Centre for Quantum Technologies

NUS National University of Singapore

annual report 2014

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"Our aim is creating a research environment in which investigations into quantum technologies can flourish for years to come."

LETTER FROM THE DIRECTOR

I was recently asked whether it is still fun to run CQT. Apparently after seven years one is supposed to be bored and tired. There is even a name for this. It is known as "the seven year itch", a time of potential crisis when you take stock of your relationship. As CQT passed its seven year mark in December 2014, I decided, with some trepidation, to pause for a moment and reflect upon the question.

Needless to say, my internal perspective on the success of the Centre differs to the one documented by the statistical data that you find in abundance in our reports. To be sure, the facts are impressive. As this report will tell you, in the past year we published more than 190 scientific papers, had eight more students graduate and added a few more grants to our portfolio. You will also read that we organised workshops and conferences, established new collaborations and even helped Singapore's Prime Minister satisfy his scientific curiosity by observing entangled photons with his own eyes. You will discover that we spread the word about quantum by taking part in the Singapore Science Festival, working with *Scientific American* and *Nature* on a film competition and having hundreds of students visit our Centre. These are commendable achievements and I am very proud of them. However, at a personal level, I take most satisfaction from the community we have built.

When you hire a bunch of creative individuals from all over the world, you must be prepared to deal with them in sometimes unconventional ways. You have to be on your toes, always ready to discuss, advise, encourage and, from time to time, calm emotions and extinguish local fires. The goal is to create a community that has more potential than the sum of its individuals, and it requires fine-tuning a complicated human dynamic. When it works, it works beautifully, and it is exactly this part of my role that I find the most rewarding.

It may sound trivial, but I truly believe that teamwork is behind our achievements, counting the effort not only of those who crank equations and turn knobs on our quantum contraptions, but also those who solder wires, check air-cons, marshal visitors, prepare contracts, count money and clean the coffee machines. There are no performance measures for shaping a community, for it can hardly be quantified. Still, when we proudly call ourselves CQTians, we instinctively acknowledge the cohesion we have nurtured over the past seven years.

Our aim is not achieving a temporary peak of research excellence, but rather creating a research environment in which investigations into quantum technologies can flourish for years to come. There are many challenges ahead. We have to consolidate our position in the field, innovate and stay competitive. The consolidation will necessarily involve closer collaborations between different groups within CQT, meaning teamwork will be even more important in years to come.

It takes time and effort to develop a sense of community, and it takes at least the same amount of energy to maintain it. Thus, to be honest, I have no time for the seven year itch. I am filling my mind with fresh ideas and getting ready for action. Taking a break is not an option. You can take it easy when you're dead - living is about the thrill of doing as much as you can. So, we will be busy and you will surely read about all we do in 2015 in our next annual report. For now, enjoy this year's edition, which follows our tradition of making our reports readable, informative and entertaining.

Artur Ekert

CQT AT A GLANCE

What?

"a major international centre for research in quantum information, quantum computing and related quantum technologies"

SAB Report 2014

The Centre for Quantum Technologies brings together quantum physicists and computer scientists to explore the fundamental nature of reality and the ways quantum physics can create new technologies. CQT was established in December 2007 as Singapore's inaugural Research Centre of Excellence.

Who?

- CQT is directed by Artur Ekert, co-inventor of quantum cryptography.
- Research at the Centre is led by 21 Principal Investigators. In total, CQT has more than 180 research staff and 60 students (see pp. 12-15). We have almost 200 alumni (see pp. 16-17).
- CQT has wide networks: in the past year, over 100 researchers visited CQT (see pp. 48-51), and CQT researchers coauthored papers with collaborators across 35 countries. CQT also has nine research agreements with other institutions (see p. 43).

Why?

Singapore's research centres of excellence carry out world-class investigator-led research aligned with the country's long-term strategic interests

- Attract and support world-class academic investigators.
- Enhance graduate education in the universities and train quality research manpower.
- Create new knowledge in the specific areas of focus of the centre.

Why quantum?

- Quantum rules: quantum physics provides our most precise model of the behaviour of the fundamental particles of nature.
- Research in quantum physics has contributed to marvels of modern technology such as the laser, with a new generation of quantum devices in prospect.
- Quantum physics allows fundamentally new modes of communication, computation and sensing. This has implications for classical technologies and applications in new ones.
- Open fundamental questions in quantum physics are driving curiosity-led research. History tells us that fundamental research can spark technological revolutions we could never have predicted.
- We are developing coherent control of the individual particles of light and matter, photons and atoms, an unprecedented level of mastery over nature.

CQT researchers have published more than 190 scientific papers in the past year and over 1000 since the Centre began in December 2007

CQT receives core funding from Singapore government agencies. Prime Minister Lee Hsien Loong, head of the council that sets the national budget for research, innovation and enterprise, is pictured here during a visit to CQT in December 2013.

How?

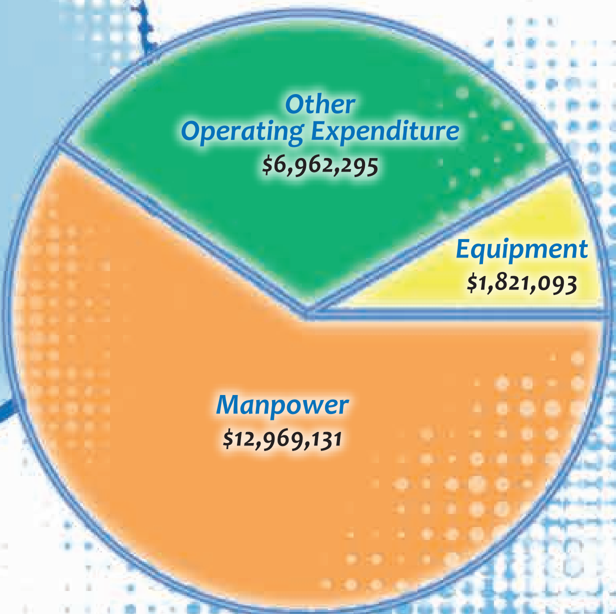
CQT is hosted by the National University of Singapore but enjoys significant autonomy in pursuing its research goals and in governance. The Centre has its own Governing Board and a Scientific Advisory Board (see pp.10-11).

The Centre is supported by its stakeholders, including Singapore's National Research Foundation (NRF) and Ministry of Education (MOE), and by competitive grants.

CQT has received two awards of core funding from NRF and MOE totalling $195 million.

$

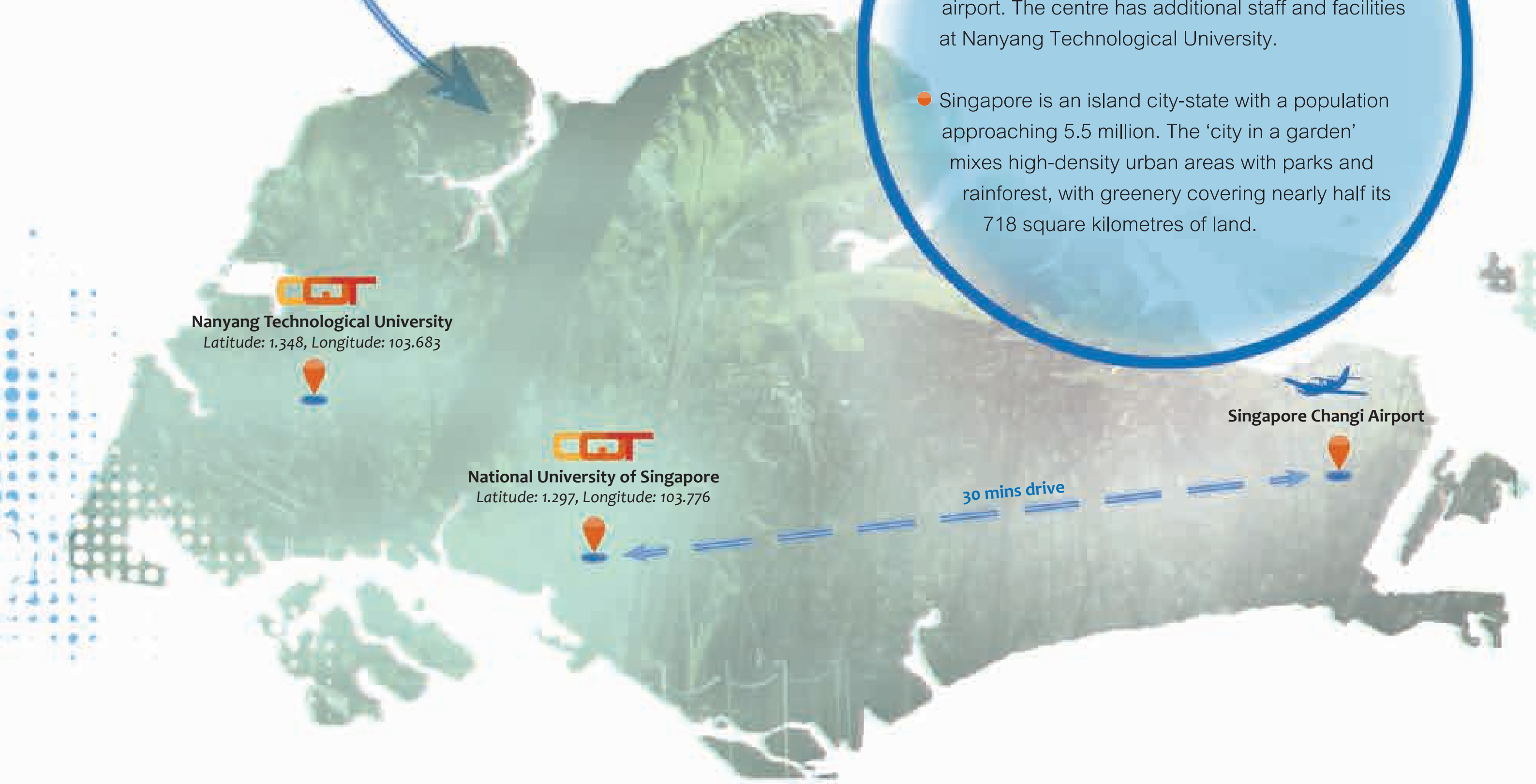
- The Centre's total spending in the year to August 2014 was $21.75 million, the majority covering salaries of the Centre's researchers, students, technical staff and administrative team (cost shown as manpower in the chart).
- Expenditure came from six active external grants, the largest being worth $9.93 million, and from core funds.
- See pp. 52-53 for a full spending breakdown and listing of external grants.



Where?

- CQT's main building is on the campus of the National University of Singapore about 30 minutes' drive from Singapore's international airport. The centre has additional staff and facilities at Nanyang Technological University.

- Singapore is an island city-state with a population approaching 5.5 million. The 'city in a garden' mixes high-density urban areas with parks and rainforest, with greenery covering nearly half its 718 square kilometres of land.



GOVERNING BOARD

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Founding Partner, Runa Capital
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Chang Yew Kong
President, Software Systems Group, ST Electronics Ltd

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

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

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

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John D. and Catherine T. Macarthur Professor and Professor of Physics, University of Illinois at Urbana-Champaign

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Director, Higher Education, 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

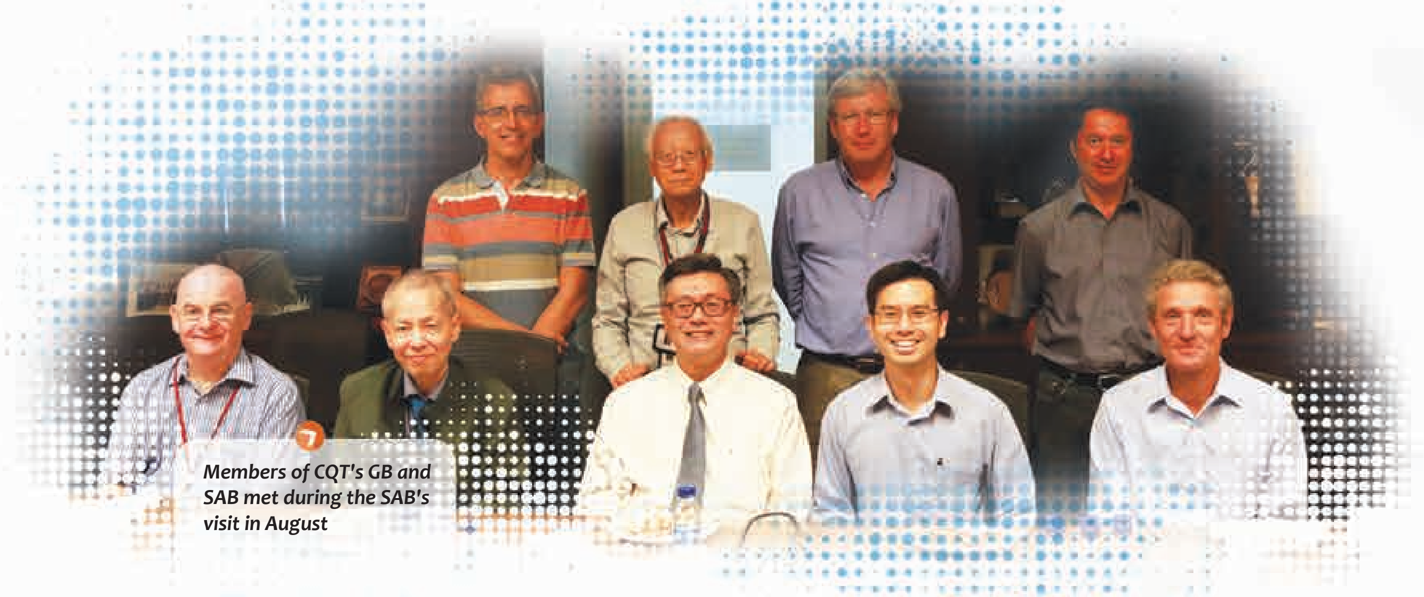
Lui Pao Chuen
Advisor, National Research Foundation

Lye Kin Mun
Deputy Executive Director, Science and Engineering Research Council, A*STAR

Changes to the Governing Board in November 2014

Nicholas Bigelow, Lee A. DuBridge Professor of Physics & Optics, University of Rochester, replaces Randal Bryant

Tan Geok Leng, Executive Director, Science and Engineering Research Council, A*STAR, replaces Lye Kin Mun



Members of CQT's GB and SAB met during the SAB's visit in August

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
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Dave Wineland
NIST Fellow, Ion Storage Group,
National Institute of Standards and Technology

Jun Ye
JILA and NIST Fellow, AMO Physics Center,
National Institute of Standards
and Technology

CQT PIs meet individually with SAB members each year, but first they all get together

PRINCIPAL INVESTIGATORS

1 ***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

2 ***Dagomir Kaszlikowski***

Theoretical Physics

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

3 ***Stephanie Wehner***

Computer Science

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

4 ***Kai Dieckmann***

Experimental Physics

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

5 ***Murray Barrett***

Experimental Physics

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

6 ***Wenhui Li***

Experimental Physics

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

7 ***Vlatko Vedral***

Theoretical Physics

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

8 ***Valerio Scarani***

Theoretical Physics

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

9 ***Troy Lee***

Computer Science

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

10 ***Rahul Jain***

Computer Science

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

11 Alexander Ling
Experimental Physics
Other appointments: Assistant Professor, Department of Physics, National University of Singapore

12 Dzmitry Matsukevich
Experimental Physics
Other appointments: Assistant Professor, Department of Physics, National University of Singapore

13 Berthold-Georg Englert
Theoretical Physics
Other appointments: Professor, Department of Physics, National University of Singapore

14 Christian Kurtsiefer
Experimental Physics
Other appointments: Professor, Department of Physics, National University of Singapore

15 Hartmut Klauck
Computer Science
Other appointments: Assistant Professor, School of Physical & Mathematical Sciences, Nanyang Technological University, Singapore

16 Choo Hiap Oh
Theoretical Physics
Other appointments: Professor, Department of Physics, National University of Singapore

17 Manas Mukherjee
Experimental Physics
Other appointments: Assistant Professor, Department of Physics, National University of Singapore

18 Leong Chuan Kwek
Theoretical Physics
Other appointments: Associate Professor, National Institute of Education and Deputy Director, Institute of Advanced Studies, Nanyang Technological University, Singapore

19 Björn Hessmo
Experimental Physics
Other appointments: Assistant Professor, Department of Physics, National University of Singapore

