transition in Lu⁺ ions that has a

In a paperⁱⁱ co-authored with CQT colleagues Kyle Arnold, Elnur Hajiyev, Eduardo Paez, Chern Hui Lee and international collaborator John Bollinger, Murray worked out the details of this effect for Lu⁺, concluding that "this approach could outperform the current state of the art by an order of magnitude in both stability and accuracy." The group has been awarded A*STAR Public Sector Funding to pursue the

very long lifetime, of around 60 hours. This means it has a very narrow frequency width – just what you want for a reference. "Clocks based on transitions with a lifetime of seconds will eventually become limited by the lifetime. This will not happen for Lutetium," says Murray.

Strength in numbers

There's another novelty in the CQT group's proposal, too. Murray and his collaborators think they can build a clock with a crystal of around 100 Lu⁺ ions. So far clocks using ions have used only one, because the radiofrequency fields used to trap ions cause micromotion that is hard to control in larger collections.

Having more atoms brings the advantage of faster readout, which leads to greater stability. JILA's record-holding Strontium clock uses a lattice of thousands of atoms. Their drawback is that neutral atoms easily escape the trap, meaning the clocks have to be constantly topped up. That causes deadtime in the measurement cycle. Because ions are more effectively trapped than neutral atoms, if the micromotion problem can be solved, an ion lattice could offer the best option of all.

(i) New J. Phys. 17, 053024 (2015) (ii) Phys. Rev. A 92, 032108 (2015) **Projects in focus**

6

MEET THE QUANTUM BUNNY

CQT Outreach Fellow Otto Fong creates science comics for kids

When author Otto Fong applied for a writer's residency at CQT, he wrote "If getting quantum mechanics to the young masses is what CQT seeks, I'm your artist". With the launch in October 2015 of The Quantum Bunny comic book for kids from primary school up, he delivered on that promise.

Otto is the creator of the Sir Fong's Adventures in Science series, of which The Quantum Bunny is book five. He came up with the idea for the comics when he was a science teacher trying to enthuse his students. He's now a full-time author and cartoonist

Whereas the first Sir Fong books concentrated on teaching topics from the science syllabus, The Quantum Bunny brings his readers to the forefront of modern research. Otto spent six months as an Outreach Fellow at CQT, attending undergraduate lectures and meeting one-on-one with CQT researchers.

Reasoning that quantum physics would be hard for children just learning mathematics to grasp, he has wrapped the science into a well-known story. The book is a retelling of the Chinese fable of the Monkey King causing uproar in heaven, now starring Qbit the guantum rabbit. Otto swapped other characters in the classic tale for scientists.



"This book will not teach quantum mechanics to young people, but it will make some of the ideas familiar" he says. "It serves up a fun story about a misunderstood bunny in his quest to be accepted."

The book was launched at the Singapore Writer's Festival, earning a feature in Today newspaper and a spot on the 'bestsellers' shelf of the festival bookshop. Cover blurbs came from US cartoonist Larry Gonick and local artists Sonny Liew and Evangeline Neo, while CQT's Director Artur Ekert wrote the foreword

But the reviews that matter most will be from the audience the book is written for: Singapore's school-age children. As Otto tours schools giving his talks on science, we look forward to gathering their feedback. The Quantum Bunny is available now from Singapore bookshops with an e-book to follow.

Check www.ottoniumcomics.com for news.

v Famous physicists from the past including Niels Bohr and Albert Einstein appear as characters in the comic



"The poppy visuals and adventure story will appeal to kids, and might just serve as a stepping stone for them to learn more about the wonders of the quantum world."

Sonny Liew Comic artist, The Art of Charlie Chan Hock Chye



The sales of Otto's books and others show there is popular appetite today for such educational comics. A manga guide to physics by my friend Professor Hideo Nitta, who is also currently the Chair of the Commission C14 (Physics Education) of the International Union of Pure and Applied Physics, has been translated into several languages.

communication.

