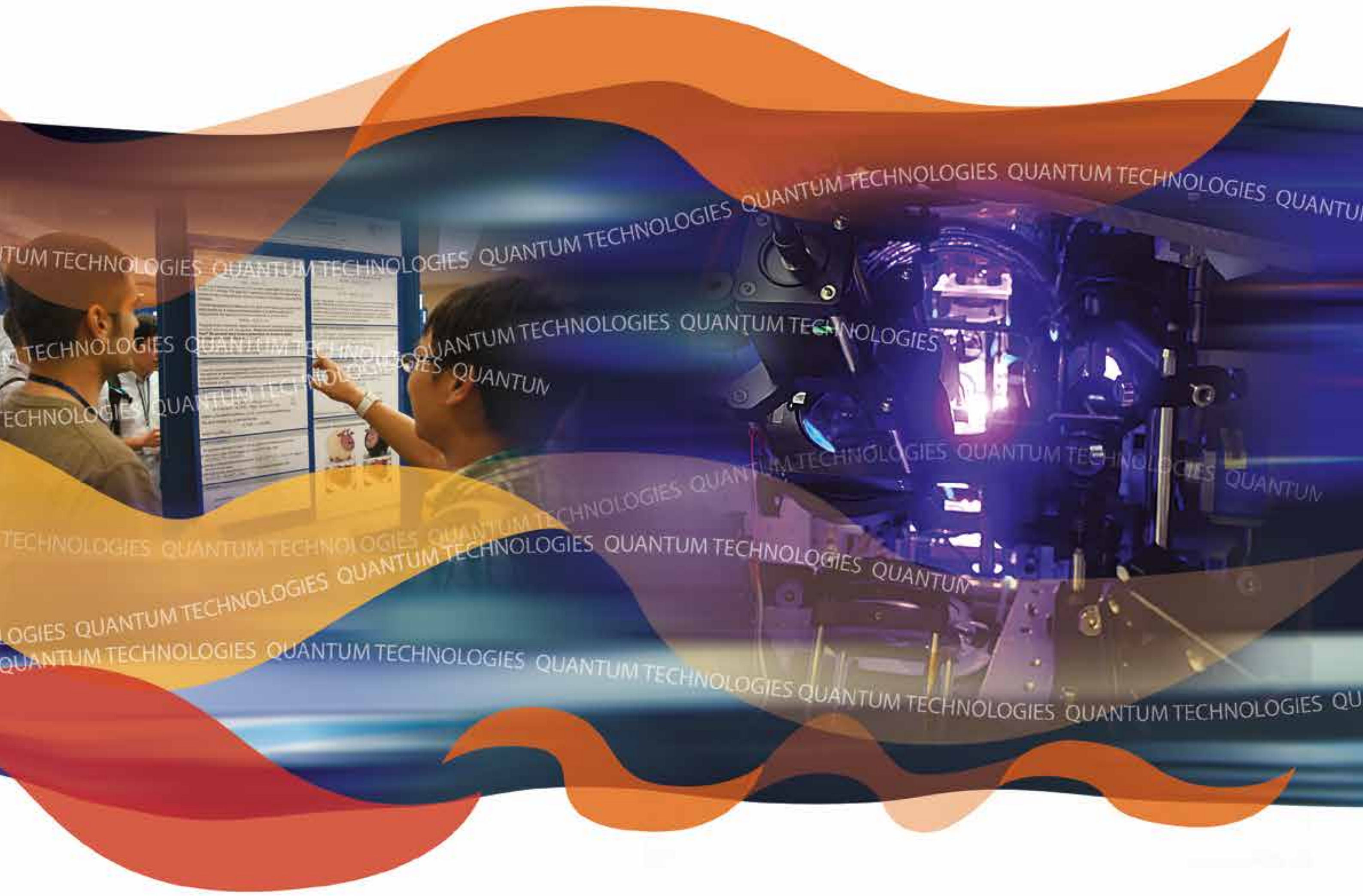
Centre for Quantum Technologies

National University of Singapore



annual report 2012

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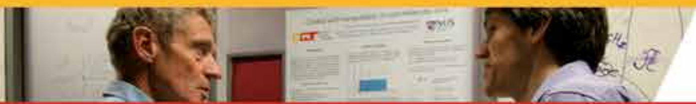

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Data and listings updated to end August 2012. Annual Report of the Centre for Quantum Technologies at the National University of Singapore.

Editorial team: Daniel Oi, Evon Tan, Jenny Hogan and Timothy Yeo.

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Who we are

I am told, by reliable sources, that we have been running the shop for five years. Five years! My imagination paints a grand picture of our labs and offices, our lasers, vacuum chambers and the many CQTians suspended in a cosmic void with the planet Earth, orbiting the Sun five times, dashing around the friendly star at more than 100,000 kilometres per hour and covering over four and a half billion kilometres. Yes, it has been a long journey but it seems as if it started yesterday.

I am shamelessly proud of what we have achieved so far. Good science is all around and Singapore has become a popular destination for budding researchers in quantum technologies. This is the place where quantum geeks of the world unite; a clear prelude to the quantum revolution. Our 219 researchers from 38 countries are jotting endless formulae on the Quantum Café whiteboards, exchanging views at numerous seminars and turning knobs of increasingly sophisticated machinery in the darkness of CQT's laboratories. They are making new discoveries about how the universe works and laying the foundations for a new generation of quantum-enhanced technologies.

Education, as much as research, is part of our mission, and this year is special for it saw the graduation of the first PhD@CQT students (see p. 40). We hope that our students will leave CQT not only with new knowledge but, more importantly, with open and inquisitive minds, ready to challenge established views. We also extend our education to the public at large. It is a great pleasure to see that our popular science talks attract more and more people, in particular Singaporean taxpayers, to whom we are grateful for paying our bills and salaries. They can rest assured that we will put to good use our ability to control atoms and photons with incredible precision.

Much else happened this year, too. We hosted Serge Haroche and his College de France lectures (see p. 36), we welcomed DPM Teo Chee Hean on his brief visit to our labs, and we travelled to Vancouver to represent Singaporean science at the Annual Meeting of the American Association for the Advancement of Science (AAAS) (see news on p. 17). We warmly congratulated Lai Choy Heng, Nelly Ng Huei Ying, Rahul Jain and Valerio Scarani on their awards (see p. 44). We were proud of Alex Ling, who knocked the socks off his audience (which included the President of Singapore) while talking about his experiment at the Lindau Nobel Laureate Meeting. And we cheered and cheered when Dave Wineland, a founding member of our Scientific Advisory Board, and Serge Haroche were awarded a certain Swedish prize.

I can go on like this, naming people, achievements, papers and happy moments of 2012, but there were also sombre days, like those in January when our Auntie Swee passed away. She was the centre's mother figure, always offering a warm hello, cleaning up after untidy researchers and making sure that we never ran short of coffee. These days of sadness showed, however, a sense of community within CQT. I found it very emotional and heartening.

It's a given that CQT has excellent scientists, but our community amounts to more than the sum of its parts. From social events to weekly football games, conversations in the Quantum Café to cartoons on doors, CQT offers an environment that we like to think is welcoming and vibrant. This environment helps us keep good people and make our research more collaborative and innovative than it might be in another setting. I hope we will enjoy this atmosphere for another five years and more.

And now, in case you have not skipped this introduction (I have to admit I never read introductions) please read on. Daniel, Evon, Jenny and Tim worked very hard to make this Annual Report not only informative but also fun to read.

Artur Ekert

"This is the place where quantum geeks of the world unite; a clear prelude to the quantum revolution... They are making new discoveries about how the universe works and laying the foundations for a new generation of quantum-enhanced technologies."