20 Dimitris G. Angelakis
Theoretical Physics
Other appointments: Assistant Professor, School of Electronic and Computer Engineering, Technical University of Crete, Greece

21 Rainer Dumke
Experimental Physics
Other appointments: Associate Professor, School of Physical & Mathematical Sciences, Nanyang Technological University, Singapore

OUR STAFF

PhD Students

Davit Aghamalyan
Anurag Anshu
Filip Auksztol
Markus Baden
Eduardo Javier Paez Barrios
Cai Yu
Rakhitha Chandrasekara
Jibo Dai
Swarup Das
Debashis De Munshi
Vamsi Krishna Devabathini
Ding Shiqian
Tarun Dutta
Gan Huat Chai Jaren
Gao Meng
Sanjib Ghosh
Goh Koon Tong
Christian Gross
Gurpreet Kaur Gulati
Roland Hablutzel
Han Jingshan
Hu Yuxin
Victor Huarcaya
Siddarth Koduru Joshi
Jedrzej Kaniewski
Lam Mun Choong Mark
Le Phuc Thinh
Lee Jianwei
Len Yink Loong
Frederic Leroux
XiKun Li
Lim Chin Chean
Manukumara Manjappa
Priyanka Mukhopadhyay
Ewan Franek Munro
Ng Tien Tjuen
Nguyen Chi Huan
Wei Nie
Sambit Bikas Pal
Jungjun Park
Attila Pereszlenyi
Corsin Pfister
Supartha Podder
Poh Hou Shun
Ved Prakash
Rafael Rabelo
Alexandre Roulet
Ritayan Roy
Seah Yi-Lin
See Tian Feng
Mathias Alexander Seidler
Bharath Srivathsan
Suen Whei Yeap
Aarthi Meenakshi Sundaram
Bobby Tan
Tang Zhongkan Kamiyuki
Jirawat Tangpanitanon
Teo Zhi Wei Colin
Giovanni Vacanti
Marek Wajs
Wu Xingyao
Yang Tzyh Haur
Penghui Yao
Ye Luyao
Jiabin You

Research Fellows

Kyle Joseph Arnold
Martin Aulbach
Joonwoo Bae
Jean-Daniel Bancal
Radu Mircea Cazan
Alessandro Cere
Saptarishi Chaudhuri
Agata Anna Checinska
Chen Qing
Chia Andy Hsiao-Li
Patrick Joseph Coles
Paul Constantine Condylis
Herbert Crepaz
Oscar Carl Olof Dahlsten
Borivoje Dakic
Priyam Das
Markus Debatin
Julien David Degorre
Carlos Antonio Perez Delgado
Martianus Frederic Ezerman
Johannes Tomas Gambari
Erik Manuel Gauger
James Anthony Grieve
Guo Ruixiang
Han Rui
Libby Heaney
David Abilio Herrera Marti
Christoph Hufnagel
Huo Mingxia
Bjorn Erik Markus Johansson
Tomos Harry Johnson
Raghav Ramesh Kulkarni
Le Huy Nguyen
Lee Changhyub
Lee Kean Loon
Lee Su-Yong
Nick Lewty
Li Ke
Li Yu
Li Yun
Loh Huanqian
Lu Xiaoming
Ma Ping Nang
Laura Mancinska
Jiri Minar
Kanhaiya Pandey
Amit Rai
Mohamed Riadh Rebhi
William Henry Rosgen
Shabnam Safaei
Daniel Sahagun Sanchez
Daniel Cavalcanti Santos
Jimmy Sebastian
Zahra Shadman
Shang Jiangwei
Arijit Sharma
Lana Susan Sheridan
Jamie Sikora
Matthias Steiner
Jayne Thompson
Marco Tomamichel
Trappe Martin-Isbjoern
Sarvagya Kumar Upadhyay
Sai Vinjanampathy
Wang Guangquan
Wei Zhaohui
Mark Simon Williamson
Mischa Woods
Yang Tao
Yao Penghui
Zhang Chengjie

Senior Research Fellows

Benny Joakim Andersson
Itai Arad
Hugo Vaughan Cable
Stephen Clark
Uwe Dorner
Markus Grassl
Martin Rudolf Kiffner
Pawel Krzysztof Kurzynski
Maslennikov, Gleb
Noh Chang Suk
James Oliver Vicary
Thibault Thomas Vogt
Yu Sixia

Assistant Professors

Ng Hui Khoon

Research Assistant Professors

Joseph Fitzsimons
Tomasz Paterek

Visiting Research Fellows

An Junhong
Chen Bing
Tristan Farrow
Zeynep Nilhan Gurkan
Kavan Kishore Modi
Qiao Youming
Stanislav Straupe
Yang Wanli
Zhang Qi

Visiting Senior Research Fellows

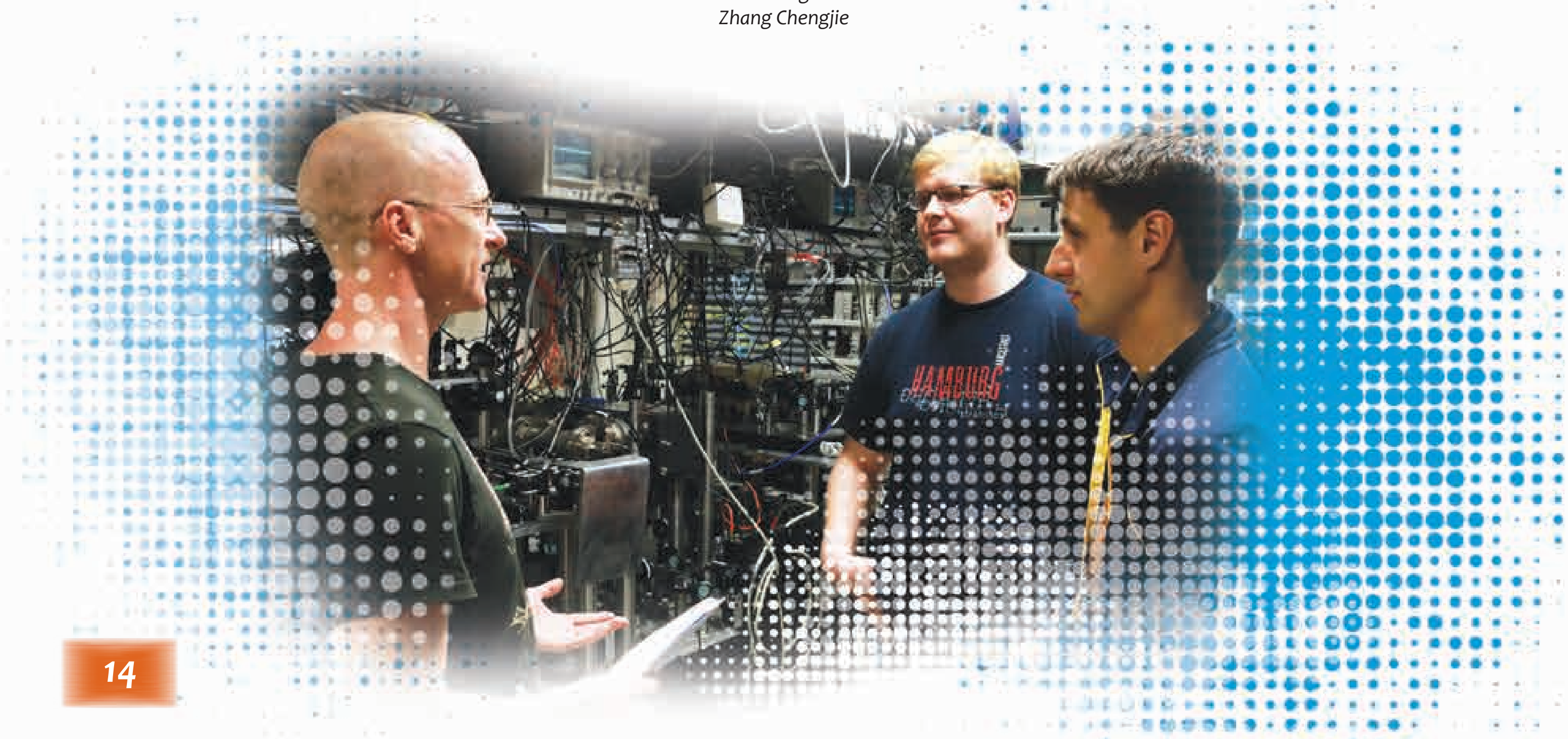
Chen Jingling
Feng Xun-Li
Kazuo Fujikawa
Dmitry Gavinsky
Mile Gu
Tomasz Karpiuk
Thomas Vidick
Yi Xuexi

Visiting Research Assistant Professors

Simon Charles Benjamin
Benoit Gremaud
David Hutchinson
Gabor Ivanyos
Antia Lamas-Linares
David Wilkowski

Visiting Research Professors

Luigi Amico
John Carlos Baez
Emilio Bagan
Ghassan Georges Batrouni
Martial Ducloy
Rosario Fazio
Thomas Francis Gallagher
Masahito Hayashi
Dieter Hans Jaksch
Jose Ignacio Latorre
Christian Miniatura
Jonathan Oppenheim
Erik Torbjorn Sjoqvist
Joannes Walraven
Paolo Zanardi



Research Assistants

Chan Kin Sung
Chia Zhong Yi
Wilson Chin Yue Sum
Do Thi Xuan Hung
Kadir Durak
Ew Chee Howe
Gan Koon Siang
Guan Yilun
Elnur Hajiyev
Ho Hui Kiat Melvyn
Tyler William Hughes
Andrew Bah Shen Jing
Kwong Chang Jian
Law Yun Zhi
Lee Chee Kong
Ley Li Yuan
Sivakumar s/o Maniam
Musawwadah Mukhtar
Nelly Ng Huei Ying
Ng Xin Zhao
Oon Fong En
Kumar Molahalli Panidhara
Vindhiya Prakash
Pramod Mysore Srinivas
Ritayan Roy
Brigitta Septriani
Shi Yicheng
Tan Peng Kian
Tan Wei Hou
Tan Yue Chuan
Thi Ha Kyaw
Tong Qingjun
Wang Zhuo
Yau Yong Sean
Zhang Jiang

Research Associates

Cheng Too Kee
Chng Mei Yuen, Brenda
Aarthi Lavanya Dhanapaul

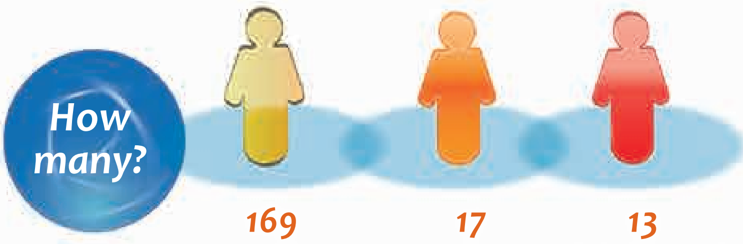
Administrative Staff

Chan Chui Theng
Chin Pei Pei
Artur Ekert
Giam Lay Enn Kelly
Jessie Ho
Jenny Hogan
Valerie Hoon
Karol Jalochowski
Lai Choy Heng
Lim Ah Bee
Lim Fang Eng Jacky
Lim Mei Yin, Valerie
Mashitah
Pay Hee Suan Jace
Resmi Poovathumkal Raju
Kuldip Singh
Tan Ai Leng Irene
Evon Tan
Tan Lay Hua
Yeo Kwan San Timothy

Research Support

Chia Zhi Neng Bob
Gan Eng Swee
Mohammad Imran
Lian Chorng Wang
Dileej Radhakrishnan Nair
Ren Yaping
Teo Kok Seng
Akimov Volodymr

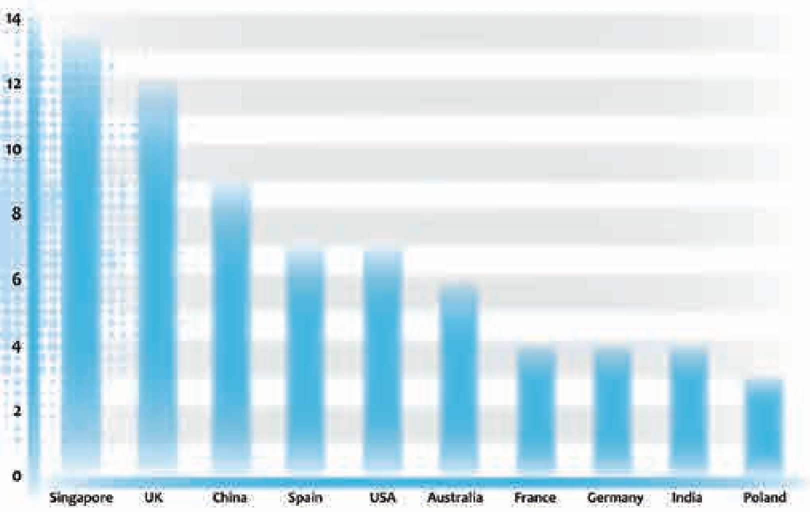
OUR ALUMNI



CQT has 199 alumni

Where?

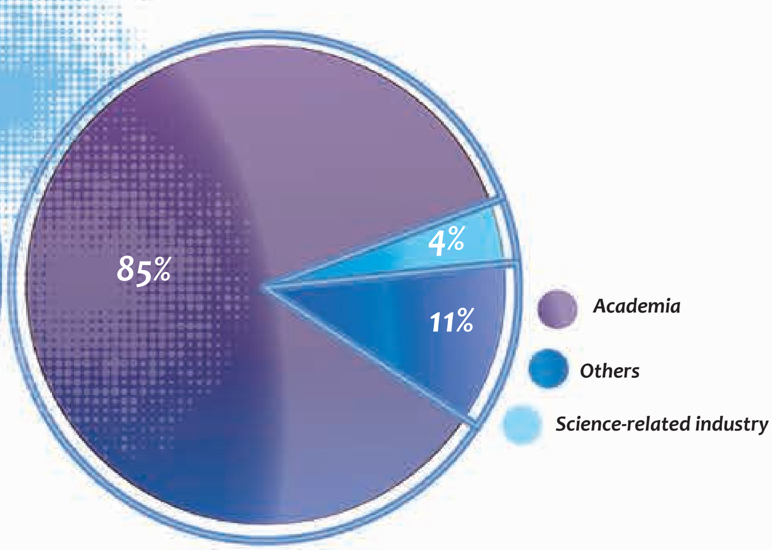
CQT alumni can be found in 17 countries



Top ten destinations

Doing what?

The majority of former CQT research staff and students remain in academic roles. The first job after graduation for 16 of 17 graduates of the CQT PhD programme was a postdoc or similar academic appointment. The pie chart shows the current job types of the 107 researcher and student alumni for whom we have recent information.



Memories of CQT

"Great science. Impeccable organization. Super cool town, well not weather-wise..."

Paolo Zanardi
Now: Professor, University of Southern California, US
Was: CQT Visiting Research Professor, Feb – Dec 2013

"Brilliant minds, beautiful views, and stimulating conversations!"

Brian Smith
Now: University Lecturer, University of Oxford, UK
Was: CQT Research Fellow, Mar 2009 – Apr 2010

"Great place with lots of good research and constant opportunities for chats and discussions in the corridors and Quantum Cafe."

Elica Kyoseva
Now: Assistant Professor, Singapore University of Technology and Design
Was: CQT Research Fellow, Feb 2009 – Jul 2011

"Working in the lab! I still dream of it sometimes."

Thong May Han
Now: Master's Student, University of Malaya, Malaysia
Was: CQT Research Assistant, Oct 2011 –July 2013

"I was extremely happy in Singapore and miss it, especially the discussions in the Quantum Cafe after the delicious food in the canteen."

David Herrera Marti
Now: Postdoctoral Fellow, Hebrew University of Jerusalem, Israel
Was: CQT Research Fellow, Sep 2012 – Mar 2014

Meet a CQT alumnus: Li Ke

Li Ke was a CQT Research Fellow from January 2012 to April 2014. He worked in the group of Kai Dieckmann, cooling and trapping Lithium atoms. He is now a Principal Engineer with Singaporean company DenseLight Semiconductors.

Why did you decide to move into industry?

I like to make things with my hands. I had a feeling that I wanted to use the skills I learned from my experience in science research to make products that could be sold to the market. I wanted to see the value of my skills more directly.