An educational perspective **Kwek Leong Chuan**

There is a beautiful saying: "A picture paints a thousand words." Educational research has consistently pointed to the effectiveness of combining text with images to improve retention and reading performances (see Educ. Psychol. 14, 5 (2002)). Otto's book weaving the somewhat mysterious world of quantum physics into a storyboard of comics can tap into this effect.

The use of comics as an educational medium has been generally underrated. For a time comics were even suspected of being bad influences, although proposals for using them in education can be found as early as 1944. W. Sones, a Professor of Education at the University of Pittsburgh, wrote then (J Educ Sociol. 18, 232 (1944)), "It is appropriate to examine from the standpoint of the educational method this most recently arrived entertainment device that has attracted such an extraordinary following."

Indeed, case studies by educators trying to establish and sustain interest in science learning have found that comics help (see for example CBE Life Sci. Educ. 10, 309 (2011)). I believe comics provide an extremely powerful and effective means of science

Kwek Leong Chuan is a Principal Investigator at CQT doing research in theoretical guantum information. He is also a lecturer at Singapore's National Institute of Education and a former physics teacher.

Education

SCIENTISTS IN TRAINING

CQT welcomes students from all over the world to begin research in the exciting field of quantum technologies

PhD Programme

It is part of the Centre's mission to offer high-quality education for graduate students. Students joining CQT are immersed in the fast moving field of quantum technologies, where research spans experimental and theoretical physics and computer science.

In 2015, CQT had 69 students studying under its PhD@CQT programme, which offers 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 also accepts students funded by other sources.

Find more information on the student programme and a description of how to apply at *quantumlah.org/openings/phd*

Internships

CQT offers internships to 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. Successful interns making follow up applications to the PhD@CQT programme will be given high priority.



 "I love physics but I did my undergraduate degree in computer science. Quantum information is the perfect way to join them together. Having that mix of people here keeps your mind fresh."

Anurag Anshu CQT PhD student Rahul Jain's group



"I was a physics undergraduate at NUS and did a project at CQT. I liked it so much I stayed! I've had great opportunities, like spending a semester in Canada taking different courses. "

Goh Koon Tong CQT PhD student Valerio Scarani's group

Main State A Physical Activity Contract State Ac

student has been so far one

of the best experiences in my

life. I've had the opportunity

to meet a lot of new people

and learn the most modern

techniques in quantum

Francesca Tosto

Rainer Dumke's group

COT PhD student

physics."



 "I enjoy the atmosphere here. I find it friendly and constructive. The physics community in Singapore may be small but it is very active in terms of hosting conferences and inviting big international speakers."

Ulrike Bornheimer CQT PhD student Berge Englert's group

Markus Philipp Baden Quantum Optics with Cavity-assisted Raman Transitions Supervised by Murray Barrett

Gurpreet Kaur Gulati Narrowband Photon Pairs from a Cold Atomic Vapour for Interfacing with a Single Atom Supervised by Christian Kurtsiefer

CQT offers lots of room for your own personal growth. Besides my main project, my professor has encouraged me to learn more about what I like and even try different projects for a while."

Nguyen Chi Huan CQT PhD student Christian Kurtsiefer's group

has many researchers who

come from different places.

Singapore is full of diversity.

Vlatko Vedral's group

This experience is different for

Atoms

Quantum Correlations in Composite Particles Supervised by Dagomir Kaszlikowski



me." **Yoshihito Hotta** CQT intern

2015 GRADUATES

Hu Yu-Xin

Artificial Gauge Fields and Topological Effects in Quantum Gases Supervised by Berge Englert

Siddarth Koduru Joshi Entangled Photon Pairs: Efficient Generation and Detection, and Bit Commitment Supervised by Christian Kurtsiefer

Attila Pereszlenyi Studies in Models of Quantum Proof Systems Supervised by Rahul Jain

Bharath Srivathsan Heralded Single Photons for Efficient Interaction with Single

Supervised by Christian Kurtsiefer

Tan Kok Chuan Bobby

Yang Tzyh Haur

Device Independent Playground: Investigating and Opening Up a Quantum Black Box. Supervised by Valerio Scarani

Find CQT PhD theses at quantumlah.org/publications/theses.php

Education

PUTTING A PHD TO USE Life after CQT

"We are proud of our PhD graduates for who they are as people, as well as the scientists they have become. Their training, skills and character mean they have a lot to contribute to society whatever they choose to do next," says CQT Director Artur Ekert.