Letter from the Director

Governing Board

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Ministry of Education

Lawrence Koe
Director (Projects),
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Artur Ekert
Director, Centre for Quantum Technologies and
Lee Kong Chian Centennial Professor,
National University of Singapore
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President, Software Systems Group
President, ST Electronics (Info-Software Systems) Pte Ltd

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

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

Lui Pao Chuen
Advisor, National Research Foundation

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

▶ A meeting of minds. Pictured are members of the GB, SAB and representatives from NRF, from left to right (back row) Christophe Salomon, Chong Chee Wei, Karen Tan, Tan Eng Chye, Lye Kin Mun, Dave Wineland and Ignacio Cirac; (front row) Atac Imamoglu, Lam Chuan Leong, Barry Halliwell, Umesh Vazirani and Michele Mosca.

Changes to the Governing Board in 2012

A*STAR member: Lye Kin Mun replaced Raj Thampuram in August 2012
MoE member: Tan Gee Keow to be replaced by John Lim in September 2012
MoE alternate member: Chong Chee Wei to be replaced by Lee May Gee in October 2012
New member: Serguei Beloussov to join the Board in November 2012. Serguei's appointments include Senior Founding Partner, Runa Capital, Chairman of the Board and Chief Architect, Parallels and Chairman of the Board of Trustees, Russian Quantum Center.

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

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

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

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

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

Christophe Salomon
Research Director,
Laboratoire Kastler Brossel, CNRS

Hartmut Klauck

Appointed CQT Principal Investigator in 2010
Other appointments: Assistant Professor, Division of Mathematical Sciences, Nanyang Technological University, Singapore

Miklos, Rahul and Hartmut lead a computer science group exploring the intersection of computer science and quantum theory, including quantum algorithms, communication complexity, interactive proofs and quantum games.

Miklos Santha

Appointed CQT Principal Investigator in 2008
Other appointments: Head, Algorithms and Complexity Division, Laboratoire d'Informatique Algorithmique: Fondements et Applications at the University Paris Diderot, CNRS, France

Rahul Jain

Appointed CQT Principal Investigator in 2008
Other appointments: Assistant Professor, Department of Computer Science, National University of Singapore

Dagomir Kaszlikowski

Appointed CQT Principal Investigator in 2007
Other appointments: Associate Professor, Department of Physics, National University of Singapore

Dagomir's team explores the foundations of quantum theory. Particular interests include whether there exists a quantum-classical boundary, contextuality and constraints on quantum correlations.

Wenhui Li

Appointed CQT Principal Investigator in 2008
Other appointments: Assistant Professor, Department of Physics, National University of Singapore

Wenhui's group explores quantum many-body physics in and applications for ultracold Rydberg gases. The group also collaborates with Kai Dieckmann's group to experiment on atoms in optical lattices.

Rainer Dumke

Appointed CQT Principal Investigator in 2011
Other appointments: Assistant Professor, School of Physical & Mathematical Sciences, Nanyang Technological University, Singapore

In Rainer's labs at NTU, his team is working on superconducting atom chips, Bose–Einstein condensates, miniaturised optical systems for quantum information processing and a portable atom gravimeter.

Bjorn Hessmo

Appointed CQT Principal Investigator in 2009
Other appointments: Assistant Professor, Department of Physics, National University of Singapore

Bjorn leads a team investigating cold atoms in microtraps built with technologies from the semiconductor industry, integrating electrical chip structures with micro-optics.

Christian Kurtsiefer

Appointed CQT Principal Investigator in 2007
Other appointments: Professor, Department of Physics, National University of Singapore

Christian's quantum optics group implements quantum information building blocks with photons and atoms. The team has expertise in entangled photon pair sources, single photon detection and unconventional atom–photon interactions.

Murray Barrett

Appointed CQT Principal Investigator in 2007
Other appointments: Assistant Professor, Department of Physics, National University of Singapore

Murray's group focuses on the interfacing of atoms and photons via cavity QED for quantum information applications and precision metrology.

Kai Dieckmann

Appointed CQT Principal Investigator in 2009
Other appointments: Associate Professor, Department of Physics, National University of Singapore

Kai's group conducts experiments on ultracold gases, including investigation of Fermi mixtures. The group also has a collaborative project with Wenhui Li's group on atoms in optical lattices.

Berthold-Georg Englert

Appointed CQT Principal Investigator in 2007
Other appointments: Professor, Department of Physics, National University of Singapore

Berge's group investigates what can be known about a quantum system, for example through quantum state tomography. Also works on cold atoms in lattices including graphene-like structures.

Leong Chuan Kwek

Appointed CQT Principal Investigator in 2007
Other appointments: Professor, National Institute of Education and Deputy Director, Institute of Advanced Studies, Nanyang Technological University, Singapore

Kwek's group works on quantum information with a special focus on applied systems, including quantum processors and simulators.

Vlatko Vedral

Appointed CQT Principal Investigator in 2007
Other appointments: Professor, Department of Physics, National University of Singapore and Professor, University of Oxford, UK

The theory group that Vlatko leads investigates topics in quantum information ranging from discord, an alternative measure of quantum correlation, to thermodynamics. Researchers in his group have also ventured into quantum biology.

Manas Mukherjee

Appointed CQT Principal Investigator in 2012
Other appointments: Assistant Professor, Department of Physics, National University of Singapore

Manas's group is preparing ion trap systems with goals including emulating condensed matter systems and tests of fundamental physics. His team is also interested in using ions for information processing and metrology.

Andreas Winter

Appointed CQT Principal Investigator in 2007
Other appointments: Professor, Mathematics, University of Bristol, UK

Andreas heads a group studying quantum channel capacities, statistical mechanics, quantum hypothesis testing, entropic inequalities, non-locality and combinatorics.

Alexander Ling

Appointed CQT Principal Investigator in 2011
Other appointments: Assistant Professor, Department of Physics, National University of Singapore

Alex leads a group specialising in building compact, rugged and effective optical entanglement systems for experiments including a satellite-borne test of entanglement. His team has an active interest in nonlinear optics.

Stephanie Wehner

Appointed CQT Principal Investigator in 2010
Other appointments: Assistant Professor, Department of Computer Science, National University of Singapore

Stephanie's group combines expertise in physics and computer science to tackle problems ranging from quantum information theory and cryptography to fundamental concepts such as entanglement.

Choo Hiap Oh

Appointed CQT Principal Investigator in 2007
Other appointments: Professor, Department of Physics, National University of Singapore

Choo Hiap's group has three main research areas: quantum phase factors and their application in information processing, decoherence, entanglement and other measures of quantum correlations.

Dimitris G. Angelakis

Appointed CQT Principal Investigator in 2009
Other appointments: Faculty, Science Department of the Technical University of Crete, Greece

Researchers in Dimitris' group work on theoretical quantum optics and implementations of quantum information. Particular interests include quantum simulations of condensed matter effects with photons.

Valerio Scarani

Appointed CQT Principal Investigator in 2007
Other appointments: Professor, Department of Physics, National University of Singapore

The ConneQt group that Valerio heads bridges theory and experiment in quantum optics and atomic physics, with particular focus on the usefulness of non-locality in device-independent processing.

Dzmitry Matsukevich

Appointed CQT Principal Investigator in 2010
Other appointments: Assistant Professor, Department of Physics, National University of Singapore

Dzmitry's group is developing methods to prepare, manipulate and detect the internal states of trapped molecular ions for spectroscopy, precision measurements and quantum information processing.