What do you do in your new job?

I do R&D on various projects in the company. We have just finished one project on fabricating fiber combiners (FC). These are devices that can take multiple fibers as inputs, coupling the light into a single output fibre. My work involves process developing, writing up procedures and testing and characterizing the fabricated FCs.

What skills have been useful?

The skills I learned in the lab on working with lasers and fibers are quite helpful in the company. I have also learned new skills, for example, fiber etching, splicing, tapering etc.

Do you have any advice for graduates or postdocs looking for industry jobs?

I found this job after asking a friend for a recommendation. I suggest using Linkedin to collect information on different and successful companies to find the most suitable job. When shifting from science to industry, be aware that you need to adjust to a new working style.

OUR ANNUAL REVIEW

Comments from the Centre's Scientific Advisory Board

Each year CQT invites its Scientific Advisory Board (SAB) to review the Centre's activities. The SAB members spend an intensive week in August examining data on our operations, discussing science with our researchers and touring our laboratories. "The SAB members are wise and experienced scientists. We benefit hugely from our interactions with them and from the advice they give us," says Artur Ekert, CQT's Director.

One product of the SAB visit is a report presented to CQT's Governing Board and Principal Investigators. It considers the status of CQT in a global context and gives advice on what CQT can do to increase its strength.

The SAB's 2014 report states "CQT is established as a major international centre for research in quantum information, quantum computing and related quantum technologies". The report adds that "the distinguishing features of CQT are its broad scientific base in theory and experiment, a commitment to basic science and autonomy of operation".

This year we asked the SAB members to share some personal impressions of CQT, too. "I am on the advisory boards of a number of similar centres around the world. CQT has a world class research portfolio to compete with all of these in both theory and experiment," says Gerard Milburn, Director of the Centre for Engineered Quantum Systems at the University of Queensland, Australia, who joined CQT's SAB this year. "There is a strong feeling of collegiality at CQT. This is a very difficult thing to foster and it is a strength of CQT," he adds.

Atac Imamoglu, a member of the SAB since the Centre was founded, says "CQT is a real centre – I feel that it is more than sum of its groups. This is interesting since the students and postdocs keep telling us that they would like to be more exposed to other research topics within CQT." Atac heads research in quantum photonics at ETH Zurich in Switzerland.

Compared to other Centres in the world, says Ignacio Cirac, also a long-serving SAB member, CQT "is broader in scope, and has a great potentiality of doing something really different". Ignacio is Director of the Theory Division of the Max Planck Institute of Quantum Optics in Garching, Germany.

The SAB report states "Internationally leading research centres like CQT are a testament to the success of Singapore's investment in scientific innovation. With the establishment of CQT, and similar research centres, it is not surprising to see the rise of NUS in rankings of the Global Top 100 and the regional top 20."

Planning ahead

The report makes recommendations for the Centre across funding, personnel, facilities, intellectual property and integration of CQT's theory and experiment groups.

CQT has received S$195 million in core funding from the Singapore National Research Foundation and Ministry of Education since it was established in 2007. "The core funding is one of the major reasons talented people choose to come to CQT. Core funding is also a key enabler of the major international centres in this field competing with CQT," says the report. The report also recommends that PIs hold at least one grant jointly or individually, with the caution that "the Centre must maintain its broad research base in basic science as it moves to more external funding".

CQT currently has six active external grants, the largest of which is a S$9.93 million project by 13 PIs over five years (see pp. 52-53).

The centre is at a steady-state size of around 200 research staff and students, but with scope to bring in new PIs in strategic areas. The SAB comments on bridging computer science and physics, recommending that "further strengthening of this interface through future hires would be desirable". The SAB also says that "the Centre should look out for opportunities to hire a first class experimentalist, especially in one of the new areas such as quantum nanophotonics, circuit QED, opto-mechanics, etc. and further broaden its research base".

On collaboration between theoretical and experimental scientists at CQT, the SAB report says: "the broad scientific base of CQT offers some unique opportunities for novel collaborations. These cannot be created *de novo*, but need to arise out of a daily interaction between interested parties. As the experimental programs in the Centre come to maturity, there will be increasing opportunities for the theorists to become involved in collaborations." The SAB recommends a joint theory/experiment journal club be held at least once per month.

Such a journal club would add to the existing open culture at the Centre, which staff and visitors enjoy. SAB member Christophe Salomon, who leads an experimental program at Laboratoire Kastler Brossel, in Paris, France, is among them. He says "I very much enjoy the CQT working atmosphere and the many interactions with CQT members at the quantum cafe, both theoreticians and experimentalists. There are always new ideas floating around and something to think about for the CQT research or my own research."

Engaging with industry

As CQT plans for its long-term future, one area of focus is the Centre's interface with industry. The SAB considered this topic. "A number of the Centre's research programs, in both theory and experiment, are capable of generating significant intellectual property," notes the 2014 SAB report. The SAB's recommendations include raising the awareness of all Centre members of IP policy.

The report notes that connections with end-users of quantum technologies could bring jobs for PhDs and postdocs. "As the Centre makes links to end-users, both commercial and governmental, there will be increasing opportunities for PhDs and postdocs to consider non-academic careers in quantum technology. In order to capture these opportunities, and to increase the involvement of end-users with the Centre, it should develop a forum for end users to visit CQT and interact with all members of the Centre, especially students."

NEWS HIGHLIGHTS

A year is a short time in the life of a research centre but a lot can happen. Here's a roundup of news and research results from CQT and our community in 2013-14.

September 2013

30.6 *maximum air temperature*

4.6 *bright sunshine daily mean hours / day*

257 *rainfall (mm)*

3 *visitors*

20 *papers*

We start here

CQT's annual reports traditionally begin in September because we make our new year's resolutions this month, after the visit of the Centre's Scientific Advisory Board in August. The SAB report (see pp. 18-19 for extracts from the 2014 report) may inform new directions for the Centre or give fresh impetus to ongoing projects. Statistics in this report run 1 September 2013 to 31 August 2014 unless indicated otherwise.

October 2013

31.4 *maximum air temperature*

6.3 *bright sunshine daily mean hours / day*

285.4 *rainfall (mm)*

9 *visitors*

15 *papers*

News

The Times Higher Education World University Rankings published in October 2013 put CQT's host University NUS at 26th in the world. In the 2014–15 rankings released since, NUS has climbed to 25th spot. NTU, where CQT also has staff and laboratories, is climbing too. It was 76th in the 2013–14 ranking and is 61st in 2014–15.

Research

CQT researchers and their collaborators described a technology in *Nature Communications* (vol. 4, article no. 2432) for which they have applied for a patent. The team showed how novel optical devices known as q-plates that 'twist' and 'untwist' a beam of light could increase the sensitivity of angular measurements over current state of the art almost 100-fold. CQT PI Kwek Leong Chuan and his former student Li Ying, now a postdoc at the University of Oxford, UK, did theoretical work for the project. The 'q-plates' are patterned sheets of liquid crystal that act on the orbital angular momentum of light.

Research

In a paper published in *Nature Physics* (vol. 9, p. 727), CQT's Joe Fitzsimons and his collaborators demonstrated a way to 'verify' the output of a quantum computer. The scheme works by sending the computer test calculations hidden within a program. If the computer is malfunctioning, the answer to these calculations will show that something is going wrong. "You're checking that the device functions as you expect it to function," Joe says. The verification scheme will be useful for checking a computer is free from random errors or imperfections in construction. It could also help reassure a user working on a rented device, or to certify the trustworthiness of a machine bought from an untrusted dealer.

Visit

Masanao Ozawa from Nagoya University in Japan came to CQT to give a colloquium in November. His talk on the "Uncertainty Principle and Quantum Reality" was one of 9 colloquia this year (see pp. 44-45), and Masanao was one of over 100 academic visitors. He says CQT is "an excellent research center for quantum technology in Asia" and he expects to come back again to collaborate. Visitors contribute to the Centre's vibrant culture (see pp. 48-51).

November 2013

31.3	4.5	292.4	17	18
maximum air temperature	bright sunshine daily mean hours / day	rainfall (mm)	visitors	papers

December 2013

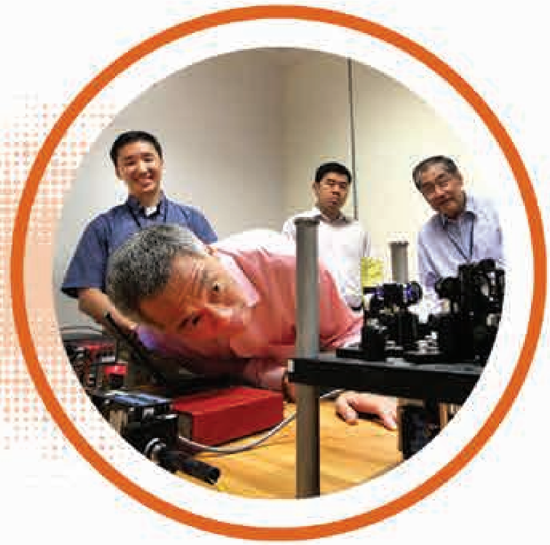
30.2	3.5	348.2	19	14
maximum air temperature	bright sunshine daily mean hours / day	rainfall (mm)	visitors	papers

News

CQT celebrates its birthday on 7 December. This month marked its sixth full orbit of the Sun.

Visit

CQT was honoured with a visit by the Prime Minister of Singapore, Lee Hsien Loong, on 18 December. PM Lee chairs the country's Research, Innovation and Enterprise Council, which guides science policy. After his visit, PM Lee posted to his Facebook page: "Visited the Centre for Quantum Technologies (CQT) at NUS this morning. We set up CQT in 2007 as part of our national R&D effort. It applies quantum mechanics to secure communications (cryptography), ultra-precise measurements and new types of computing devices. CQT has become one of the leading research centres in its field in the world. The researchers were a good mix of Singaporean and international talent. It was fun to listen to them explain their projects, and to see their enthusiasm and passion...There are many potential uses for CQT's research, e.g. for online banking and secure internet transactions. I hope talented young people interested in physics and computing will learn more about these subjects, do research and make new breakthroughs one day! – LHL "



Research

CQT researchers led by PI Christian Kurtsiefer described in *Physical Review Letters* (vol 111, article no. 123602) a technique that could help interface different types of quantum system in technologies for communication or computation. Photons are good for zipping information around, atoms are good for storage: the challenge is combining the two. The CQT team produced entangled photons well-matched for absorption by atoms by a method known as four-wave mixing. The work was highlighted by the journal as an Editors' Suggestion.

January 2014

29.6 maximum air temperature | 5.3 bright sunshine daily mean hours / day | 75.4 rainfall (mm) | 8 visitors | 20 papers

Outreach

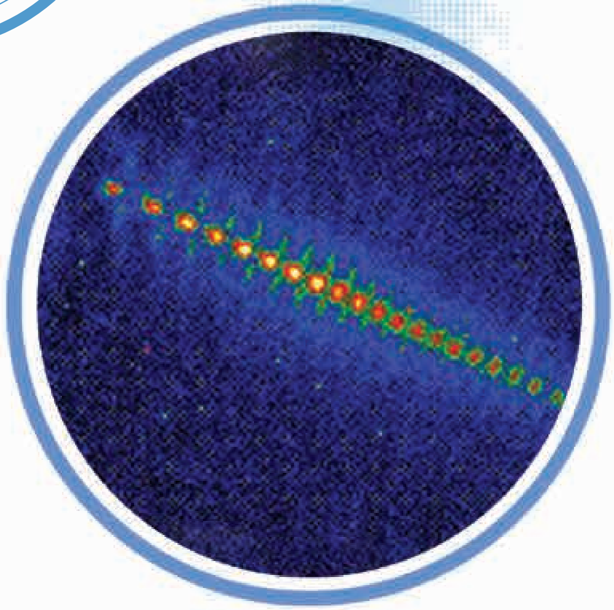
After months of preparing video lectures and course notes, CQT PI Valerio Scarani launched the eight-week online course "Upredictable? Randomness, Chance and Free Will" on 6 January. Over 39,000 students registered to take the course on Coursera.org. (see pp. 36–37).

Research

CQT experimentalists came up with a new scheme for cooling and entangling the information-processing ions used in some of the most advanced demonstrations of quantum computing (*Physical Review Letters*, vol. 111, article no. 170406). Charged atoms held in vacuum and cooled to very low temperatures form a trapped ion quantum processor. As this report goes to press, the group, led by PI Manas Mukherjee, has control over 24 trapped ions in a line (pictured) and is working towards implementing the new proposal. Such trapped ion systems are promising for quantum simulations exploring the properties of materials.

Outreach

In July CQT launched a competition for short stories drawing inspiration from quantum physics, with Scientific American and Tor as media partners. This month we announced the winners selected from over 500 entries (see pp. 32–33).



February 2014

31,.9 maximum air temperature | 8.8 bright sunshine daily mean hours / day | 0.2 rainfall (mm) | 9 visitors | 17 papers

Event

CQT co-organised the annual meeting of the Institute of Physics Singapore, held 26–28 February at NUS. The meeting is a forum for the exchange of ideas among all physical science researchers in Singapore, modelled after similar events in the US and Europe. In 2014 it had four plenary speakers, over 70 technical talks, 50 poster presentations and 11 exhibitors.

March 2014

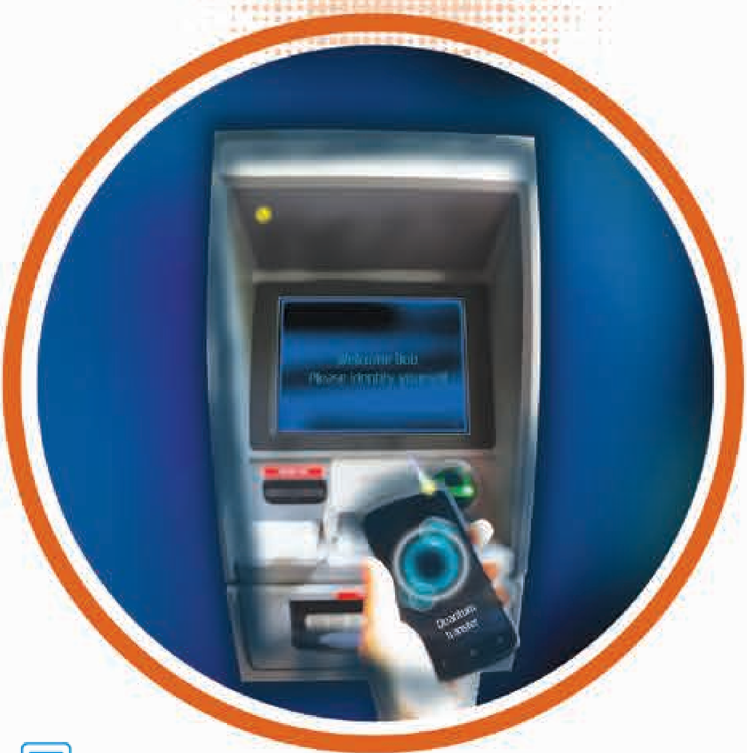
32.8 maximum air temperature
8 bright sunshine daily mean hours / day
66 rainfall (mm)
9 visitors
17 papers

Research

Writing in *Nature Communications* (vol. 5, article no. 3418), CQT researchers and their collaborators reported the demonstration of a cryptographic building block known as 'oblivious transfer'. The quantum scheme could enable secure ways for two mutually distrustful parties to interact. "I expect that quantum technologies will gradually become integrated with existing devices such as smartphones, allowing us to do things like identify ourselves securely or generate encryption keys," says Stephanie Wehner, the CQT PI who led the research.

Research

Revelations in 2013 of the extent of government surveillance threw a spotlight on data security. Is privacy possible? In a review article in *Nature* (vol. 507, p. 443) on "The ultimate physical limits of privacy", CQT's Director Artur Ekert and his coauthor wrote that "The days we stop worrying about untrustworthy or incompetent providers of cryptographic services may not be that far away". The semi-popular essay covering developments in quantum cryptography was featured on the journal's cover and widely reported in the media.



April 2014

32.4 maximum air temperature
5.7 bright sunshine daily mean hours / day
110 rainfall (mm)
22 visitors
15 papers

Event

We hosted some 130 physicists from 22 to 26 April for BergeFest, a conference organised in honour of CQT PI Berge Englert's 60th birthday.