So what do our graduates do next? For 31 of the 34 CQT PhD students who have successfully defended their theses so far, their next job was in academia.

This year's eight graduates have become postdocs at institutions including CQT, the University of Waterloo in Canada, the Institute for Quantum Optics and Quantum Information in Austria and the Max Planck Institute for the Science of Light in Germany. Other graduates have taken their skills into industry and government jobs.

We've interviewed a few of our recent graduates about their experience after leaving CQT. Thank you Tzyh Haur, Gurpreet and Ved for telling us about your new roles.



Ved Prakash Data Scientist Ministry of Defence, Singapore

What was your path to working at MINDEF?

What is your role?

What is different to academic research?

Where do you see yourself in the future?

Gurpreet Kaur Gulati Postdoc University of Sussex, UK

What research are you doing now?

I am working on a hybrid quantum system that links two vital fields of research: ion trap technologies and cavity quantum electrodynamics (CQED). I am part of the group of Professor Mathias Keller at the University of Sussex.

How is it different to doing your PhD?

I am more like a boss of PhDs now! But honestly, I am learning a lot of new things and that's really encouraging and motivating.

What's your best memory of CQT?

I made many good friends. CQT is like a family. People are easily approachable and ready to help you, whether its admin staff, professors or the Centre's Director.

What do you hope to be doing 10 years from now?

It's a difficult question to answer, but one thing I'm sure of is that I like research and want to keep exploring this path.

What else do you enjoy?

Being from a small town in India, I always dreamt of travelling around the world. Thanks to my research career, through conferences and workshops, I've had the opportunity to visit places that I used to read about in books. I've also made good connections through visiting different labs around the world.



Yang Tzyh Haur Model Validation DBS Bank, Singapore

What do you do at DBS?

I work in the model validation team. We make assessments of

How did you end up working there?

I did an internship with DBS while I was still a student in CQT. I wanted to look for an industry where I could use my skills and at

What is your working day like?

very similar to what I did in CQT! The models are very much like

How do you benefit from your PhD training?

What is the most useful thing you learned at CQT?

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EVENTS

Conferences
&
Workshops



Date	Event	Venue
7 Dec 2015	CQT Annual Symposium: The Famous, The Bit & The Quantum	University Hall, NUS
28 Jun – 3 Jul 2015	The 22nd International Conference on Laser Spectroscopy, ICOLS 2015	Shangri-La's Rasa Sentosa Resort & Spa
26–27 Mar 2015	UK-Singapore Quantum Symposium	University Hall, NUS
19–20 Jan 2015	UMI Majulab Kick-Off Meeting	University Hall, NUS









OUTREACH

Listings

CQT online

The centre's website at quantumlah.org offers up to date news, event listings and links to the group's research pages. It received over 70,000 visitors in 2015.

CQT's YouTube channel hosts videos including interviews, artistic shorts and recorded colloquiua, accumulating over 700 hours of 'watch time' in 2015.

CQT is also active on Facebook (2.2k followers) and Twitter (1.5k followers).

Schools outreach

Some 180 young students visited CQT this year. These visite ranged from lab tours to week-long shadowing experiences and a three-day workshop on quantum physics and cryptography organized by the Centre's postdocs.

Outreach Fellow Otto Fong created Sir Fong's Adventures in

Science Book 5: The Quantum Bunny to introduce quantum physics to the under 16s (see pp 36–37).