Researchers

Senior Research Fellows

Alastair Kay
Chen Jingling
Feng Xun-Li
Gleb Maslennikov
Joakim Andersson
Joseph Fitzsimons
Markus Grassl
Pawel Kurzynski
Tomasz Paterek
Thibault Thomas Vogt
Troy Lee
Uwe Dorner
Yu Sixia

Research Assistants

Aarthi Lavanya Dhanapaul
Andrew Bah Shen Jing
Cheng Too Kee
Chia Chen Ming
Chia Zhong Yi
Chng Mei Yuen, Brenda
Chuah Boon Leng
Elnur Hajiyev
Haw Jing Yan
Ho Hui Kiat Melvyn
Kadir Durak
Law Yun Zhi
Le Huy Nguyen
Lee Chee Kong
Len Yink Loong
Lim Chin Chean
Marta Wolak
Nelly Ng Huei Ying
Ng Xin Zhao
Oon Fong En
Shi Xuan
Sivakumar s/o Maniam
Su Hongyi
Tan Peng Kian
Tan Yue Chuan
Tang Weidong
Tarun Johri
Teo Yong Siah
Thi Ha Kyaw
Thong May Han
Wang Zhuo
Zhu Huangjun

Research Fellows

Agata Checinska
Agnieszka Gorecka
Akihito Soeda
Alexandre Monras
Amir Kalev
Amit Rai
Arun
Bill Rosgen
Carlos A. Perez Delgado
Chen Qing
Christoph Hufnagel
Ciara Morgan
Dai Li
Daniel Cavalcanti
Daniel Sahagun
Erik Gauger
Guo Ruixiang
Herbert Crepaz
Hugo Cable
Jacob Biamonte
James Grieve
James Vicary
Jayne Thompson
Jimmy Sebastian
Jin Xianmin
Jiri Minar
Johannes Gambari
Joonwoo Bae
Julien Degorre
Kanhaiya Pandey
Krzysztof Gawryluk
Lana Sheridan
Lee Changhyub
Lee Kean Loon
Lee Su-Yong
Li Ke
Li Ke
Li Yu
Libby Heaney
Loick Magnin
Lu Xiaoming
Mafalda Almeida
Marco Tomamichel
Mark Williamson
Markus Johansson
Martin Aulbach
Martin Kiffner
Matthew Mckague
Mile Gu
Mirco Siercke
Ng Hui Khoon
Noh Chang Suk
Oscar Dahlsten
Patrick Coles
Paul Condylis
Philippe Raynal
Priyam Das
Qiao Youming
Radu Cazan
Sai Vinjanampathy
Sarvagya Uphadhyay
Stanislav Straupe
Stephen Clark
Thomas Decker
Tristan Farrow
Wei Zhaohui
Wu Chunfeng
Yang Tao
Zahra Shadman
Nilhan Gurkan
Zhang Chengjie

Visiting Research Professors

Christian Miniatura
David Hutchinson
Dieter Jaksch
Rosario Fazio
Georges Batrouni
Erik Sjoqvist
John Baez
Martial Ducloy
Thomas Gallagher

Visiting Research Associate Professors

Benoit Gremaud
Cord Muller
David Wilkowski
Masahito Hayashi
Simon Benjamin

Visiting Senior Research Fellows

Fernando Brandao
Tomasz Karpiuk

Visiting Research Fellows

An Junhong
Chen Lin
Huang Yunfeng
Kavan Modi
Yang Wanli
Yi Xuexi
Zhang Qi

Administrative staff

Artur Ekert
Ben Kek Chun Peng
Chan Chui Theng
Chan Hean Boon Thomas
Chin Pei Pei
Evon Tan
Jessie Ho
Jenny Hogan
Kuldip Singh
Lim Ah Bee
Lai Choy Heng
Mashitah Bte Mohammad Moasi
Valerie Hoon
Tan Ai Leng, Irene
Tan Lay Hua
Timothy Yeo

Technical support

Chia Zhi Neng Bob
Darwin Gosal
Gan Eng Swee
Kwek Boon Leng Joven
Lian Chorng Wang
Lim Jeanbean, Ethan
Mohd Imran Bin Abdol Raman
Teo Kok Seng
Vladimir Akimov
Yau Yong Sean

PhD students

Ved Prakash, Penghui Yao, Attila Pereszlenyi, Ritayan Roy, Ng Tien Tjuen, Syed Abdullah Aljunid, Bharath Srivathsan, Gurpreet Kaur Gulati , Hou Shun Poh, Siddarth Joshi, Shiqian Ding, Gao Meng, Sambit Bikas Pal, Christian Gross, Kyle Arnold, Nick Lewty, Markus Baden, Manukumara Manjappa, Marta Wolak, Han Rui, Guangquan Wang, Yu-Xin Hu, Jiangwei Shang, XiKun Li, Jibo Dai, Bobby Tan, Ravishankar Ramanathan, Mingxia Huo, Li Ying, Davit Aghamalyan, Jiabin You, Yimin Wang, Tzyh Haur Yang, Rafael Rabelo, Colin Teo, Le Phuc Thinh, Cai Yu, Elisabeth Rieper, Giovanni Vacanti, Mark Lam, Supartha Podder, Jedrzej Kaniewski, Rakhitha Bandara Chandrasekara, Frederic Leroux, Wei Nie, Debashis De Munshi, Filip Auksztol, Corsin Pfister, Tarun Dutta, Swarup Das, Rohit Ramakrishnan, Han Jingshan

Our annual review

The Centre's Scientific Advisory Board visited in August. Here are some extracts from their 2012 report.

In December 2012, CQT turns five. Every year since the Centre's birth, the distinguished members of the Centre's Scientific Advisory Board (SAB) have visited CQT to assess its science and direction. CQT's milestone birthday provided a particular opportunity for reflection.

"CQT has achieved critical mass of expertise in theory (both computer science and physics) and experiment, and is recognized and respected worldwide as one of the reference research centres in quantum science. CQT is at a point where it can transition out of its rapid build-up phase into a phase of slower strategic growth enabled by its critical mass and strong global reputation," the SAB noted.

The future

Wrapped up in the Centre's future plans is a shift in funding balance, as the Centre seeks renewal of its direct funding and looks increasingly to supplement the direct funding with competitive grants. This was the model set out for Singapore's Research Centres of Excellence, of which CQT was the first established.

The SAB wrote: "Many seeds for outstanding research have been planted. The number and quality of the research work produced so far has again continued to grow and strengthen CQT's global reputation. Assuming CQT maintains its current trajectory, there is every expectation that it will harvest great benefits from this investment… CQT can leverage the broad range of expertise and the increasing ties between groups that have been built up."

"We therefore strongly recommend the continuation of the Centre at its current level of operation and research intensity."

The SAB includes senior leaders of other quantum research centres and groups in Europe, the United States and Canada. They reflected on how "to maintain CQT's current momentum and its desirable and hard-fought place on the world stage". The report noted that "Striking the right balance between core and competitive funding is very important at the current stage of development of the Centre and for its future success."

Activity today

The SAB also reviewed operational details. The SAB noted, for example, that "the visibility of the experimental groups has been increasing as other groups continue to establish themselves and produce more results", and that for groups which were trying to grow, "the situation has improved considerably in the past year, though it will be important to continue making strong efforts to recruit excellent students and postdocs to the experimental groups".

Some CQT research projects are spurring collaboration with industry. "We are pleased to see first steps in the development of links to applications and industry, including Alex Ling's work on the satellite projects and Kai Dieckmann's work with Menlo systems."

Also seen as a positive development were links with CQT's neighbour at NUS, the Graphene Research Centre. The SAB had previously suggested that CQT explore collaboration in this area. "Some initial attempts have been made… and other positive informal interactions have occurred," the SAB wrote in its 2012 report.

An area the SAB recommended that CQT give continued focus is integration, to ensure that CQT makes the most of its size and interdisciplinary composition. "It is important to continue to explore and implement practical ways of enabling researchers to be aware of the work going on in other groups and the expertise residing across CQT. This will provide researchers broader perspectives on the field of quantum information, and increase the likelihood of collaborative and interdisciplinary research. This is an important area where CQT has a competitive advantage over most other quantum information groups in the world."