May 2014

32.1	5.8	125.8	19	13
maximum air temperature	bright sunshine daily mean hours / day	rainfall (mm)	visitors	papers

Event

We hosted two workshops in May: Beyond I.I.d in information theory and the 9th Conference on the Theory of Quantum Computation, Communication and Cryptography. Both were held in the beautiful surroundings of NUS University Town.

News

In a ceremony on 30 May, the France-Singapore laboratory "MajuLab" for research in quantum physics and condensed matter physics was signed into existence. The lab is a partnership between NUS, NTU and the French national research organisation CNRS. CQT Visiting Research Professor Christian Miniatura (pictured) is the lab's Director.

June 2014

32.1	6	71.1	4	13
maximum air temperature	bright sunshine daily mean hours / day	rainfall (mm)	visitors	papers

Research

PhD student Tan Peng Kian led CQT to its first publication in astronomy (*Astrophysical Journal*, vol. 789, article no. L10). Working with CQT's quantum optics group, he built a device to study an effect known as photon-bunching in light from the sun. The technique may be applied to light from more distant stars to help determine the size of extra-solar planets and constrain theories of quantum gravity. Peng Kian has begun a collaboration with astronomers in Italy.

News

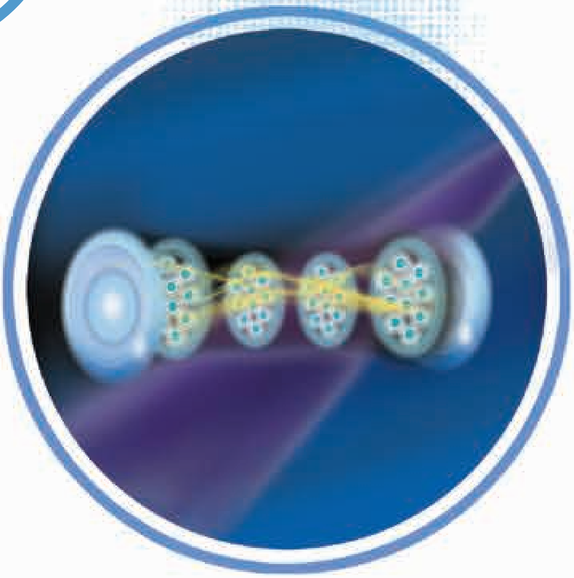
This month Singapore's National Research Foundation (NRF) awarded CQT $36.9 million to support the Centre's operations as an independent research centre. This supplements grant income (see pp. 52-53) and the $158 million core funding provided by NRF and the Singapore Ministry of Education when CQT was founded.

July 2014

31.6	5.5	148.6	12	14
maximum air temperature	bright sunshine daily mean hours / day	rainfall (mm)	visitors	papers

Research

A team led by CQT PI Murray Barrett reported that pancakes of ultracold atoms (illustrated below) can be used to investigate the Dicke model of atom light interactions (*Physical Review Letters*, vol. 113, article no. 020408). "We're excited about the possibilities," says Markus Baden, a CQT PhD student and first author on the paper. The Dicke model has effectively guided quantum experiments, but it has some puzzling features. The team reported having already seen one such feature – superradiance – by tuning the parameters of their quantum setup.



Outreach

Hundreds of families found us this month at Singapore's Science Festival, exhibiting hands-on physics at a shopping mall and at the Singapore Mini-Maker Faire.

People

Eight students graduated from CQT's PhD Programme in 2014 (see pp. 34–35), officially receiving their doctoral degrees at the University's commencement ceremony in July.

August 2014

30.4	4.5	241	13	19
maximum air temperature	bright sunshine daily mean hours / day	rainfall (mm)	visitors	papers

Research

CQT and Oxford researchers found a previously unrecognised advantage of the quantum uncertainty principle, which sets a limit on how much we can know about a system (*Nature Communications*, vol. 5, article no. 4592). The uncertainty principle defines the shape of a quantum bit to be a 'Bloch sphere', describing the qubit's position and phase. CQT PI Vlatko Vedral and his collaborators showed that the quantum state evolves by the sphere rotating about its poles, as a ballerina pirouettes on pointes. A bit with less uncertainty would be flat-bottomed and stuck, unable to change.

Research

In a paper published in *Physical Review Letters* (vol. 113, article no. 040401), CQT PI Valerio Scarani and his collaborators presented an improved scheme for 'certification' of quantum devices. The scheme checks whether a device is providing its promised quantum output without requiring any inspection or calibration of its components. This could support a vibrant market for quantum technologies with security applications because consumers could test devices for themselves.

News

Two members of CQT's Governing Board won national awards for their public service to Singapore. Mr Lam Chuan Leong, Chairman of CQT's Governing Board was presented the Meritorious Service Medal and Professor Tan Eng Chye, Provost of the National University of Singapore, was awarded the Public Service Medal (Gold) on Singapore's National Day on 9 August.

Credit: Weather data from Singapore's National Environment Agency downloaded from www.data.gov.sg on 04/11/2014 and governed by Terms of Use available at www.data.gov.sg/common/terms.aspx.

THE RANDOMNESS PROJECT

Why are we interested in quantum randomness? Valerio Scarani, lead PI for an interdisciplinary five-year project, explains

In May 2013, a team of 13 Principal Investigators at CQT were awarded a $9.93 million grant to study "Random numbers from quantum systems". The five-year project aims at a comprehensive approach to understanding, quantifying and ultimately harnessing the intrinsic randomness provided by quantum physics.

If ten million dollars seems a lot to spend on random stuff, consider the potential payoffs. We are not only pursuing a deeper understanding of nature, but also developing technologies with foreseeable, near-term applications. Devices that generate random numbers through measurement of quantum systems could easily take the place of the classical or pseudo-random number generators used in computing and communication today, with advantages I'll explain below.

Global attention speaks to the promise of the field. A few months before ours, a similar project was started in the National Institute of Standards and Technology in the United States. A few months later, Antonio Acin from ICFO in Barcelona, Spain, obtained a grant from the Templeton Foundation to explore quantum randomness from a slightly more philosophical perspective. We are proud of having such serious competitors, and even more proud to be on friendly terms with them. We are involved in the organization of a conference on randomness, to take place in Barcelona sometime in 2015.

1, 2, 3

The CQT randomness project is divided in three nodes. The first node addresses the ultimate level of production and certification of quantum randomness. It is well known that entangled quantum states lead to the "violation of Bell inequalities": certain measurements on the states give results that are impossible in classical physics.

The mathematician George Boole had written down some of the inequalities over a century before they were proposed by John Bell. Boole described them as conditions that must always be satisfied. When Bell presented them, it was because he had discovered quantum predictions violate them.

The implications of this violation on our view of nature have led to heated debates, but there is an uncontroversial operational interpretation: the outcomes of the measurements performed in a Bell test could not have been predicted in advance by any observer. Moreover, the outcomes can only be known by those who have access to the detectors. This is a level of certification that no classical device can offer. Black-box classical devices may always be reading from a pre-recorded list: then, even if the list looks perfectly random in the statistical sense (e.g. if the original was generated by a random process), it is certainly not random for those who created it. The quantum advantage is of interest when randomness is meant to be private, for example for encryption.

The second node is meant to explore the production and certification of randomness under less rigid requirements, that is, when some parts of the apparatus are supposed to be well-characterized. By adding this layer of trust, other experiments than the one needed to violate a Bell inequality can be considered to produce random numbers: in other words, one trades trust with practical benefits like simplicity and faster production of randomness.

The third node is the most speculative one. The goal is to see what light can be shed by applying tools and concepts from quantum information theory to thermodynamics and statistical physics. These are the traditional arenas of randomness insofar as they deal with statistical descriptions of systems. Thermalisation is randomisation by another word.

Each node has theoretical and experimental goals. In our first year, as expected, the theorists have already been able to produce papers, while the experimentalists have started setting up their devices. I have selected a few achievements to highlight (see box Random Samples), favouring those most amenable to a simple description. I hope they will convey an idea of the variety of questions we are pursuing and of the fascinating topics that we are going to deal with in the following years.

Read more at http://www.quantumlah.org/research/topic/randomness

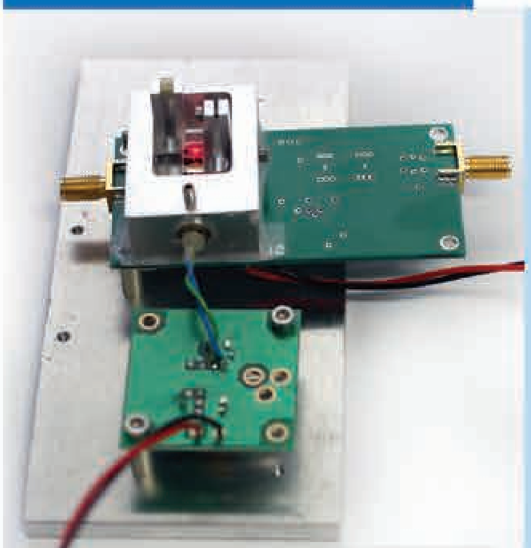
Participating PIs

Experimental physics: Bjorn Hessmo, Christian Kurtsiefer, Alexander Ling

Theoretical physics: Dimitris Angelakis, Berthold-Georg Englert, Dagomir Kaszlikowksi, Oh Choo Hiap, Valerio Scarani, Vlatko Vedral

Computer science: Rahul Jain, Hartmut Klauck, Miklos Santha, Stephanie Wehner

Random samples



A prototype quantum random number generator

- Valerio's group quantified how much randomness can be achieved in the "trusted provider scenario". Thus, they certify against adversaries that have never tampered with our equipment, even if they have a perfect description of the apparatus. *Journal of Physics A* 47, 424028 (2014)
- For many measures of quantum correlations, it is known that if Alice is correlated to Bob, they cannot be also correlated with a third party Charlie --- another way of saying that Alice's and Bob's data will be random for Charlie. Dagomir Kaszlikowski and his collaborators have found a new form of such 'monogamy of correlations', which bridges entanglement correlations and 'contextual' correlations. *Physical Review Letters* 112, 100401 (2014)
- In Christian Kurtsiefer's quantum optics lab, they have built a prototype random number generator (pictured) based on measurements of quantum fluctuations in laser light. Early results are promising: the simple device offers a high output rate in a portable package.
- In node 3, a paper by Stephanie Wehner and collaborators has been the object of several invited talks. It bears the enticing title "The second laws of thermodynamics". If it sounds familiar, you have missed the plural. Preprint at arXiv:1305.5278

Coffee made the Singapore way (pictured) fuelled work on a new way to measure quantum correlations. There's a video to explain it (stills centre and right).

COMPRESSING THE UNIVERSE

Just zip it. Dagomir Kaszlikowski describes the discovery of a different way to distinguish quantum from classical reality

Visits to colleagues in other parts of the world can really expand your horizons. Being somewhere new reboots your mind. You start to look at things from a different perspective. You may wander into territories you never knew were there.

In summer 2013, I took a journey from Singapore with my friend and collaborator Pawel Kurzynski to the beautiful city of Sevilla in Spain. We were visiting Adan Cabello, a world-class expert in quantum theory. It was a rather long trip during which we had plenty of time to talk. Exploring the ancient town of Sevilla, enjoying superb tapas and inspired by the passion of our host, our thoughts took an unexpected scientific turn.

Life is unpredictable

One of the startling predictions of quantum physics is that measurements don't have a predetermined result. Suppose I have a red Lamborghini in my garage. Everyone will agree that the colour of my car is independent of who is looking at it, or on whether Wall Street is doing well. The car is always red. But if I park a quantum particle somewhere, its properties are not so fixed. What we measure when we look at the particle can depend on the circumstances. For example, whether it points up or down could depend on the behavior of a 'correlated' particle elsewhere.

Traditionally, we think about quantum measurements in terms of the probabilities of different outcomes. This approach is almost a century old, dating back to Erwin Schrodinger's proposal that a quantum system is described by a 'wave function' capturing all its possible states. Max Born postulated that the modulus squared of Schrodinger's wave function gives a probability distribution of the possible outcomes.

The inception of probability into physics famously worried their contemporary, Albert Einstein. Einstein, along with Boris Podolsky and Nathan Rosen, proposed in 1935 that quantum theory's seemingly probabilistic behaviour might instead be controlled by deterministic but hidden variables. This appealing idea of 'local hidden variable theories' survived until the 1960s, when John Bell presented scenarios involving pairs of quantumly correlated particles for which hidden variable theories could not match quantum predictions. Numerous laboratory experiments have since sided with quantum theory. Physicists have not only come to terms with probability in quantum physics, but have even proposed practical uses, such as quantum key distribution and randomness generation (see pp. 26-27)

Kopi-O

One night in Sevilla after watching a fiery flamenco performance, Pawel and I took a long night walk back to our hotel. We suddenly recalled an old paper by Benjamin Schumacher, a physicist at Kenyon College in Ohio who has done pioneering work on quantum information. Schumacher discovered that there is a 'geometrical' analogue of the scenarios Bell had described. In a paper he published two decades ago (*Physical Review A* **51**, 2738 [1995]) he introduced a way of measuring the 'distance' between the sets of probabilities one can observe in experiments. The distance is a quantitative measure of how different are the probabilities.

Distance measures typically obey the so-called triangle inequality, which states an obvious fact from everyday life: if you want to go from X to Y, a route that leads though a point Z (off the straight line between X and Y) is always longer than the direct path. Schumacher showed that the triangle principle is obeyed by probabilities predicted by hidden variables theories, but not by quantum mechanical ones.

Joining forces with Marcin Markiewicz, a young physicist from Poland, we decided to pursue this beautiful discovery further. After many months of intense discussions watered with incredible amounts of kopi-o, a Singapore take on a small black coffee, we ended up finding a way to apply the triangle principle directly to the results of measurements made in a Bell test, rather than to probabilities computed from them.

The results you get from doing a quantum experiment are a sequence of detector clicks and nothing more. How we choose to interpret those clicks depends on us. The simplest quantum system, a qubit, can generate two types of clicks, i.e., bits that are registered as 0 or 1. If we repeat our experiment many times we will obtain a string of bits.

It's the status quo to count up the bits and calculate probabilities of their occurrence. We found that instead of working out probabilities that individual bits take particular values, we can treat the string as a whole.

Imagine that you have two observers, Alice in Tokyo and Bob in New York. Both have a black box with two buttons in front of them. Only one button can be pressed at a time, and each press generates a bit. So Alice and Bob happily press their respective buttons at random generating long bit strings. Later they meet for a kopi-o and compare their strings. They ask: are our boxes quantumly correlated?

So far this is the standard Bell scenario. But this time Alice and Bob do not measure probabilities functions of their data. What do they do instead? It's simple.

Our solution uses lossless compression like that performed by the gzip programme on a laptop. Alice and Bob must compress the strings they have collected on each button. They also compress subsets of their strings, added modulo two, which correspond to particular combinations of button presses (eg, Alice's 1st button, Bob's 1st button; Alice's 1st button, Bob's 2nd button etc). Having these compressed strings, they calculate a quantity known as the normalised compression distance (NCD) between them. This is a count of how many bits differ.

NCD was introduced by Paul Vitanyi and Rudi Cilibrasi as a tool to look for similarities in data strings. For instance, it has been applied to look at the similarities between two DNA strands, and between the use of language by the great novelists Lev Tolstoi and Fyodor Dostoyevski.

In our case, Alice and Bob end up with four numbers, where NCD(1,1) is the distance between Alice's bit substring corresponding to her pressing the button number 1 and Bob's substring corresponding to the button 1, etc . It can be shown that classical results should obey a simple inequality: NCD(1,1)+NCD(1,2)+NCD(2,1)>NCD(2,2). This inequality is nothing more than two triangle inequalities combined to express another simple fact of life: if you want to go from X to Y it is always shorter to go directly between them than taking a detour through W and Z. We showed that the above inequality is violated by quantum correlations.

In other words, we found a new way to see a difference between the quantum universe and a classical one, using nothing more complex than a compression program! Our work is presented in a preprint at http://arxiv.org/abs/1310.5644.

Now we're collaborating with Christian Kurtsiefer's experimental quantum optics group at CQT to get real data to analyse. It will be an unimaginable joy to apply our theoretical predictions to data in a way nobody has tried before. We're also thinking about where else the triangle principle and lossless compression could be useful.