PI Kwek Leong Chua offered a workshop at the Thai Science Camp in Bangkok.



In the news

CQT or CQT research was mentioned in over 40 news stories in 2015. Highlights include:

• PI Valerio Scarani recorded a segment on quantum randomness for *The Academic Minute*, a public radio show aired in the US and available online.

• Singapore's *Straits Times* newspaper reported the recovery of a CQT satellite payload that had been presumed lost after the rocket launching it exploded.

- Singapore's *HerWorld* magazine profiled PI Kwek Leong Chuan (pictured) in a feature about men fighting for women's rights, noting his work supporting women in physics.
- The online news portal *Phys.Org* carried seven stories in 2015 about research involving CQT scientists.



Public outreach

CQT participated in three public exhibitions this year, including collaborating with the NUS Science Demo Lab to run a one day quantum showcase at the ArtScience Museum.

We co-organized three public talks with the Science Centre Singapore in 2015, two in conjunction with conferences hosted by CQT.

CQT's Director Artur Ekert was in a panel discussion at the World Science Festival in New York in May. He also spoke to an audience including the public, policymakers and media at the Annual Meeting of the American Association for the Advancement of Science in San Jose in February.

Special projects

The Quantum Shorts contest series reached more than 10,000 people online in 2015. After CQT awarded prizes for 2014's short film contest (see p. 22), our new competition for quantum-inspired flash fiction drew over 400 entries. The 2015 contest is supported by media partners *Scientific American, Nature* and *Tor* and international scientific partners the Australian Research Council Centre of Excellence for Engineered Quantum Systems, the Institute for Quantum Computing at the University of Waterloo, the Institute for Quantum Information at Caltech and the Joint Quantum Institute of the University of Maryland and National Institute of Standards and Technology.

We welcomed Tania De Rozario (pictured) as CQT writer-inresidence for five months from September. She is writing a novella that borrows from quantum physics to inform both its narrative and its structure, in a choose-your-ownadventure style of story. Tania's appointment follows the conclusion of playwright Eleanor Wong's 2014 residency (see p. 20).





Listings

VISITORS



Scott Aaronson MIT, US

Charles Adam Durham University, UK

Luigi Amico Uni-Catania, Italy

Rotem Arnon Friedman ETH. Switzerland

Bai Xueliang University of Sydney, Austria

Nikhil Balaii Chennai Mathematical Institute, India

Alexander Belov MIT. US

Benoit Descamps Vienna Center for Quantum Science and Technology, Austria

Nicholas Bigelow University of Rochester, US

Alessandro Bisio Pavia University, Italy

Blair Blakie University of Otago, New Zealand

Adam Bouland MIT, US

Philippe Bouyer Laboratoire Charles Fabry, France

Michael Brooks Freelance writer, UK

Chen Qing Yun Nan University, China

Kai Chen University of Science and Technology of China

Zhang Chengjie Soochow University, China Ignacio Cirac Max-Planck-Institute for Quantum Optics, Germany

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Alex Kuzmich University of Michigan, US

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Dai Li National Chung Hsing University, Taiwan

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Nana Liu University of Oxford, UK

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Liu Peiliang National Institute of Information and Communications Technology, Japan

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Chabely Pollier TU Delft, the Netherlands

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Apichayaporn Ratkata Chiang Mai University, Thailand

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Luis Sanchez Soto Universidad Complutense de Madrid, Spain