Still learning

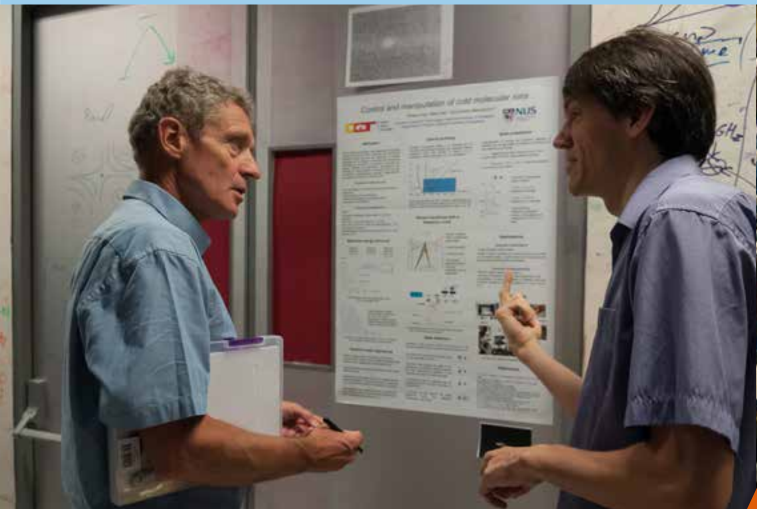
There are 68 graduate students studying at CQT, counting both those with PhD@CQT scholarships and students funded by other sources. Six students, including one Master's student, completed their degrees in the past 12 months. The SAB encouraged CQT to introduce additional graduate courses, suggesting that some could be taught by postdocs.

"We reiterate that the quality of the PhD students is crucial to achieving the highest level of excellence pursued by CQT," the SAB wrote. "Overall, CQT has been attracting good students, and they seem to be doing well both in their coursework and in their research. A most important indicator will be how successful they are when they leave CQT, so this should be tracked systematically, and ties should be maintained with the alumni. Since the Centre is still young, there are only a handful of graduates to date, and overall they seem to be doing well."

SAB becomes even more distinguished

In October 2012, CQT joined the celebrations and offered its congratulations as the 2012 Nobel Prize in physics was awarded to two fellow explorers of the quantum world. David Wineland, an SAB member since the Centre's inception, was recognised along with Serge Haroche from the College de France (see interview on p. 36), "for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems".

The SAB also became more distinguished in 2012 as it welcomed a new member. The panel's existing six eminent researchers were joined by a seventh: Christophe Salomon from Laboratoire Kastler Brossel, Centre National de la Recherche Scientifique, in Paris, France. Christophe is an experimentalist known for his research on cold atoms.



This year, CQT has...

These are some highlights from CQT's busy calendar in 2011-12. See the Events pages from p. 42 for a complete listing. Research updates fill the rest of this section.

. . . Graduated its first PhD students

The first of CQT's brilliant and hard-working graduate students defended their theses in 2012. Arun, supervised by Berge Englert, became the first CQT PhD student to collect his degree at the NUS Commencement ceremony in July 2012 (pictured below, Arun on far right). He is now a postdoc at CQT. Elisabeth Rieper, supervised by Vlatko Vedral, was also awarded her degree. She has returned to her native Germany to work in industry and will collect it in 2013. Another four students from NUS faculties supervised by CQT PIs have also completed degrees (one Master's, three PhDs) in the past 12 months. See p. 40 for more about the PhD@CQT programme.

. . . Immersed a writer in the quantum world

For two months from mid-October 2011, CQT hosted as a writer-in-residence George Musser, then an editor with *Scientific American*, through the CQT Quantum Immersions programme. George is writing a book that will explore the meaning of 'space' given the non-locality of quantum mechanics. George also commissioned Artur to write a feature article for *Scientific American*. The feature "Beyond the quantum horizon", co-authored with Oxford physicist David Deutsch, appeared in a special issue of the magazine in September 2012.

. . . Sent quantum optics kit to the edge of space

A weather balloon (pictured below) launched 18 May 2012 in Germany carried a CQT payload to the upper reaches of Earth's atmosphere. The payload was a prototype Small Photon-Entangling Quantum System (SPEQS) from the group led by Alexander Ling. The group is redesigning and rebuilding the typical sprawl of an experiment that creates pairs of entangled photons in a controlled lab setting into a compact, robust package suitable for launch into space. The project could lead to the first creation of entangled photon in orbit and serves as a test-bed for technology for future quantum communication networks. The payload performed well in the test flight, which reached 37.5km.

. . . Mingled with Nobel laureates and high-flying youngsters

Singapore hosted the international day of the 62nd Lindau Nobel Laureate Meeting in Germany on 2 July 2012, and CQT was invited to showcase Singapore's research strength. The physics-focused meeting brought together 580 bright, young scientists — including CQT PhD student Colin Teo — and 27 Nobel Prize winners in physics. Colin participated as a speaker in a panel discussion on quantum technologies with Nobel Laureate Bill Phillips and CQT Director Artur Ekert. In the evening, Artur and CQT PI Alexander Ling gave before-dinner speeches. They were congratulated by Singapore President Tony Tan Keng Yam, who told reporters the next day that home-grown talent like Alexander formed the bedrock of Singapore's scientific growth.

. . . Reached a global audience

CQT participated 16 – 20 February 2012 in one of the world's most significant gatherings in science — the Annual Meeting of the American Association for the Advancement of Science (AAAS). The international event, held in Vancouver, Canada, had over 10,000 participants including leading scientists, policy-makers and the media.

CQT Director Artur Ekert gave an invited talk in the symposium "Quantum Information Science and Technology: A Global Perspective". CQT was also proud to represent quantum research and Singapore in the meeting's exhibition hall. A story in *The Economist* about quantum cryptography, reported from the meeting, featured both Artur and CQT's ambitions to send a quantum entanglement experiment into space

. . . Hosted Singapore's Deputy Prime Minister

Singapore's Deputy Prime Minister Teo Chee Hean, who is also Chairman of the National Research Foundation, visited the Centre for Quantum Technologies on 11 June 2012. The visit was hosted by NUS President Tan Chorh Chuan, NUS Deputy President Barry Halliwell, CQT Director Artur Ekert and Director of the NUS Graphene Research Centre Antonio H. Castro Neto. DPM Teo and his delegation were briefed about the research being done in CQT and visited two laboratories.

. . . Turned into a temporary art gallery

A light-and-fabric sculpture inspired by atoms in optical lattices was among the objects displayed in a "Cabinet of Curiosities" at CQT from April 2012. The cabinet resulted from a month-long art/science collaboration initiated by German artist Grit Ruhland. Grit formed a panel of researchers, students and Singapore artists to reinterpret the Renaissance idea of a Cabinet of Curiosities — a room that displayed astonishing objects from art and science — for quantum research. Grit also ran workshops and gave talks at CQT and Singapore's ArtScience museum. She was selected and supported by the 2012 NUS Art/Science Residency programme.

. . . Hosted a prestigious lecture series

Serge Haroche, holder of the Chair in Quantum Physics in the College de France, delivered a lecture series in Singapore, 6–17 February 2012, just a few months before he won the 2012 Nobel Prize in Physics. Serge, who has made many important contributions in quantum optics and quantum information science (see p. 36 for an interview), also heads a research group at Laboratoire Kastler Brossel at the Ecole Normale Supérieure in Paris, France. The series "Quantum information with real or artificial atoms and photons in cavities" was included in an NUS graduate course.