We can't know if we may still hit a dead end – that's the nature of research – but we are excited about the path we are following. It may give us a new way of thinking about the quantum world.

The movie version

For a different presentation of our work, you can watch a short film about it. There are so many papers published on the arXiv preprint server every day that no-one can hope to read them all. I like the way that some journals publish short video abstracts, in which the authors present their findings in a few minutes, so we made one about our work. These videos can hook your interest (or not) to read the full paper.

Our video abstract isn't the standard show-and-tell. I like to experiment with humour and drama. We filmed the five-minute movie in a café in Poland called Pikawka (translating to π–small black coffee) which has science-themed décor. It's run by a former chemist. When he found out that we were shooting a movie about quantum physics, he said the place was all ours!

Watch the film at http://goo.gl/5JtbMa

Theorists in their natural habitat: Dimitris (standing) is pictured with members of his group (from left to right) Changyoup, Amit and Changsuk

THE SIMULATOR

Dimitris Angelakis describes how his group is using one quantum system to learn about another

What proposals have you made for 'quantum simulators', and which is your favourite?

Our work relates to reproducing and understanding phenomena from the whole range of physics. We have discussed, for example, how to reproduce exotic neutrino oscillations, how to investigate the inner workings of quantum materials, and how to mimic relativistic effects such as the renormalization of mass due to interactions. For each case, we found a way to model the phenomenon in a controllable setup with photons and atoms or ions.

It's difficult to choose a favourite as we really like all of them! You learn a lot trying to link seemingly different areas of physics. If I have to choose one, I might go for our most recent proposal for probing exotic and even forbidden physics in a photonic chip. It was recently verified experimentally by a collaborating group in Europe.

There is an international race to produce working simulations of complex phenomena such as quantum phase transitions, quantum magnetism and superconductivity

What is 'forbidden' physics?

Sometimes the equations of physical theories have solutions we dismiss as 'unphysical' or 'forbidden' because of their properties. Our example comes from Ettore Majorana, a famous Italian physicist working in the early 1900s. He predicted exotic particles known as Majorana fermions: particles that are their own antiparticle. This kind of particle is interesting for quantum computing, and hints of them have recently been seen in experiments.

Majorana's work also suggested the existence of an even more exotic relativistic particle we have dubbed a 'Majoranon'. By nature these particles would break a fundamental law of physics, the conservation of charge. That's why they are considered forbidden within current physical theories. But there do exist theories, for example with higher spacetime dimensions, which allow violation of charge conservation. Who knows, one day such theories might replace our current approaches!

How can such physics appear in a simulation?

Going through the maths of Majorana's theory, we found a way to indirectly reproduce the dynamics of the impossible particle by decomposing them into superpositions of another particle called a Dirac fermion. Moreover, we proposed a way to implement the proposal in a table top experiment using either cold ions or photons (*Physical Review A* 87, 040102 [2013]).

When we put the proposal out in 2013, it caught the attention of different experimental groups. The group led by Professor Alexander Szameit at the Friedrich Schiller University Jena in Germany was particularly interested. Someone from there happened to be visiting Singapore at the time, so the collaboration took off very fast. The group in Jena is one of the world's leading groups in integrated photonic chips. They implemented our idea in an amazing double lattice photonic system (see arXiv:1404.5444)

How much does it matter to see your proposals realised?

It matters a lot of course. Without the experimental tests, the theory by itself is not worth pursuing. Other groups are working towards realising some of our other proposals. For example, we are discussing with a few groups the possibility of realising another relativistic model, named the Jackiw-Rebbi model after the two scientists that first wrote it down. The interesting bit there is a connection to topological physics. The model predicts a zero energy particle which is topologically protected, i.e., is robust to noise and perturbation from background fields and potentials. Our theoretical proposal for realising this with slow light pulses was recently published in *Nature Scientific Reports* (vol. 4, article no. 6110).

How do you set up collaborations?

We have several collaborations both within CQT and worldwide, some with other theorists, some with experimentalists. There is no specific recipe. They might start in discussions at an international meeting, or with emails over a new paper that appears on the arXiv, or over a cup of coffee in our Quantum Cafe. Our strongest active links are with groups in Oxford, UK; Jena, Germany; Aalto, Finland; Maryland, US; Palermo, Italy; Barcelona, Spain and Crete, Greece.

What is your priority to follow up next?

I would like to explore more the direction of implementing quantum simulations in superconducting and photonic chip architectures. We are external partners of a large international consortium that is currently running in Europe on this. I would also like to keep the group going at our current pace and size. We are seven people, with three postdocs, three students and a few international visitors. We will be welcoming one or two new students next year.

What are groups elsewhere doing?

There is an international race to produce working simulations of complex phenomena such as quantum phase transitions, quantum magnetism and superconductivity. Different groups work on different aspects of these questions using different technologies. In CQT our strength is in cold atom, photon and ion technologies.

We have also seen companies starting work on quantum simulations. For example, Google in 2013 launched a Quantum Artificial Intelligence Lab and announced in September 2014 a partnership with John Martinis at the University of California, Santa Barbara, to build its own quantum hardware using superconducting circuits. The aerospace company Lockheed Martin is another working in this area.

What real-world applications might your research have?

The quantum simulators we're developing are already starting to impact areas ranging from condensed matter and relativistic physics, to nanotechnology and materials science. Understanding complex phenomena in materials, for example, can help us improve device design, such as building nanocircuits that are robust to impurities. The experimental tools developed may also assist in the development of devices, such as photonic chips that serve as optical quantum memories. In the long term, we believe that quantum simulators could take a major step towards scalable quantum computing, replacing large-scale classical computer simulations for problems involving 50-100 qubits with complex interactions.

What is a quantum simulator?

Tomi Johnson, co-author of a 2014 review on the topic, explains how the question goes surprisingly deep

There are questions – not unimportant ones either, like 'how does a superconductor work?' – for which you'd have to wait an unimaginably long, long time for your normal computer to come up with an answer. We'd all be stardust by the time it happens. But with a quantum simulation, looking at how a few, well-controlled atoms move in a lattice of laser light, say, we might get the answer out during our lives.

Quantum simulation is a really hot topic now. There are lots of theorists proposing ways to simulate, and as many experimentalists building simulators in state-of-the-art labs. Things seem to be at a transition point: we are able or on the verge of being able to learn things using quantum simulations that we simply could not learn in any other way.

The very fact that quantum simulators are becoming so powerful means it's time we started asking hard questions about what it means for a simulator to be good or useful. The answers to such questions are not always obvious and are sometimes even contentious. We were forced to go back and address even more basic questions, such as what is a simulator, how is it different from a computer, how is one used, and even what it means for a simulator to be quantum.

Hopefully our review can shape how people judge and even plan future simulations, as well as providing a nice summary and introduction for someone who wants to know what quantum simulations are all about.

Tomi Johnson, Stephen Clark and Dieter Jaksch, researchers at CQT and the University of Oxford, wrote the review "What is a quantum simulator?", EPJ Quantum Technology *1, 10 (2014). The article appeared in a thematic series edited by Dimitris on quantum simulations.*

Simulations have a long history in science. Taken from a 1759 book, this engraving shows an orrery: a mechanical contraption to simulate the motion of the planets and moons of our solar system. Image: Wellcome Library, London CC-BY-4.0

OF FILM AND FICTION

CQT's Quantum Shorts competitions have called for creative content inspired by quantum physics. Jenny Hogan explains

If you're not a quantum physicist, quantum physics can seem daunting: it has particles too small to see, phenomena that defy experience and technologies that sound outlandish. So how should CQT engage people in exploring the excitement and promise we see in our science?

CQT launched the Quantum Shorts contests in 2012 to do just that. The annual competition, now in its third year, calls for stories that draw inspiration from quantum physics, offering prizes in open and student categories with eminent judges to decide the awards. The medium has alternated from film to prose and back again. It's human nature to learn from stories, so we think this offers a powerful approach to outreach: connecting not only with the people who write the stories and make the movies, but also with those who read and watch them.

Mariette di Christina, Editor in Chief at *Scientific American*, was a judge for the Quantum Shorts 2013 contest for flash fiction – stories under 1000 words. "This stranger-than-fiction discipline has inspired some first-class narrative thrills," she wrote when she posted the winning story to *Scientific American*'s blog. The winning story, reproduced below, was chosen from over 500 entries.

The competitions have been supported by media partners contributing advertising, judges and prizes. We are grateful to *Scientific American* and *Nature* for their involvement in the 2014 film competition; *Scientific American*, Tor, and Tor.com for supporting us in 2013; and *New Scientist* magazine for backing the inaugural film contest in 2012.

Find the competition online at shorts.quantumlah.org

Winner 2013

The Knight of Infinity **by Brian Crawford**

They wouldn't let him build a train track over the Grand Canyon, so Rider Quinn bought his own canyon in the California desert and built it there. The setup was simple: a magnetic track led across the desert to the lip of the canyon, where it split into two. One track continued over a bridge, the other terminated in thin air. The fate of the train hinged on an apparatus that measured the spin value of a proton at a given moment. Based on this measurement, a railroad switch would either trigger or not, causing the train to stay on course over the bridge, or plunge into the void below -- or into another universe, depending on to which faith one subscribed.

The faithful generally divided into two camps. The "Copenhagens" believed that while a quantum particle existed in all possible states at once, the instant it was measured it would be forced into one probability or another. Quinn would live or die, and that was that. But for the other camp, the "Many-Worlders," the quantum event triggered a divergence not just of trains but of universes: the train went all directions, Quinn lived and died, and infinite crowds were thrilled and dismayed by the outcomes. In the days leading up to the event, the debate grew, and there were conferences, demonstrations, and even fisticuffs.

Quinn didn't care much about either theory, or even the outcome; he just wanted something big to fill the void that had hollowed out his life. Ovarian cancer had taken his wife the previous spring. Bethany had been with him since their college days at Stanford, before Quinn was the "Knight of Silicon Valley," as Time Magazine had named him. And Bethany had stood by him through a dozen tech enterprises, personal and political scandal, and years of fruitless fertility treatments. The rest of Quinn's world had unravelled as quickly as Bethany's red hair had fallen out during her treatment. The stock in his electrical car company tanked after a series of highly-publicized battery fires. His magnetic levitation train, theoretically capable of going from Los Angeles to San Francisco in an hour, had run into a political tsunami, and was all but dead in its tracks. The silver lining was that he now had plenty of extra railroad materials on hand.

Quinn poured the bulk of his dying enterprise into building the train. Depending on whom you asked, it was by far the most expensive daredevil stunt, or the most publicized physics experiment, of all time. And there were plenty of people to ask. Cameras captured every swing of the hammer, every drop of sweat. Las Vegas was overwhelmed with bettors on the outcome of what the media had dubbed the "suicide switch." The internet frothed with commentary, calling him everything from the word's first time traveler, to a murderer who should be arrested upon arrival on the other side of the canyon – for killing his parallel self.

Winner
2012

Quantum Daughter **by GLeNK TV**

In the short film Quantum Daughter, the daughter of Ernest Rutherford is using the Parallel Universe App of her Really Smart Phone to gather ID points to renew her Quantum Computer Phone contract. The striking three-minute stop-motion animation was produced in Australia by GLeNKTV, with visuals and story by Chris Willoughby, sound by Phil Okerstrom and voices by Megan Jameison, Tim Denton and Steve Fresser.

Renowned physicist Lisa Randall, a judge in the 2012 competition, acclaimed it as easily her favourite entry of the year. "It's clever, creative, had some of the physics and is funny," she said.

Watch at http://goo.gl/PjYX1L

On the morning of Q-Day, as it came to be known, Quinn kissed the amulet that held a lock of Bethany's red hair, waved to the seething crowd, and fired up the train. Of course, he could be the only driver and passenger, although there was no shortage of weirdoes from around the world who wanted to buy a seat. While the train warmed up, he concentrated on the vacuum-cleaner-like sound and retreated into his mind, as he had done through many high-stakes situations in his life. In his mind, there were no news vans or cameras. There were no spectators, hoards of them who had camped out for days to get a seat in the grandstands, most of them hoping for a spectacular crash. But Bethany was there – she was always there.

He was startled out of his mind by a bang on the window. A white-haired man in a lavender track suit gesticulated outside. He yelled through a megaphone, “Don’t worry, you have done this an infinite number of times, and survived!”

Quinn, a born showman with lightning reflexes, flashed a smile and responded through the external microphone, so the crowd could hear. “If you’re right, then I have also crashed into the canyon just as many times.” The man didn’t have a chance to respond; security was already dragging him back across the crowd barrier.

After the national anthem, Quinn gave a short but inspiring speech, and the crowd joined in a countdown. He flipped the power lever, and the train’s acceleration rammed him into his seat. He had built enough track to bring the train up to its top speed just before it reached the canyon. The scenery whipped by – sand and tents and people – until it blurred. Quinn gritted his teeth and braced for an impact, but the train swooshed over the bridge, the canyon flashed below, and then he was on the other side.

The sun seemed brighter here and Quinn squinted against it as he tried to gauge the reaction of the crowds lining the track. People passed by so quickly that they appeared to be all one connected mass, stretching to the horizon. There was a sudden break in the crowd, and instead of the desert, it was another train he saw, keeping pace with his, on another track. He could see into the lighted cockpit, but he couldn’t make out the face of the man driving it. Next to the driver sat a woman with the most radiant red hair, thick and flowing over her shoulders, and in her lap was a young boy. Quinn reached out his arm to wave, but then the crowd was in the way again.

Only one train stopped at the end. Three passengers stepped out of the door, and the crowd erupted. Reporters flooded the platform, thrusting cameras and microphones in Quinn’s face, but for once, he had no idea what to say.

About the Author:

Brian Crawford is a biotechnology manager and writer living in the San Francisco Bay Area. One of his (extremely) short stories was published in an anthology featuring award-winning authors such as Joyce Carol Oates and Peter Straub, along with emerging writers.

STUDENTS AT CQT

The Centre for Quantum Technologies is committed to training the next generation of scientists, offering top-class education in a vibrant environment

Earn a PhD@CQT

Students at CQT develop expertise in the exciting, interdisciplinary field of quantum technologies. The centre's research spans experimental and theoretical physics and computer science. Students receive multidisciplinary training with a focus in science, engineering or computing. We currently have around 60 students working towards a PhD.

The PhD@CQT programme 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.

Of the 17 students graduated since the programme's first intake in 2008, 16 advanced into postdoc positions and one moved into the finance industry.

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

Internships

CQT offers internships to students near the end of an undergraduate degree or in the middle of an MSc who are contemplating a career in research. Application is by email 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.

Graduates in 2014

Giovanni Vacanti
Manifestations of Quantum Mechanics in Open Systems: From Opto-Mechancis to Dynamical Casimir Effect
Supervised by Vlatko Vedral

Nick Lewty
Experimental Determination of the Nuclear Magnetic Octupole Moment of 137Ba
Supervised by Murray Barrett

Li Ying
Entangled Many-body States as Resources of Quantum Information Processing
Supervised by Kwek Leong Chuan

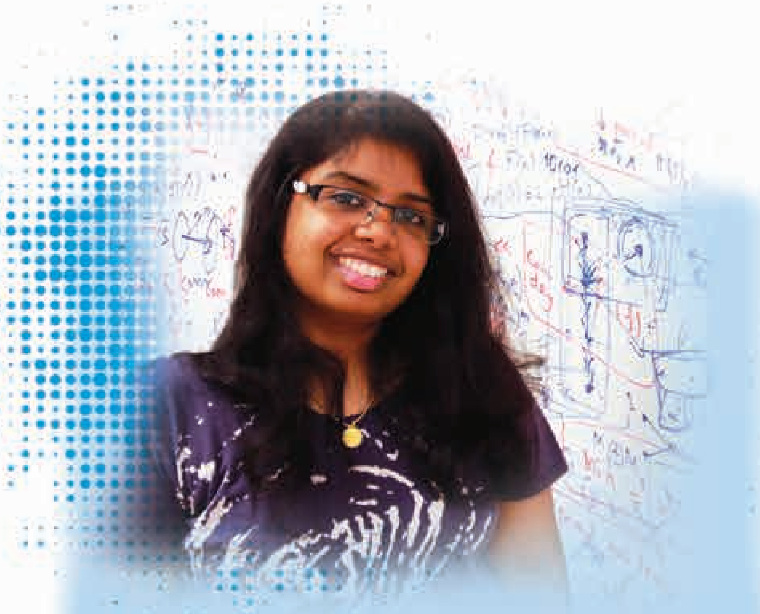
Rafael Rabelo
On Quantum Nonlocality and the Device-Independent Paradigm
Supervised by Valerio Scarani

Shang Jiangwei
Symmetric Minimal Quantum Tomography and Optimal Error Regions
Supervised by Berge Englert

Teo Zhi Wei Colin
Quantum Optics in Information and Control
Supervised by Valerio Scarani

Huo Mingxia
Quantum Simulations with Photons in One-Dimensional Nonlinear Waveguides
Supervised by Kwek Leong Chuan and Dimitris Angelakis

Penghui Yao
Studies in Communication Complexity and Semidefinite Programs
Supervised by Rahul Jain



Aarthi Sundaram

Aarthi is a PhD student supervised by Miklos Santha

Tell us about you...