Adam Sawicki MIT, US

Frank Scheffold University of Fribourg, Switzerland

Daniel Schlenk Ludwig-Maximilians-Universität München, Germany

Jörg Schmiedmayer Vienna Center for Quantum Science and Technology, Austria

Ulrich Schollwöck LMU, Germany

Robert Sewell ICFO - Institut de Ciències Fotòniques, Spain

Yashpal Singh Physical Research Laboratory, Navrangpura, Ahmedabad, India

Umesh Vazirani

Marco Tomamichel University of Sydney, Australia

Alessandro Tosini Pavia University, Italy

Edward Truong-Cao

Nickos Sxetakis Anna Szymusiak

Jun Suzuki

Japan

Cyril Stark

MIT, US



Daniel Sternheimer Rikkyo University, Japan & Université de Bourgogne, France

The University of Electro-Communications,

Technical University of Crete, Greece

Institute of Mathematics, Krakow, Poland

University of California Berkeley, US

Stanley Williams Hewlett Packard Labs, US

Bai Xueliang The University Of Sydney, Australia

Yang WanLi Chinese Academy of Science

Jun Ye NIST, Boulder, US

Ki-Hvuk Yee Hanyang University, South Korea

Zhen Yizheng, University of Science and Technology of China

Dahyun Yum Tsinghua University, China

Yicong Zheng University of Southern California, US

Zheng Yulin University of Science and Technology of China

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MONEY MATTERS

Expenditure in 2015

	Manpower	Other	Equipment	TOTAL
Core	8,050,102	4,806,017	1,700,298	14,556,417
External				
NRF CRP	764,052	590,779	152,807	1,507,638
MOE Tier 2 & 3	946,398	466,751	149,230	1,562,379
FQXi	29,963	20,447	-	50,410
NRF Fellowship	-	43,761	5,313	49,074
The John Templeton Foundation	50,956	24,082	-	75,038
Total	9,841,4721	5,951,837	2,007,648	17,800,956

For a listing of all current grants, see http://www.quantumlah.org/main/funding **NRF CRP** Two Grants from Singapore's National Research Foundation (NRF) under its Competitive Research Programme support projects "Hybrid Quantum Technologies" (\$4,325,456) led by Christian Kurtsiefer and "Space Based Quantum Key Distribution" (\$6,059,084) led by Alexander Ling.

MOE Tier 2 & 3 CQT has three research projects supported in 2015 by competitive funding from Singapore's Ministry of Education (MOE). The largest is "Random numbers from Quantum Processes" (\$\$9,931,731) involving 13 PIs led by Valerio Scarani. The other two projects are "Dynamics of coherent dipole-dipole energy transport of Rydberg excitations" (\$650,201) led by Wenhui Li and "Controlling Quantum Matter: Dipolar Molecules in Optical Lattices" (\$616,711) led by Kai Dieckmann.

FQXi The US-based Foundational Questions Institute (FQXi) supports a joint project by CQT and the Adam Mickiewicz University in Poland on the "Operational and information theoretic meaning of contextuality" (USD 98,900) led by Dagomir Kaszlikowski. Dagomir also holds an FQXi mini-grant "Short film 'Three men and the Bell'" (USD 2,500).

NRF Fellowship Computer scientist Troy Lee is funded by a five-year Fellowship (\$2,710,660) from Singapore's National Research Foundation. Portions of the grant are managed by the Nanyang Technological University.

The John Templeton Foundation A grant supports the project "Occam's Quantum Mechanical Razor" (USD 246,100) led by Mile Gu until December 2017.

2007: \$158 million from Singapore's National Research Foundation and Ministry of Education to establish the Centre and fund its operations for up to ten years

CQT is an autonomous research centre hosted by the National University of Singapore, with additional staff and facilities at the Nanyang Technological University (NTU). Support from the universities includes provision of building space, administrative staff and contributions to PI salaries commensurate with the PI's

Stakeholder support

CQT's operations are supported by its stakeholders through direct funding and other contributions. Two major awards of core funding have been made:

■ 2014: \$36.9 million from Singapore's National Research Foundation to fund core operations

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SUPPORTERS



Ministry of Education



PRIME MINISTER'S OFFICE SINGAPORE









FOUNDATIONAL QUESTIONS INSTITUTE

-MajuLab*

CQTians



See you next year!

Centre for Quantum Technologies

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