. . . Made a French connection

A signing ceremony on 9 November 2011 at CQT inaugurated an International Associated Laboratory (LIA) that will facilitate collaboration between CQT and research centres affiliated with the French public research organisation the Centre National de la Recherche Scientifique (CNRS). An LIA is a "laboratory without walls" — an agreement at the institutional level that provides a structure for the exchange of people and funds. The France–Singapore Quantum Physics and information Laboratory (LIA FSQL), formalised in the signing ceremony, grows from ongoing successful joint projects.

CQT researchers have helped bring the quantum phenomenon of discord to global attention, explains Mile Gu, CQT Research Fellow.

Standing on the podium, I was in a superposition of excitement and trepidation. It was January 2012, and my CQT colleagues Kavan Modi and Vlatko Vedral had just opened the first ever workshop dedicated to quantum discord.

The fact this conference was happening was remarkable. Five year ago, if you were to ask a random quantum theorist about discord, you'd likely be met with a blank stare. Yet this meeting in Singapore had drawn some of the foremost leaders in quantum information, from the US, China, Europe and countries all around the world. Discord was centre stage, and CQT researchers had helped to put it there.

An idea before its time

The idea of discord has been around for a decade, since a few groups independently proposed some new ways to measure the correlations between two physical systems, devising an approach to split total correlations into classical and quantum components.

Out of this split came a surprise: quantum correlations go beyond the entanglement correlations associated with shared quantum states. This surprise is what now has researchers tantalised, but at the time it doomed the idea to live in obscurity. Entanglement was the poster-child resource for everything quantum. Since discord persisted in situations where there exists no entanglement, few saw discord to be of any potential use.

Perspectives shifted in 2008 when DQC1, a protocol for computing the trace of a unitary matrix exponentially faster than any known classical algorithm, was found to feature negligible entanglement and yet nonzero discord. In a matter of months, discord was propelled into the scientific spotlight. One insight on discord followed another, as scientists concentrated their effort on understanding this new concept.

Some of these new insights came from researchers at CQT. Kavan, Daniel Cavalcanti and Andreas Winter set out one of the first operational interpretations of discord [1]. Oh Hoo Chiap and others from his group discovered an observable which could be used as a litmus test for the presence of discorded correlations in a general class of bipartite systems [2]. And earlier this year, a team of CQTians compiled a comprehensive review on this burgeoning field that will be published in *Reviews of Modern Physics* [3].

All this work on discord has sown a new idea: is discord the catalyst for the advantage of quantum processing?

Many outside the new field regard the idea with open reservation. No direct causal link between discord and the power of DQC1 has been found. In addition, researchers have shown since 2008 that any state picked at random has some discord. Suggesting that discord causes a quantum speed-up in DQC1, argued some, is then akin to concluding that water causes heart attacks since everyone who has had a heart attack likely drank H_20.

Discord over discord

"Whenever you discuss an idea, there is a good indicator on whether it is important," a prominent scientist once told me. It's a good sign, they said, "when half the audience tells you that your results are so utterly trivial that they thought it was true all along, while the other half asserts that what you've shown is so completely counter to their intuition that it has to be wrong."

What is

Whenever two systems share quantum discord, it is possible to lock information within these discorded correlations so that it can only be accessed by interacting the systems quantum mechanically.

discord?

This is exactly the reaction that researchers talking about the potential for quantum discord to be a resource for quantum processing first encountered. When Vlatko introduced the subject to me, I was hooked.

Over the last two years, I have been working with Kavan and Vlatko at CQT and experimentalists led by Ping Koy Lam at the Australian National University, on an idea to measure the operational potential of discord and so address the debate. We expected that discord, from a certain perspective, captured the idiom that 'knowledge is power', that it would quantify the power of quantum mechanical knowledge.

Let us make a brief detour to the 1962 James bond movie 'Dr No', which taught children around the world a valuable lesson in how to detect whether nosy siblings are snooping into their rooms. You stick a small piece hair across the door and the doorframe.

"Let us make a brief detour to the 1962 James bond movie 'Dr No', which taught children around the world a valuable lesson in how to detect whether nosy siblings are snooping into their rooms"

When the door is opened, the hair falls to the floor. The unsuspecting perpetrator has unwittingly communicated to you their rather unscrupulous action. The Bond hair trick demonstrates the power of knowledge; by knowing how a system is initially configured (the location of hair), one can gain information about actions that have affected the system (opening the door).

However, what if the position of Bond's hair was quantum, and Bond possessed a quantum replica of this state? Can Bond gain additional information about how a system is manipulated, by comparing his memory with the system 'quantum mechanically'?

Our motivation for exploring this question is more fundamental than finding more efficient ways to incriminate a kid brother. Any knowledge only accessible by quantum processing is, by definition, a resource that only a quantum computer can take advantage of.

Discord draws international audience

CQT's Quantum Discord Workshop 2012, held 9–13 January, attracted some 70 experimental and theoretical researchers from around the world to discuss what discord is and what can be done with it.

"New and exciting ideas came out of the meeting," says local coorganiser Kavan Modi, now a CQT Visiting Research Fellow. To encourage collaboration among the participants, the workshop was punctuated with long breaks, held in a room lined with whiteboards and ended each day with an outing. Having so many experts in one place created a powerful hive mind. In one talk, Kavan recounts, the speaker pointed out a conjecture they hadn't been able to prove "and in five minutes someone had a proof".

The participants of the workshop included some of the founders of the idea of discord: Vlatko Vedral, now a CQT Principal Investigator (and one of the meeting coorganisers), Wojciech Zurek of the United State's Los Alamos National Laboratory, and Jonathan Oppenheim of the University of Cambridge.

The retro-themed décor and pink walls of the meeting venue, Singapore's Hotel Re in the city centre, were, says workshop coorganiser and CQT Research Fellow Hugo Cable, "a talking point".

What we found is that quantum discord is exactly such a resource.

We demonstrated the effect using two optical beams. One acts as the system Bond wished to track (call this A), the other as Bond's memory of this system (call this B). The system and memory were injected with enough correlations to generate discord but not entanglement.

Then, like the scenario in Dr No, a perpetrator took beam A and manipulated it with a 'kick' in position and momentum. Our task in the role of Bond was to take the resulting beam, harness it to the memory, and then make the best possible guess on the magnitude of the perpetrator's kick.

We showed that the amount of information we could extract beyond classical limits was indeed related to the amount of discord originally injected between A and B.

Testing the waters

It was these results I was presenting in February, alongside one of my experimental collaborators. The audience looked at us with expectation. Our work was not yet published even in a preprint on the arXiv. It was time to test the waters, and see if our ideas could stand up to expert scrutiny.

It would be eight months before our article was published in *Nature Physics* [4], but it was the animated discussions in that workshop that laid our reservations to rest.

Meanwhile, Vlatko and CQT researcher Tomasz Paterek have helped develop experiments that related discord to remote state preparation with results published in *Nature Physics* at the same time as our Dr No experiment [5]; Kavan Modi and I have extended our ideas to separate correlations into coherent and incoherent components [6]; and further experiments and theory are in development.

This isn't to say discord in the community is dissipated. While we have shown that discord is useful for something, it remains a big open question how much more useful discord can be. For example, can we think about some forms of computation as a form of guessing based on prior knowledge, in analogy to the model we tested? If so, then knowledge is indeed the power, and the more you can know, the faster you can compute.