I am from Bangalore, the Silicon Valley of India, and I am 24. I'm in the second year of my PhD.

What is your research about?

I'm working mostly in the area of quantum algorithms, to understand their query complexity.

Quantum algorithms are programs for quantum computers?

Well, yes, but it's not like you take a programming language and write something down. It's on a more abstract level. We are looking to describe a mathematical set of steps to solve a problem.

How did you get interested in this area?

During my undergrad degree, one professor offered a course in quantum information and computing. I had heard about Shor's quantum algorithm that would break RSA encryption, and that was enough for me to want to take the course.

Are you enjoying your work?

It's very enjoyable. For one thing, it's always fresh. There's a lot to learn. Experimentalists tinker around with things, take their experiments apart and put them together again. It's not so different as a theorist. When you talk about a problem, you may need to dig in and take it apart. You see little things, and sometimes you find connections you never expected. On the other hand, it is tough hitting more dead ends than open doors. But it's usually a one-door-closes-another-door-opens kind of thing.

Maciej Malinowski

Matt did an internship in Wenhui Li's group

Where are you from?

I'm from Poland. I just finished my third year studying physics at the University of Oxford, UK.

What did you work on at CQT?

In our system, there are atoms floating around in a very small region of space. We strip the electrons off the atoms, and we want to picture the configuration at the moment of stripping. I was coming up with designs to magnify the electrons and ions, and running simulations. The setup is for Rydberg atoms, which have very, very high energy levels. They behave like little dipoles. With this system you can simulate materials that are difficult to make or not known to exist.

What are your impressions of the place?

It was fun working in an experimental group where you see an ongoing collaboration, see the people working, and see the problems they face. I would say it reinforced my thinking I want to do a PhD.

Have you enjoyed Singapore too?

I'm not a big fan of cities so I was initially kind of daunted, thinking that all Singapore was just shopping malls, but there are a lot of nice nature places. During my internship I also made short trips into Malaysia, and afterwards I went backpacking in Malaysian Borneo and Laos.

UNIVERSITY TEACHING

CQT offers advanced courses and classes

"I understand my role as Professor as being an educator as well as a researcher," says Berge Englert, the CQT PI who oversees the Centre's graduate programme. Enhancing graduate education and training manpower is one of the main objectives of Singapore's Research Centres of Excellence.

CQT PIs teach both graduate and undergraduate courses at their host universities. We list here the graduate courses offered in the academic year 2013-14. CQT Research Fellows and guest lecturers teach some graduate courses under the supervision of PIs.

How many students are we reaching? Undergraduate and graduate courses at NUS typically have tens of students. This year one PI also reached tens of thousands of students: Valerio Scarani taught one of the National University of Singapore's first Massive Open Online Courses (see the box "Doing a MOOC" for details).

Graduate courses: 2013/14 Academic Year

Advanced Algorithms, CS6234
Rahul Jain

Advanced Solid State Physics, PC5203
Benoit Gremaud

Advanced Quantum Mechanics, PC5201
Dagomir Kaszlikowski

Breakthrough techniques in atomic and many-body physics, QT5201I
Christian Kurtsiefer, Lecturers: Thibault Thomas Vogt, Paul Condylis, Alessandro Cerè, Martin Trappe

CQT Seminar Module, QT5198
Wenhui Li and Stephanie Wehner

Photonics II, PC5247
Wenhui Li

Principles of Experimental Physics, PC5214
Christian Kurtsiefer

Quantum Information and Computation , PC5228
Dzmitry Matsukevich

Quantum Measurements and Statistics, QT5101
Dagomir Kaszlikowski

Special Problems in Physics: Quantum gases- interactions and statistics, PC5239
Kai Dieckmann

Topics in Optical Physics, PC5207
Alexander Ling

Doing a MOOC

More than 39,000 students from around the world had signed up for the course "Unpredictable? Randomness, Chance and Free Will" taught by CQT PI Valerio Scarani by the time it began in January 2014. The eight-week course was hosted on Coursera, a leading online platform for massive open online courses (MOOCs).

Valerio's course was one of the first offered by the National University of Singapore, which in 2013 became the first Singaporean university to partner Coursera. It consisted of four to six short video lectures per week and two online exams.

It's typical of MOOCs that only a small fraction of enrolled students complete the course, but the numbers are still impressive: each video was viewed by a mean of 4685 students, and over 1,100 students did well enough in the course exams to receive statements of accomplishment. The course covered the usefulness of randomness in communication and computation, the intrinsic randomness of quantum phenomena, the unpredictability of the weather, the role of chance in evolution, and the implications of the neural activity of the brain on a person's free will.

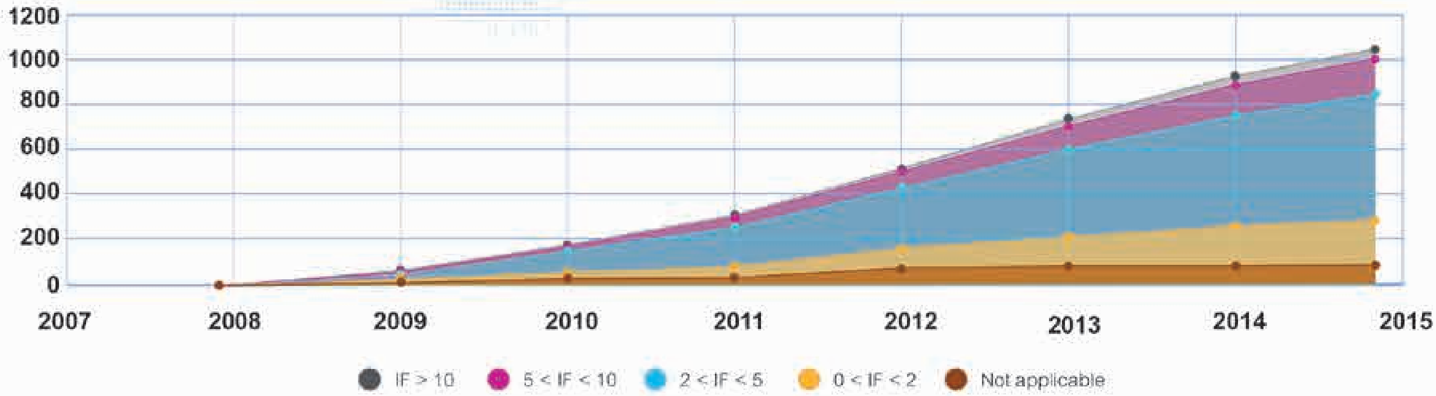
"I found the topics covered in the course to be fascinating. The professor went into enough depth to give me a taste, and make me want to learn more," said one respondent to an end-of-course survey.

Valerio saw a benefit too. He and two teaching assistants spent some 400 hours preparing the course from scratch. "I have noticed that the knowledge I developed has become very helpful both in structuring talks and in scientific conversations," he says.

PUBLICATIONS

Cumulative CQT Publications

In the year from 1 September 2013, CQT researchers authored over 190 scientific papers in peer-reviewed journals and conferences. The chart below shows the accumulating contribution of CQT research in journals by journal impact factor. There have been over 1000 CQT papers since the Centre was founded.



Full Characterization Of Quantum Correlated Equilibria
Wei, ZH; Zhang, SY
Quantum Inform. Comput. 13, 846, (2013)

Optimal Asymmetric Quantum Cloning For Quantum Information And Computation
Kay, A; Ramanathan, R; Kaszlikowski, D
Quantum Inform. Comput. 13, 880, (2013)

Distribution of entanglement in large-scale quantum networks
Perseguers, S; Lapeyre, GJ; Cavalcanti, D; Lewenstein, M; Acin, A
Rep. Prog. Phys. 76, 96001, (2013)

Photonic polarization gears for ultra-sensitive angular measurements
D'Ambrosio, V; Spagnolo, N; Del Re, L; Slussarenko, S; Li, Y; Kwek, LC; Marrucci, L; Walborn, SP; Aolita, L; Sciarrino, F
Nat. Commun. 4, 2432, (2013)

Non-Abelian off-diagonal geometric phases in nano-engineered four-qubit systems
Mousolou, VA; Canali, CM; Sjoqvist, E
EPL 103, 60011, (2013)

SpecTrap: precision spectroscopy of highly charged ions-status and prospects
Murbock, T; Albrecht, S; Andelkovic, Z; Cazan, R; Hannen, V; Johren, R; Vollbrecht, J; Schmidt, S; Segal, D; Thompson, R; Vogel, M; Weinheimer, C; Nortershauser, W; Birkl, G
Phys. Scr. T156, 14096, (2013)

Excitation of a Single Atom with Exponentially Rising Light Pulses
Aljunid, SA; Maslennikov, G; Wang, YM; Dao, HL; Scarani, V; Kurtsiefer, C
Phys. Rev. Lett. 111, 103001, (2013)

Experimental Generation of Quantum Discord via Noisy Processes
Lanyon, BP; Jurcevic, P; Hempel, C; Gessner, M; Vedral, V; Blatt, R; Roos, CF
Phys. Rev. Lett. 111, 100504, (2013)

Interacting spin-1 bosons in a two-dimensional optical lattice
de Parny, LD; Hebert, F; Rousseau, VG; Batrouni, GG
Phys. Rev. B 88, 104509, (2013)

Size of linear superpositions in molecular nanomagnets
Troiani, F; Zanardi, P
Phys. Rev. B 88, 94413, (2013)

Local characterization of one-dimensional topologically ordered states
Cui, J; Amico, L; Fan, H; Gu, M; Hamma, A; Vedral, V
Phys. Rev. B 88, 125117, (2013)

Higgs Algebraic Symmetry of Screened System in a Spherical Geometry
Li, Y; Zhang, FL; Gu, RJ; Chen, JL
Commun. Theor. Phys. 60, 278, (2013)

Multiple scattering of light in cold atomic clouds in a magnetic field
Sigwarth, O; Labeyrie, G; Delande, D; Miniatura, C
Phys. Rev. A 88, 33827, (2013)

Narrow Band Source of Transform-Limited Photon Pairs via Four-Wave Mixing in a Cold Atomic Ensemble
Srivathsan, B; Gulati, GK; Chng, B; Maslennikov, G; Matsukevich, D; Kurtsiefer, C
Phys. Rev. Lett. 111, 123602, (2013)

An experimental proposal for revealing contextuality in almost all qutrit states
Thompson, J; Pisarczyk, R; Kurzynski, P; Kaszlikowski, D
Sci Rep 3, 2706, (2013)

Tradeoff between leakage and dephasing errors in the fluxonium qubit
Herrera-Marti, DA; Nazir, A; Barrett, SD
Phys. Rev. B 88, 94512, (2013)

Entanglement Concentration is Irreversible
Kumagai, W; Hayashi, M
Phys. Rev. Lett. 111, 130407, (2013)

A framework for phase and interference in generalized probabilistic theories
Garner, AJP; Dahlsten, OCO; Nakata, Y; Murao, M; Vedral, V
New J. Phys. 15, 93044, (2013)

Drifting potential humps in ionization zones: The "propeller blades" of high power impulse magnetron sputtering
Anders, A; Panjan, M; Franz, R; Andersson, J; Ni, P
Appl. Phys. Lett. 103, 144103, (2013)

Properties and Construction of Extreme Bipartite States Having Positive Partial Transpose
Chen, L; Dokovic, DZ
Commun. Math. Phys. 323, 241, (2013)

Distinguishing Multi-Partite States by Local Measurements
Lancien, C; Winter, A
Commun. Math. Phys. 323, 555, (2013)

CSS-Like Constructions of Asymmetric Quantum Codes
Ezerman, MF; Jitman, S; Ling, S; Pasechnik, DV
IEEE Trans. Inf. Theory 59, 6732, (2013)

Quantum Rate-Distortion Coding With Auxiliary Resources
Wilde, MM; Datta, N; Hsieh, MH; Winter, A
IEEE Trans. Inf. Theory 59, 6755, (2013)

Entanglement Cost of Quantum Channels
Berta, M; Brandao, FGSL; Christandl, M; Wehner, S
IEEE Trans. Inf. Theory 59, 6779, (2013)

Greenberger-Horne-Zeilinger theorem for N qudits
Ryu, J; Lee, C; Zukowski, M; Lee, J
Phys. Rev. A 88, 42101, (2013)

A monogamy-of-entanglement game with applications to device-independent quantum cryptography
Tomamichel, M; Fehr, S; Kaniewski, J; Wehner, S
New J. Phys. 15, 103002 (2013)

Quantum thermometry using the ac Stark shift within the Rabi model
Higgins, KDB; Lovett, BW; Gauger, EM
Phys. Rev. B 88, 155409, (2013)

The structure of Renyi entropic inequalities
Linden, N; Mosonyi, M; Winter, A
Proc. R. Soc. A-Math. Phys. Eng. Sci. 469, 20120737, (2013)

Quantum Zeno effect of general quantum operations
Li, Y; Herrera-Marti, DA; Kwek, LC
Phys. Rev. A 88, 42321, (2013)

Strong spin-dependent negative differential resistance in composite graphene superlattices
Munarriz, J; Gaul, C; Malyshev, AV; Orellana, PA; Muller, CA; Dominguez-Adame, F
Phys. Rev. B 88, 155423, (2013)

Simulation of the magnetoresistance of ultracold atomic Bose gases in bichromatic lattices
Towers, J; Cormack, SC; Hutchinson, DAW
Phys. Rev. A 88, 43625, (2013)

Ramp Dynamics of Phonons in an Ion Trap: Entanglement Generation and Cooling
Dutta, T; Mukherjee, M; Sengupta, K
Phys. Rev. Lett. 111, 170406, (2013)

Three-Player Entangled XOR Games Are NP-Hard to Approximate
Vidick, T
Proceedings of FOCS, (2013)

Comment on "Quantum Szilard Engine"
Plesch, M; Dahlsten, O; Goold, J; Vedral, V
Phys. Rev. Lett. 111, 188901, (2013)

A Tight Upper Bound for the Third-Order Asymptotics for Most Discrete Memoryless Channels
Tomamichel, M; Tan, VYF
IEEE Trans. Inf. Theory 59, 7041, (2013)

A Generalized Construction and Improvements on Nonbinary Codes From Goppa Codes
Tomlinson, M; Jibril, M; Tjhai, C; Bezzateev, SV; Grassl, M; Ahmed, MZ
IEEE Trans. Inf. Theory 59, 7299, (2013)

A Hierarchy of Information Quantities for Finite Block Length Analysis of Quantum Tasks
Tomamichel, M; Hayashi, M
IEEE Trans. Inf. Theory 59, 7693, (2013)

Tight Exponential Analysis of Universally Composable Privacy Amplification and Its Applications
Hayashi, M
IEEE Trans. Inf. Theory 59, 7728, (2013)

Experimental verification of quantum computation
Barz, S; Fitzsimons, JF; Kashefi, E; Walther, P
Nat. Phys. 9, 727-731, (2013)

Experimental Bit Commitment Based on Quantum Communication and Special Relativity
Lunghi, T; Kaniewski, J; Bussieres, F; Houlmann, R; Tomamichel, M; Kent, A; Gisin, N; Wehner, S; Zbinden, H
Phys. Rev. Lett. 111, 180504, (2013)

Detecting and Estimating Continuous-Variable Entanglement by Local Orthogonal Observables
Zhang, CJ; Yu, SX; Chen, Q; Oh, CH
Phys. Rev. Lett. 111, 190501, (2013)