[1] D. Cavalcanti, L. Aolita, S. Boixo, K. Modi, M. Piani, and A. Winter, "Operational interpretations of quantum discord", *Phys. Rev. A* **83**, 032324 (2011)
[2] C.J. Zhang, S.X. Yu, Q. Chen, and C.H. Oh, "Detecting the quantum discord of an unknown state by a single observable", *Phys. Rev. A* **84**, 032122 (2011)
[3] K. Modi, A. Brodutch, H. Cable, T. Paterek, and V. Vedral, "Quantum discord and other measures of quantum correlation", *Rev. Mod. Phys.* **84**, 1655 (2012)
[4] M. Gu *et al.*, "Observing the operational significance of discord consumption", *Nature Physics*, doi:10.1038/nphys2376 (2012)
[5] B. Dakic *et al.*, "Quantum discord as resource for remote state preparation", *Nature Physics*, doi:10.1038/nphys2377 (2012)
[6] K. Modi, M. Gu *et al.*, "Coherent and incoherent contents of correlations", *Int. J. Mod. Phys. B* **27**, 1245027 (2012)

The Centre's computer science group has made Singapore the world capital for direct product theorems, write Rahul Jain, Hartmut Klauck, Troy Lee and Miklos Santha.

When there's no

Did you ever hear the heartbreaking story of the hundred prisoners? In a land far, far away they have to play a particularly cruel game whose outcome will give them all freedom…or death. In this fiendish game proposed in 2003 [1], each prisoner is identified with a unique number between 1 and 100. Their numbers are randomly placed one by one by the prison warden into 100 boxes, also uniquely numbered 1 to 100, and the boxes are put in a room. The prisoners are admitted to the room one at a time. Each prisoner can open half of the boxes, which are closed again immediately after he looks at the numbers inside them. They win their freedom if every prisoner finds his number in one of the 50 boxes he opens, but if even one of them misses his number, they are all executed. They can agree on a common initial strategy, but once the game starts no communication is permitted among them.

The prisoners get together and start to think. They figure out pretty fast that the first prisoner has exactly 1/2 chance of finding his number whichever boxes he opens. They also realise that if all the other prisoners choose independently and randomly 50 boxes, then their respective chance is also 1/2, and therefore their overall chance to win their freedom is extremely slim, only $(1/2)^{100}$ — that's about 0.0000000000000000000000000001%. This is a rather dire outlook. Can the prisoners do better?

Direct product theorems

In computer science terminology, this question asks if there exists a direct product theorem for the prisoners' situation. If such a theorem applies, the prisoners can do no better than repeat their best individual strategy. If

easy way out

the theorem doesn't hold, they might increase their odds of survival by doing something cleverer. Finding direct product theorems has emerged as something the CQT Computer Science Group is rather good at — our group has made many contributions in the past few years to showing direct product theorems for various models of computation.

It turns out that the prisoners are in luck, and nothing like a direct product theorem holds for this game. Remarkably, the following simple strategy invented by Sven Skyum [1] gives them a more than 30% chance of getting out alive. In this strategy, when prisoner i enters the room, he first opens the box numbered by i. If this box contains i, then he is done; otherwise, if it contains some other number k, then he goes and next opens box k. This process continues until he finds his number, or opens 50 boxes. Notice that the placement by the warden of the numbers into boxes defines a permutation. The strategy of player i opens exactly the boxes of the cycle containing i in this permutation. Player i succeeds if the length of the cycle is at most 50. Therefore each prisoner finds his respective number and they all win their freedom if the permutation doesn't contain a cycle of length longer than 50. A simple calculation shows that the probability that in a random permutation of n elements all cycles are of length at most n/2 is always at least 1 - ln(2), which is approximately 0.31.

A direct product theorem must rule out all clever approaches, and this makes showing them difficult.

Eliminating the clever solutions

A direct product theorem holds for a computational problem P if the following claim is true: "Let us suppose that in order to solve one instance of a problem P with success probability 0.99 we need c units of a resource. If less than kc units of the resource are provided to solve k independent instances of the problem P, then the overall success is exponentially small in k." They are known to hold in very few models of computation.

A notable example of a direct product theorem is Raz's parallel repetition theorem for two-prover games. This result is an important ingredient for inapproximability results for certain NP–hard problems, which state that it is not only hard to find exact solutions, but hard even to find approximate solutions. Another important example is Yao's XOR lemma for circuits which can be used for hardness amplification with applications to cryptography.

In the last few years, our group has found direct product theorems for other models of computation.

One such model is query complexity. In this model we want to compute some function f(x), but we can only access the input by making queries of the form "what is the ith bit of x"? In the quantum version, such queries can be made in superposition. The resource counted is the number of queries made to the input. Quantum query complexity has been a very fruitful model for thinking about algorithms. Grover's database search or the period finding routine that is the key to Shor's factoring algorithm can be formulated in this model. These two algorithms are well-known for showing that quantum computers could compute some things much faster than classical computers. We have shown with collaborators that a direct product theorem holds for the quantum query complexity of every function [2]! Thus there is nothing much better that can be done for computing many copies of a function than naively repeating the best protocol for a single copy.

A related, but weaker, result is a direct sum theorem that can be stated in the following terms: "Let us say that in order to solve one instance of a problem P with success probability 0.99, we need c units of resource. If less than kc units of resource is provided to solve k independent instances of the problem P, then the overall success is less than 0.99." We have also shown that a direct sum theorem holds for all functions (in fact more generally for all relations) in the randomised query complexity model [3]. Shortly after this, Drucker [4] gave a direct product theorem for randomised query complexity.

Communication complexity

The current frontier for direct product theorems is the model of communication complexity, where such questions tend to be more difficult than in query complexity. Communication complexity has applications throughout computer science for example to circuit lower bounds, streaming algorithms, and proof complexity. In this model Alice and Bob, with inputs x and y respectively, wish to compute a joint function of x and y. The resource measured is the amount of communication needed to do this, either in bits or qubits.

We have made progress on showing a direct product theorem for randomised communication complexity by exhibiting direct product theorems for certain restricted models and specific functions. For example, we have shown a direct product result for all functions in the model where the number of message exchanges between Alice and Bob is limited [5,6]. We have also shown a direct product theorem for important functions in communication complexity, like the set disjointness function [7], and direct product theorems for important complexity measures like the smooth-rectangle bound [8], a measure introduced by our group [9]. This implies a direct product theorem for many interesting functions, for instance the vector in subspace problem which is known to provide an exponential separation between quantum and randomised communication complexity.

A chief goal in this area remains to show a fully general direct product theorem for randomised and quantum communication complexity. Interestingly, in the case of query complexity the quantum direct product theorem is more natural than in the randomised case, because of the rich mathematical structure of the quantum model. This might be true for communication complexity as well. We hope this body of work will help us towards resolving this major open question.

[1] Anna Gál and Peter Bro Miltersen, "The cell probe complexity of succinct data structures", The 30th International Colloquium on Automata, Languages and Programming (ICALP), pp. 332-344 (2003)
[2] Troy Lee and Jeremie Roland, "A strong direct product theorem for quantum query complexity", The 27th IEEE Conference on Computational Complexity (CCC), pp. 236-246 (2012)
[3] Rahul Jain, Hartmut Klauck and Miklos Santha, "Optimal Direct Sum Results for Deterministic and Randomized Decision Tree Complexity". *Information Processing Letters*, **110**, 893 (2010)
[4] Andrew Drucker, "Improved direct product theorems for randomized query complexity". The 26th IEEE Conference on Computational Complexity (CCC), pp. 1-11 (2011)
[5] Rahul Jain, "New strong direct product results in communication complexity". ECCC-TR11-024 (2011)
[6] Rahul Jain, Attila Pereszlenyi and Penghui Yao, "A direct product theorem for bounded-round public-coin randomized communication complexity", The 53rd Annual IEEE Symposium on Foundations of Computer Science (FOCS) (2012)
[7] Hartmut Klauck. "A Strong Direct Product Theorem for Disjointness". The 42nd ACM Symposium on Theory of Computing (STOC), pp. 77-86 (2010)
[8] Rahul Jain and Penghui Yao, "A strong direct product theorem in terms of the smooth rectangle bound" arXiv:1209.0263 (2012)
[9] Rahul Jain and Hartmut Klauck, "The partition bound for classical communication complexity and query complexity", The 25th IEEE Conference on Computational Complexity (CCC), pp. 247-258 (2010)

In August, Nelly presented the bit commitment project at the 11th International Conference on Quantum Communication, Measurement and Computing in Vienna, Austria.