Programmable discrimination with an error margin
Sentis, G; Bagan, E; Calsamiglia, J; Munoz-Tapia, R
Phys. Rev. A 88, 52304, (2013)

Four-qubit pure states as fermionic states
Chen, L; Dokovic, DZ; Grassl, M; Zeng, B
Phys. Rev. A 88, 52309, (2013)

Brave new quantum world
Cable, H; Modi, K
New Sci. 220, 30, (2013)

Device-independent certification of the teleportation of a qubit
Ho, M; Bancal, JD; Scarani, V
Phys. Rev. A 88, 52318, (2013)

Validity of the rotating-wave approximation in nonadiabatic holonomic quantum computation
Spiegelberg, J; Sjoqvist, E
Phys. Rev. A 88, 54301, (2013)

On quantum theory
Englert, BG
Eur. Phys. J. D 67, 238, (2013)

Sequential state discrimination and requirement of quantum dissonance
Pang, CQ; Zhang, FL; Xu, LF; Liang, ML; Chen, JL
Phys. Rev. A 88, 52331, (2013)

Analysis of a proposal for a realistic loophole-free Bell test with atom-light entanglement
Teo, C; Minar, J; Cavalcanti, D; Scarani, V
Phys. Rev. A 88, 53848, (2013)

Frozen photons in Jaynes-Cummings arrays
Schetakis, N; Grujic, T; Clark, S; Jaksch, D; Angelakis, D
J. Phys. B-At. Mol. Opt. Phys. 46, 224025, (2013)

On the problem of contextuality in macroscopic magnetization measurements
Soeda, A; Kurzynski, P; Ramanathan, R; Grudka, A; Thompson, J; Kaszlikowski, D
Phys. Lett. A 377, 2856-2859, (2013)

Tensor network methods for invariant theory
Biamonte, J; Bergholm, V; Lanzagorta, M
J. Phys. A-Math. Theor. 46, 475301, (2013)

On quantum Renyi entropies: A new generalization and some properties
Muller-Lennert, M; Dupuis, F; Szehr, O; Fehr, S; Tomamichel, M
J. Math. Phys. 54, 122203, (2013)

Non-Equilibrium Statistical Mechanics Inspired by Modern Information Theory
Dahlsten, OCO
Entropy 15, 5346, (2013)

Coherent states of composite bosons
Lee, SY; Thompson, J; Kurzynski, P; Soeda, A; Kaszlikowski, D
Phys. Rev. A 88, 63602, (2013)

Optimal Blind Quantum Computation
Mantri, A; Perez-Delgado, CA; Fitzsimons, JF
Phys. Rev. Lett. 111, 230502, (2013)

Experimental Distribution of Entanglement with Separable Carriers
Fedrizzi, A; Zuppardo, M; Gillett, GG; Broome, MA; Almeida, MP; Paternostro, M; White, AG; Paterek, T
Phys. Rev. Lett. 111, 230504, (2013)

Three-Body Bound States in Dipole-Dipole Interacting Rydberg Atoms
Kiffner, M; Li, WH; Jaksch, D
Phys. Rev. Lett. 111, 233003, (2013)

Role of complementarity in superdense coding
Coles, PJ
Phys. Rev. A 88, 62317, (2013)

Effective dynamics of cold atoms flowing in two ring-shaped optical potentials with tunable tunneling
Aghamalyan, D; Amico, L; Kwek, LC
Phys. Rev. A 88, 63627, (2013)

Optimal error regions for quantum state estimation
Shang, JW; Ng, HK; Sehrawat, A; Li, XK; Englert, BG
New J. Phys. 15, 123026, (2013)

Resource Theory of Quantum States Out of Thermal Equilibrium
Brandao, FGSL; Horodecki, M; Oppenheim, J; Renes, JM; Spekkens, RW
Phys. Rev. Lett. 111, 250404, (2013)

Finite f-electron bandwidth in a heavy-fermion model
Euverte, A; Chiesa, S; Scalettar, RT; Batrouni, GG
Phys. Rev. B 88, 235123, (2013)

Noise-assisted Ramsey interferometry
Dorner, U
Phys. Rev. A 88, 62113, (2013)

Hardy's paradox for high-dimensional systems
Chen, JL; Cabello, A; Xu, ZP; Su, HY; Wu, CF; Kwek, LC
Phys. Rev. A 88, 62116, (2013)

From antiferromagnetic ordering to magnetic textures in the two-dimensional Fermi-Hubbard model with synthetic spin-orbit interactions
Minar, J; Gremaud, B
Phys. Rev. B 88, 235130, (2013)

QUANTUM PHYSICS Isolate the subject
Bancal, JD
Nat. Phys. 10, 11-12, (2014)

New binary codes from extended Goppa codes
Tomlinson, M; Jibril, M; Tjhai, C; Grassl, M; Ahmed, MZ
Designs Codes Cryptogr. 70, 149, (2014)

A universal setup for active control of a single-photon detector
Liu, Q; Lamas-Linares, A; Kurtsiefer, C; Skaar, J; Makarov, V; Gerhardt, I
Rev. Sci. Instrum. 85, 13108, (2014)

Hidden Translation And Translating Coset In Quantum Computing
Friedl, K; Ivanyos, G; Magniez, F; Santha, M; Sen, P
SIAM J. Comput. 43, 1-24, (2014)

Pairing correlations in the two-layer attractive Hubbard model

Zujev, A; Scalettar, RT; Batrouni, GG; Sengupta, P
New J. Phys. 16, 13004, (2014)

Information-theoretic metric as a tool to investigate nonclassical correlations
Kurzynski, P; Kaszlikowski, D
Phys. Rev. A 89, 12103, (2014)

Towards photonic quantum simulation of ground states of frustrated Heisenberg spin systems
Ma, XS; Dakic, B; Kropatschek, S; Naylor, W; Chan, YH; Gong, ZX; Duan, LM; Zeilinger, A; Walther, P
Sci Rep 4, 3583, (2014)

An efficient algorithm for finding the ground state of 1D gapped local hamiltonians
Landau, Z; Vazirani, U; Vidick, T
Proc. ITCS 301 (2014)

Robust device independent quantum key distribution
Vazirani, U; Vidick, T
Phys. Rev. Lett. 113, 140501 (2014)

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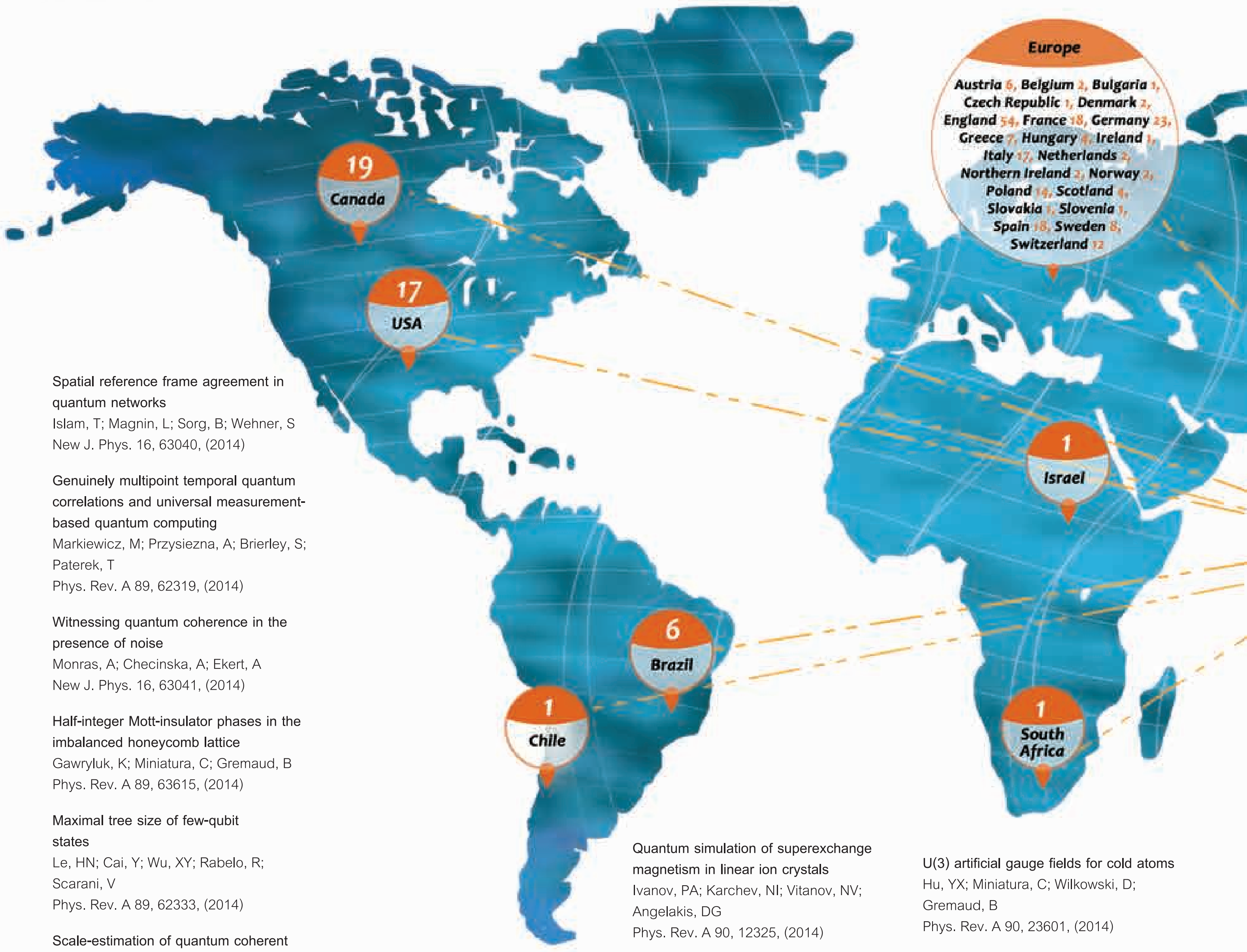

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Fujikawa, K; Oh, CH; Zhang, CJ
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Entanglement and quantum phase transition of spin glass: A renormalization group approach
Koh, CY; Kwek, LC
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Muller, MP; Oppenheim, J; Dahlsten, OCO
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Quantum quenches, linear response and superfluidity out of equilibrium
Rossini, D; Fazio, R; Giovannetti, V; Silva, A
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Dahlsten, OCO; Garner, AJP; Vedral, V
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Canonical form of three-fermion pure-states with six single particle states
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J. Math. Phys. 55, 82203, (2014)

COLLABORATIONS

International reach

CQT has broad international networks through the collaborations of individual CQT researchers with colleagues abroad and through formal research agreements with other academic entities. The world map to the left shows the number of publications coauthored by CQTians with researchers from each country. The table below lists entities which have research agreements with CQT.

CQT has research agreements with...

- University of Oxford, UK
- Institute for Quantum Computing (IQC), University of Waterloo, Canada
- University of Ulm, Germany
- University of New South Wales & Australian National University, Australia
- Max Planck Institute for Nuclear Physics, Germany
- University of Science, Vietnam National University, Ho Chi Minh City, Vietnam
- University of Otago, New Zealand
- Scuola Normale Superiore (SNS), Italy
- UMI MajuLab Agreement between NUS, NTU and CNRS, the French national research organisation, acting on behalf of the University of Nice Sophia Antipolis

Relating different quantum generalizations of the conditional Renyi entropy
Tomamichel, M; Berta, M; Hayashi, M
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Local random quantum circuits: Ensemble completely positive maps and swap algebras
Zanardi, P
J. Math. Phys. 55, 82204, (2014)

Second-Order Coding Rates for Channels With State
Tomamichel, M; Tan, VYF
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A solenoidal synthetic field and the non-Abelian Aharonov-Bohm effects in neutral atoms
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Microwave Control of Trapped-Ion Motion Assisted by a Running Optical Lattice
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Probing the topological properties of the Jackiw-Rebbi model with light
Angelakis, DG; Das, P; Noh, C
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Muller, CA; Shapiro, B
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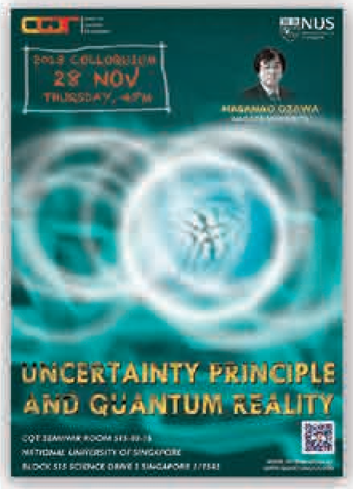
Quantum and classical superballistic transport in a relativistic kicked-rotor system
Zhao, QF; Muller, CA; Gong, JB
Phys. Rev. E 90, 22921, (2014)

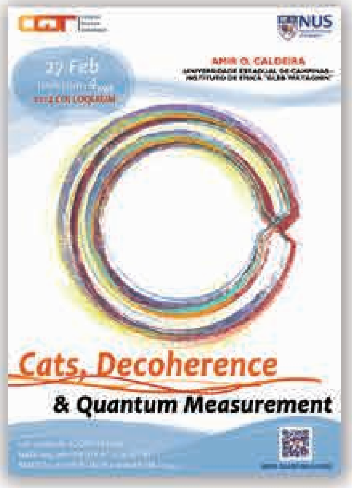
EVENTS

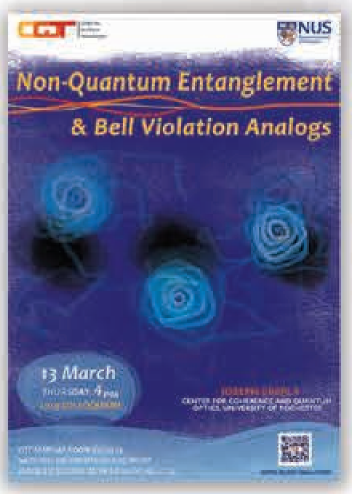
Conferences and Workshops

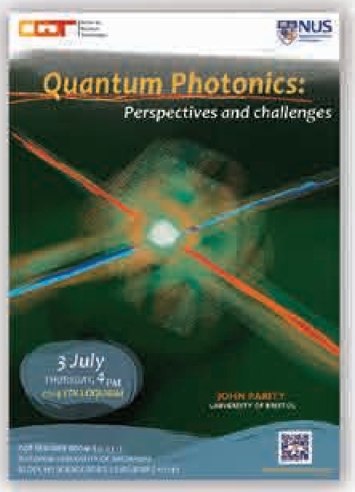
Date	Location	Workshop/School Title
12 Aug-11Oct 2013	Institute for Mathematical Sciences, NUS	Mathematical Horizons for Quantum Physics 2
6 Dec 2013	Centre for Quantum Technologies, NUS	Annual Symposium: The Famous, The Bit & The Quantum
9-13 Dec 2013	Institute for Mathematical Sciences, NUS	Quantum Computing Workshop on Inverse Moment Problem
26-28 Feb 2014	Town Plaza, University Town, NUS	IPS 2014 Meeting
22-26 Apr 2014	Ngee Ann Kongsi Auditorium, ERC, University Town, NUS	BergeFest 2014
19-21 May 2014	Global Learning Room, ERC, University Town, NUS	Beyond I.I.d 2014
21-23 May 2014	Ngee Ann Kongsi Auditorium, ERC, University Town, NUS	Theory of Quantum Computation, Communication and Cryptography, TQC 2014

Colloquia & Symposium






NUS
Non-Quantum Entanglement
& Bell Violation Analogs
13 March
THURSDAY, 4 PM


NUS
Quantum Photonics:
Perspectives and challenges
3 July
THURSDAY, 4 PM
JOHN RARITY
UNIVERSITY OF BRISTOL


NUS
19 August
TUESDAY, 4 PM
2014 COLLOQUIUM
A Mixture of Fermi &
Bose Superfluids
CHRISTOPHE SALOMON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THE FAMOUS,
THE BIT &
THE QUANTUM
Friday, 6 Dec 2013
SUPERCONDUCTING CIRCUITS FOR QUANTUM INFORMATION PROCESSING
SIMULATING QUANTUM BEHAVIOUR WITH QUANTUM COMPUTERS
MAKE IT SMALL AND TAKE IT OUTSIDE!

OUTREACH

CQT online

- The CQT website has up to date research news and publications listings. *www.quantumlah.org*
- CQT's YouTube channel hosts video recordings of CQT colloquia delivered by distinguished scientists and other short films with a quantum flavour. *www.youtube.com/quantumblah*
- CQT also has Facebook, Twitter and Google+ channels under the name quantumlah. These channels have over 5000 followers combined.

In the news

CQT research was mentioned in over 40 news items this year. Highlights include:

- Media coverage of a *Nature* review co-authored by CQT's Director Artur Ekert included an op-ed piece in Singapore newspaper Today ("Quantum physics may be key to keeping data safe", April 2014) and a segment for US public radio
- *New Scientist* magazine published a "Big idea" feature co-authored by CQT Research Fellow Hugo Cable ("Noise is the key to quantum computing", November 2013)
- A feature in *The Economist* on quantum cryptography mentioned projects at CQT ("The devil and the details", September 2013)

School talks

- PI Christian Kurtsiefer taught two masterclasses in Singapore schools on the real-life applications of quantum mechanics.
- PI Kwek Leong Chuan and Research Fellow Sai Vinjanampathy ran an eight-week course on quantum physics for students in Singapore's National Junior College.
- PI Manas Mukherjee and Research Fellow Johannes Gambari gave talks to school groups at the Singapore Science Centre.

School visits

We hosted more than 400 students for visits during the past year, ranging in age from high school to undergraduate.

- 200 participants in the Asian Physics Olympiad
- 40 attendees at the NUS Faculty of Science Open House
- 5 participants from Singapore's Global Young Scientists Summit
- 90 students from the Singapore Space Academy
- 30 advanced science students from the Netherlands on a study tour of Asia

Public events

CQT participated in the Singapore Science Festival and co-organised public talks with the Singapore Science Centre:

- During the Singapore Science Festival, we took hands-on optical demos to the Xperiment! carnival held in a shopping mall and to Singapore's Mini Maker Faire at a community centre. Both events ran over full weekends in July 2014.
- Public talks "At the Edge of Uncertainty" by British science writer Michael Brooks and "The Elusive Higgs Particle" by CQT Visiting Research Professor Jose Ignacio Latorre were booked out with over 100 registrations each.

Special projects

- We run the Quantum Shorts series of competitions for quantum-inspired films and fiction through dedicated websites. Supported by media partners such as the magazine *Scientific American* and the journal *Nature*, these reach a large international audience online (see pp. 32-33).
- PI Valerio Scarani taught an online course on Coursera.org called "Unpredictable? Randomness, Chance and Free Will" over eight weeks from January 2014 (see pp. 36-37).
- CQT launched an open call supported by Singapore's National Arts Council for proposals for a writer's residency. Two appointments were made to start in September 2014.

VISITORS

Alexey Akimov
Russian Quantum Center

Mathias Albert
INLN (Nice)

Luigi Amico
Uni-Catania, Italy

Syed Assad
Australian National University

Kamel Ariffin bin Mohd Atan
Universiti Putra Malaysia

Robert Bedington

Ariel Bendersky
ICFO – Institut de Ciències Fotòniques

Michael Berry
University of Bristol

Mario Berta
ETH Zürich

Adam Bouland
MIT

Hans Briegel
University of Innsbruck and IQOQI

Michael Brooks
Freelance writer

Nicolas Brunner
University of Geneva

Dagmar Bruss
Heinrich-Heine-Universitaet Duesseldorf

Kaushik Chakraborty
Kolkata Albert Chang Duke University

Nicolas Cherroret
Laboratoire Kastler Brossel

Frederic Chevy
LKB, ENS, Paris.

Ignacio Cirac
Max Planck Institute for Quantum Optics

Charles Clark
National Institute of Standards and Technology, USA

Richard Cleve
IQC, Waterloo

Casey Coleman
Chapman University

Dai Li
National Chung Hsung University, Taiwan

Borivoje Dakic
University of Vienna

Michele Dall'Arno
Nagoya University

Gonzalo de la Torre
ICFO – Institut de Ciències Fotòniques

Michel de Rougemont
Université Paris VII, France

Martial Ducloy
Universite Paris-Nord

Frederic Dupuis
Aarhus University

Joe Eberly
University of Rochester

Michael Evans
University of Toronto

Bess Fang
Institut d'Optique

Omar Fawzi
ETH, Zurich

Simone Felicetti
University of the Basque Country UPV/EHU

Jean-Marc Gambaudo
Institute of Physics - INP CNRS

Yuval Gefen
Weizmann Institute of Science

Roy Glauber
Harvard University

John Goold
International Centre for Theoretical Physics, Trieste, Italy

Steve Greenland
Clyde Space

Arne Løhre Grimsmo
Norwegian University of Science and Technology

Haw Jing Yan
Australian National University

Jaesuk Hwang
Imperial College

Atac Imamoglu
ETH, Zurich

Stacey Jeffery
IQC, Waterloo

Aisling Johnson
Institut d'Optique

Alastair Kay
Royal Holloway, University of London

Kihwan Kim
Center for Quantum Information, Institute for Interdisciplinary Information Sciences, Tsinghua University, Beijing

Vasily Klimov
Lebedev Institut, Moscow

Tom Krenzke
Concordia University–Nebraska

Amine Laghaout
University of Toronto

Chang-Woo Lee
Texas A&M University at Qatar

Eunwoo Lee
South Korea

Gerd Leuchs
Max Planck Institute for the Science of Light

Yeong-Cherng Liang
ETH Zurich

Liu Jinming
East China Normal University

Hong-Gang Luo
Lanzhou University

Marcin Markiewicz
University of Gdansk, Poland

Eduardo Martin-Martinez
University of Waterloo

Paolo Mataloni
Sapienza Università di Roma

William Matthews
University of Cambridge

Matthew Mckague
University of Otago

Gerard Milburn
University of Queensland

Kavan Modi
Monash University

Joanna Modlawska
Adam Mickiewicz University

Alex Monras
Universit`a degli Studi di Salerno

Michele Mosca
IQC, Waterloo

Milan Mosonyi
Universitat Autònoma de Barcelona

Kilian Müller
Institut d'Optique

Phong Nguyen
INRIA and Tsinghua University

Raymond Ooi
University of Malaya

Masanao Ozawa
Nagoya University

Panagiotis Papanastasiou
Freiburg University

Saverio Pascazio
Universita di Bari

Anna Przysiezna
University of Gdansk, Poland

John Rarity
University of Bristol

Guillermo Romero
University of the Basque Country UPV/EHU

Denis Rosset
University of Geneva

Christophe Salomon
CNRS

Kaushik Seshadreesan
Louisiana State University

Alexander Shurupov
Palacký University, Olomouc, Czech Republic

Nana Siddarth
Chennai Mathematical Institute India

Germán Sierra
Instituto de Física Teórica UAM/CSIC

Jamie Sikora
Université Paris Diderot - Paris 7, France

Sergey Skipetrov
Laboratoire de Physique et Modelisation des Milieux Condenses

Enrique Solano
University of the Basque Country UPV/EHU

Priyaa Varshinee Srinivasan
University of Waterloo

Matthias Steiner
University of Cambridge

Xiaoming Sun
Institute of Computing Technology, Chinese Academy of Sciences.

Jun Suzuki
The University of Electro-Communications

Nickos Sxetakis
Technical University of Crete

James Ing Wei Tang
University of Malaya

Teo Yong Siah
Olomouc, Czech Republic

Daniel Terno
Macquarie University, Australia

Jason Teutsch
Penn State University

Toyohiro Tsurumaru
Mitsubishi Electric

Bart Van Tiggelen
Institute of Physics - INP CNRS

Thomas Vidick
MIT

Mark Wilde
Louisiana State University

Andreas Winter
Universitat Autònoma de Barcelona

David Xiao
Princeton University

Daoxin Yao
Sun Yat-sen University

Yasunobu Nakamura
University of Tokyo

Seokwon Yoo
Hanyang University, South Korea

Hishamuddin Zainuddin
Universiti Putra Malaysia

Yanbao Zhang
IQC, Waterloo

Zhu Huangjun
Perimeter Institute

Karol Zycykowski
Jagiellonian University

VISITORS' VIEWS

What impression do visitors to CQT leave with? What are their hopes for research in quantum technologies? We asked a few of them.

Richard Cleve was invited to CQT in December 2013 to be one of three speakers for the Centre's Annual Symposium, a scientific celebration of the Centre's birthday. "I had always wanted to visit CQT, so this seemed an ideal time," he says. He is a Professor in the School of Computer Science at the University of Waterloo, where he holds the Institute of Quantum Computing (IQC) Chair in Quantum Computing. He says one of his dreams for the outcome of research in quantum technologies is "a large scale quantum computer". But he adds that "my guess is that we're in an area of research where the ultimate useful outcomes will emerge as a surprise." CQT has many ties with Richard's home institute, IQC, including support for student exchange. "I think that CQT is one of the world's great centres of quantum computing research. It has outstanding scientists and is very well run," he says.

Holding the title "Visiting Scholar" at CQT, **Charles Clark**, co-director of the Joint Quantum Institute of the US National Institute of Standards and Technology and the University of Maryland, has made many trips. "My visits to Singapore began a few years before CQT was founded, so I have seen it grow from its birth," he says. When asked what he thinks of CQT, he says "It is remarkably successful! There are four or five quantum institutes in the world that every knowledgeable person agrees are in the top rank, and CQT is on everyone's list." Charles has also enjoyed becoming "experienced to some degree in local culture, participating in a Singaporean family's Chinese New Year festivities, hawker center dining, and the Botanic garden".

CQT in 2014 became the host of the MajuLab, a joint laboratory of NUS and NTU in Singapore and, from France, national research organization CNRS and the University of Nice. ***Bart van Tiggelen***, from CNRS and the University of Grenoble, France, was involved in this initiative. Bart initially struck up a connection with CQT to share expertise on research in cold atomic gases. He and CQT PI Kwek Leong Chuan held a joint grant from the Institut Francais Singapore to support their collaboration. Now the MajuLab exists, he is sure he'll be back for new projects. Something he has enjoyed during his visits to CQT is “The open-door policy and the ease to chat with colleagues over coffee on any subject.” That has drawbacks, too. “I guess that I had far too much coffee!” he says.

Visitor ***Saverio Pascazio*** from the Universita di Bari in Italy was hosted by CQT PI Vlatko Vedral for scientific collaboration. “We focus on classicality, entanglement and quantum phase transitions,” says Saverio. He is impressed by CQT's “high scientific standards, interesting young people, high-level research, and friendly atmosphere”. He and Vlatko have coauthored a number of papers. Asked about his dreams for quantum technologies, Saverio says “to blend fundamental research with practical applications”. He adds “This may be difficult nowadays, but can definitely be achieved with quantum technologies.”

"I was invited in 2012 to give a CQT colloquium, I liked the place and the people, and visited there twice since," says ***Yuval Gefen***, from the Weizmann Institute of Science in Israel. He is a Professor in the institute's department of condensed matter physics. CQT's emphasis on quantum information is, he says "complementary, but not orthogonal, to my interests. So my stay there is useful, to me and, hopefully, to the locals". He plans to visit CQT again to continue joint research work. He sums up what he considers highlights of Singapore as "friendly, good food, bustling".

MONEY MATTERS

Expenditure: Sep 13 – Aug 14

	Manpower	Other	Equipment	TOTAL
Core	11,393,459	6,326,075	1,539,068	19,258,602
External				
Merlion		30,182		30,182
NRF CRP	27,618	673	0	28,291
MOE Tier 3	1,136,751	603,202	89,686	1,829,639
DSO	383,222		192,340	575,562
FQXi	28,081	2,733		30,814
NRF Fellowship*	0	61	0	61
Total	12,969,131	6,962,925	1,821,093	21,753,150

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
- 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 service to the university.

*Two $30,000 grants from Institut Francais, Singapore, supported **French-Singaporean collaborations** involving PIS Kwek Leong Chuan and Bjorn Hessmo for two years to March 2014.*

*A three-year project by 4 PIs on **Hybrid Quantum Technologies** began July 2014 with a $4,325,456 grant from Singapore's National Research Foundation, Singapore.*

*A five-year project by 13 PIs on **Random Numbers from Quantum Processes** initiated in May 2013 with a $9,931,731 grant from Singapore's Ministry of Education (MOE). The project is led by PI Valerio Scarani.*

*A **Research Collaboration on Quantum Sensing** involving six CQT researchers and DSO National Laboratories, Singapore, is supported by a DSO grant of $863,000 running October 2012 to January 2015.*

For listing of all current grants, see http://www.quantumlah.org/main/funding

*PI Troy Lee was awarded a **Fellowship** offering $2,710,660 over five years from September 2013 by Singapore's National Research Foundation. Portions of the grant are managed by the Nanyang Technological University (*expenditure by NTU is not included in the table).*

*A USD 89,700 grant from the Foundational Questions Institute (FQXi), United States, supported PI Dagomir Kazlikowski and collaborator to study the **Operational and information theoretic meaning of contextuality** from September 2013 to October 2014. This grant is shared with Adam Mickiewicz University in Poland.*

SUPPORTERS

Ministry of Education
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NANYANG
TECHNOLOGICAL
UNIVERSITY

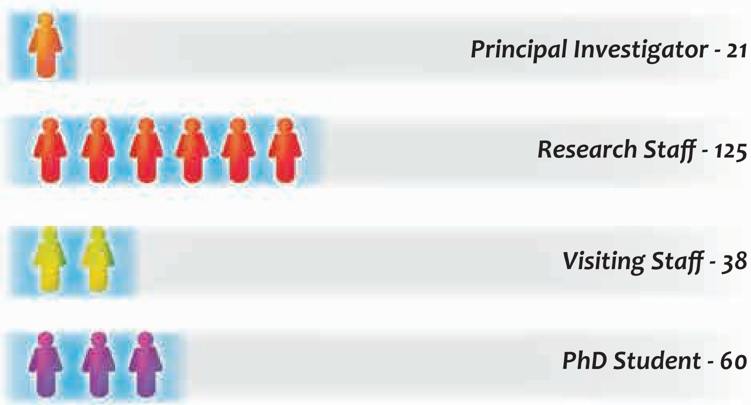
cnrs
dépasser les frontières

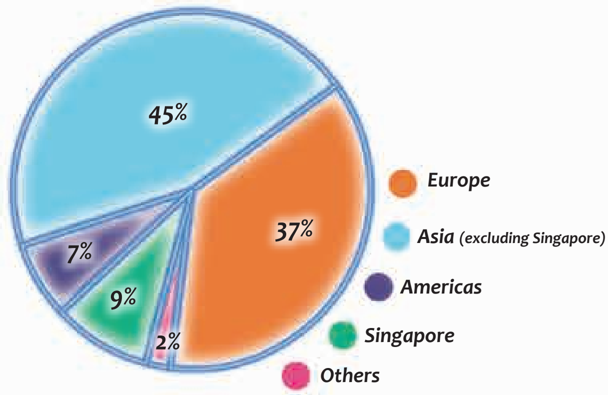
DSO
NATIONAL
LABORATORIES

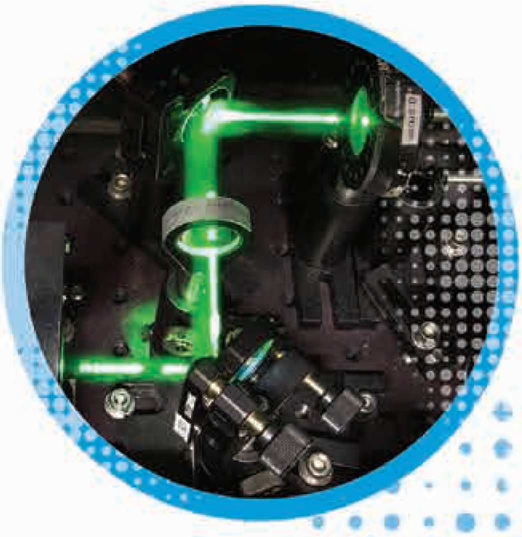
FQXi
FOUNDATIONAL QUESTIONS INSTITUTE

CQTians

... In total, 200+ CQTians from around 30 countries







Centre for Quantum Technologies
National University of Singapore
S15 #03-18 Science Drive 2
Singapore 117543