Committed bits

Theorists and experimentalists collaborate to demonstrate a secure communication protocol that conquers lack of trust.

Computer science research at CQT isn't all done in the abstract. The group led by Stephanie Wehner has collaborated with the quantum optics group led by Christian Kurtsiefer to perform the world's first demonstration of secure bit commitment: a communication protocol for people who don't trust each other [1]. Bit commitment is similar to submitting a sealed bid in a house auction. One party, usually known as Alice, 'commits' some information (a bit) to another party, usually known as Bob, with Alice later choosing when to reveal that bit. A bit commitment protocol is secure if Bob can't learn anything about the bit until Alice reveals it, and if Alice can't change the bit between committing and revealing it.

Compare this with a sealed-bid auction: the bidder must commit to an amount they will pay, and they should remain the only one who knows what the amount is until all the bids are revealed. A dishonest auctioneer or third party who accessed the information early could influence the bidding. But if the bidder is allowed to keep hold of their bid, they might be dishonest and change the amount. Traditional solutions to this problem — think sealed envelopes or data held by a third party — always depend on trust. Indeed, it has been proven that with classical information there is no solution that can totally protect the bidder and the bid receiver from unscrupulous behaviour.

In the new demonstration, the researchers harness some of the strange behaviours of the quantum world to guarantee secure bit commitment. They used hundreds of thousands of pairs of quantum entangled photons. But even quantum effects aren't enough on their own: the protocol depends on the assumption that the cheating party is limited to some degree. In earlier papers, Stephanie introduced and developed the idea of the dishonest party being limited by 'noisy storage' for quantum information. It is a realistic, physical assumption to make: that the dishonest party has a memory of finite size, which is subject to noise that can introduce errors in any stored information. The papers made various theoretical proposals for how to do secure bit commitment under these conditions.

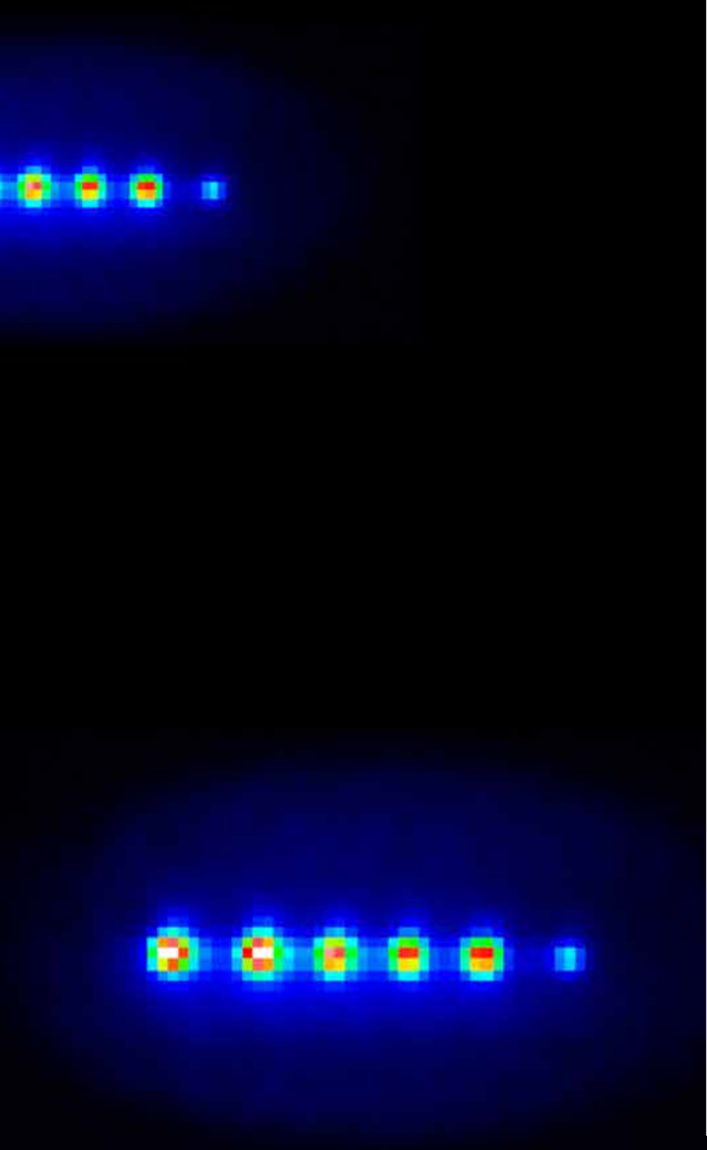
"I wanted to demonstrate that it can work in the real world, and to gain insight into the challenges to security in such a setting," says Stephanie. Having Christian's group at CQT made this possible: the group has an entangled photon source and detection kit used for previous quantum cryptography demonstrations that was readily adapted.

In the experiment, Alice and Bob used 250,000 pairs of entangled photons to commit a single bit. This vast number of photons is needed to counter losses in the experiment and guard against the possibility of cheating. Alice encodes her committed bit in the photons by choosing one of two possible measurements for each photon she receives. The other half of each photon pair is sent to Bob to measure. Because the photons are entangled, Bob's results will match Alice's when he picks the right measurement type but be random when he picks the wrong one. The idea is that Bob ends up seeing enough of the 250,000 bits to decide whether Alice has tried to cheat when she reveals her committed bit by sending the whole lot over, but not enough that he can guess the bit beforehand.

The noisy storage comes in because Bob could cheat perfectly if he could store all the photons until Alice told him about her measurement choices (an intermediate step in the protocol). He could then repeat the measurements exactly, revealing the committed bit early. Today it's only possible to store a handful of qubits, and the team showed that their 250,000 photon exchange would be secure against a memory of 972 qubits suffering a certain noise. If quantum memories get bigger, security could be restored by increasing the waiting time or boosting the total number of bits sent.

Deciding on the strategy took much theoretical work, since the original protocols could not tolerate nearly enough errors. "It's really cool that it worked — we can achieve security!" says Nelly, first author on the paper. The team also worked through challenges that came from being cross-disciplinary. "Some of the common experimental terms I used turned out to have very specific and different meanings in theoretical computer science," says co-author Siddarth Joshi, a PhD student in Christian's group. He adds, "Theoretical protocols currently outstrip experimental capabilities by several decades and if I am to live to own a quantum laptop, these kind of collaborative efforts are a must."

[1] Huei Ying Nelly Ng, Siddarth Koduru Joshi, Chen Ming Chia, Christian Kurtsiefer, Stephanie Wehner "Experimental implementation of bit commitment in the noisy-storage model" http://arxiv.org/abs/1205.3331; *Nature Commun*. (In press)



CQT's most recently arrived ion trappers, PIs Dzmitry Matsukevich and Manas Mukherjee, reveal their plans. There's also news from the established lab of PI Murray Barrett.

Inventions often have unexpected applications. Some of us here at the Centre for Quantum Technologies are using for cutting-edge quantum experiments a device that was invented more than half a Century ago, when our experiments could hardly have been imagined. The device is known as a Paul trap (see box) and offers a way to confine charged particles known as ions.

The fact that ions are easy to trap and manipulate is a major advantage for carrying out all kinds of precision experiments. Indeed, ions were used in many of the classic experiments in atomic physics before they became the darlings of quantum physicists. An ion was the first single atom system that was isolated and trapped. Trapped ions were also the first system where laser cooling was demonstrated, the system where the most precise measurements of the electron g-factor were made, and the system that currently provides the world's most precise clocks.

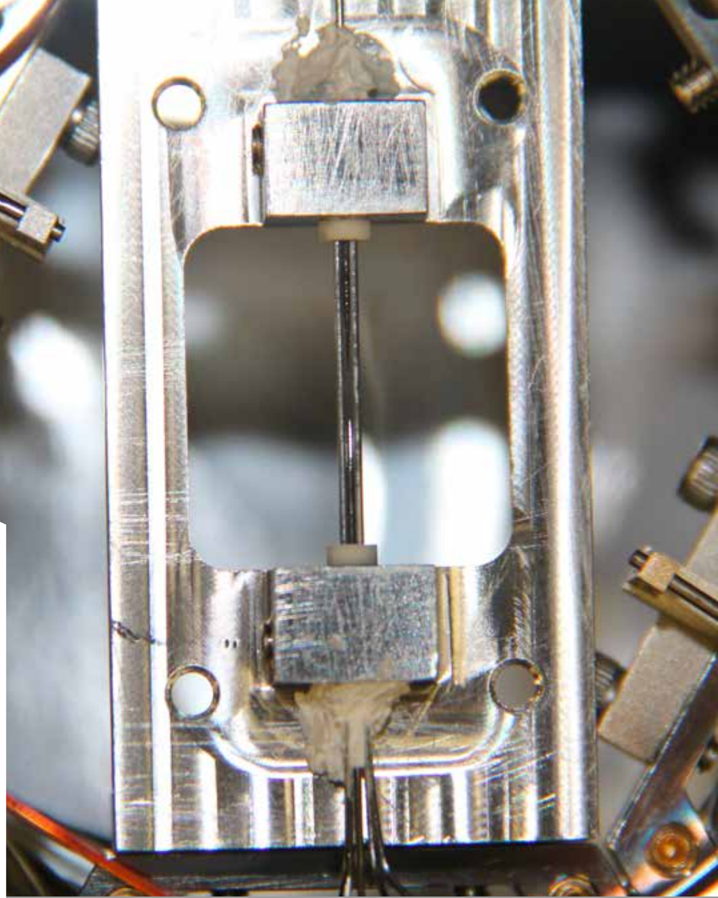
That ions have found renewed importance is reflected by this year's Nobel Prize in Physics, shared by one of the pioneers of quantum experiments using trapped ions, David Wineland at the National Institute of Standards and Technology in Boulder, Colorado. The award was given to Dave — as he's better known at CQT, as a member of the Centre's Scientifc Advisory Board — and Serge Haroche of the College de France "for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems".

Research in quantum information and quantum computation sparked the new wave of interest in trapped ions. In 1994, Peter Shor proposed his famous factorisation algorithm, which demonstrated that a quantum computer could solve efficiently problems considered difficult for classical computers (Shor's algorithm would break the RSA encryption protocol widely used to secure communications over the internet). The next year Ignacio Cirac and Peter Zoller proposed a way to implement the kind of gate required for quantum computation using cold trapped ions. Two years later, this proposal was implemented experimentally, opening a new direction for research and generous funding from 'spooks', among others.

Ions remain one of the most promising technologies for implementing quantum computing. Experimentally achievable gate fidelities exceed 99% and the number of ions that can be involved in simple quantum algorithms now is about 15. This is among the best of the many different quantum systems being explored for computation.

Our groups at CQT are applying the methods developed for ion trap quantum computing to new problems.

Ions: what are they good for?



The here and now

Dzmitry's group seeks to control and manipulate molecular ions using techniques such as sideband cooling and quantum gates. Precise measurements of molecular spectra can help answer fundamental questions. One such question is whether the mass of the proton and electron are physical constants, or if they change over time. Molecular spectra can be an extremely sensitive measure of this since the spectrum contains both electronic levels that depend on the electron mass, and vibrational/rotational states that depend on the nucleus mass.

Unfortunately, manipulation and detection of molecular states is difficult. The simplest way to interact with and detect ions is to scatter photons from the particle, but this does not work for all molecules. A lot of molecules lack cycling transitions, meaning they don't always return to their initial state after they have a scattered photon. Therefore traditional methods of laser cooling and state detection cannot be applied directly. To get round this, Dzmitry's group is planning to have atomic and molecular ions confined in the same trap, and to couple the internal state of molecular ions to their more easily measured motion.

When the atomic and molecular ions are together, they interact strongly due to their charge and share common modes of motion. The atomic ions can be cooled using laser cooling and the sideband cooling technique, which results in simultaneous sympathetic cooling of the molecular ion. To couple the molecular ions' state and motion, two laser beams of different frequencies will be shone on the ions. If the frequencies of the two beams are detuned from the energy difference between the molecular levels by one trap frequency, stimulated absorption of photons from one beam and subsequent reemission into the other one results in a change of the ion internal state accompanied by a change of its motional state. The change in the ion's motion can then be detected using the co-trapped atomic ion. While this goal still requires a lot of work, Dzmitry's group can already trap, laser cool and detect the state of atomic Yb^+ ions (pictured left). The group is currently working on the trapping and sympathetic cooling of SiO^+ molecules.

The study of molecular ions is a relatively young field. Several groups around the world are trying various approaches to keep molecular ions under control. Dzmitry's approach [1] is based on the 'quantum logic' technique used for example to build the most precise atomic clocks based on Al^+ ions, (the technique was even mentioned in this year's Nobel Prize award). The group believes that the extension of this approach to molecular species will provide us with the tools necessary to control and manipulate quantum states of molecules.

The Paul trap

The type of ion trap we use was invented by Wolfgang Paul and his colleagues in the 1950s. The design is based on Newtonian mechanics and is so conceptually simple that it is possible to build one at home with spoons or a paperclip and a high voltage transformer (just search YouTube). In a Paul trap, electrodes generate an electric field that traps charged particles between them. The polarity of the voltages applied to the electrodes is rapidly reversed, typically several millions times per second. If the frequency and strength are matched correctly to the charge-to-mass ratio of the ions, this rapid change of the electric field leads to an effective potential that confines the particles in all three directions.

The most common applications of Paul traps are in leak detectors and mass spectrometers: useful but boring classical devices found in many research and industry laboratories. But several properties of trapped ions also make them attractive for quantum research. The trapped ions are well isolated from external fields, their motion is easily described by a simple harmonic oscillator model, and the trapping effect is strong, meaning ions survive collisions with background gas and have long trapped lives.

The versatility of an ion trap setup provides the opportunity to look into seemingly different problems in physics using the same trap. Manas's group is taking advantage of this with two plans for the ion trap experiment the group members started building at CQT in June, when optical tables arrived in their until-then empty labs.

One project aims to understand and use the inherent geometry of a quantum system, manifested by a special case of a geometric phase known as the Berry phase. Researchers have proposed various ways to exploit geometric phases to implement quantum gates.

A classical analogue of the geometric phase is seen in Foucault's pendulum, first demonstrated in the 19th Century to show the rotation of Earth. The plane of oscillation of a pendulum suspended anywhere except at the Equator will gradually rotate in a circle, as the pendulum's anchor point rotates with Earth. Similarly, a quantum state gathers an extra phase, in addition to the dynamical phase, when the applied Hamiltonian is slowly cycled in time. The Hamiltonian describes properties of the environment that affect the state's energy. The phase is independent of any external parameters except for the geometry of the rotating Hamiltonian.

In Manas' experiment, an electric field gradient will define a quantization axis. A smaller rotating field gradient applied on top defines a cone about the quantization axis. The phase depends only on the opening angle of the cone, and is therefore inherently fault tolerant and attractive for implementing quantum gates.

Experimentally, however, very little is known about the different inherent geometries, which depend on, for example, the presence or absence of a magnetic field (non-Abelian and Abelian). Manas will explore these geometries and their potential in information processing.

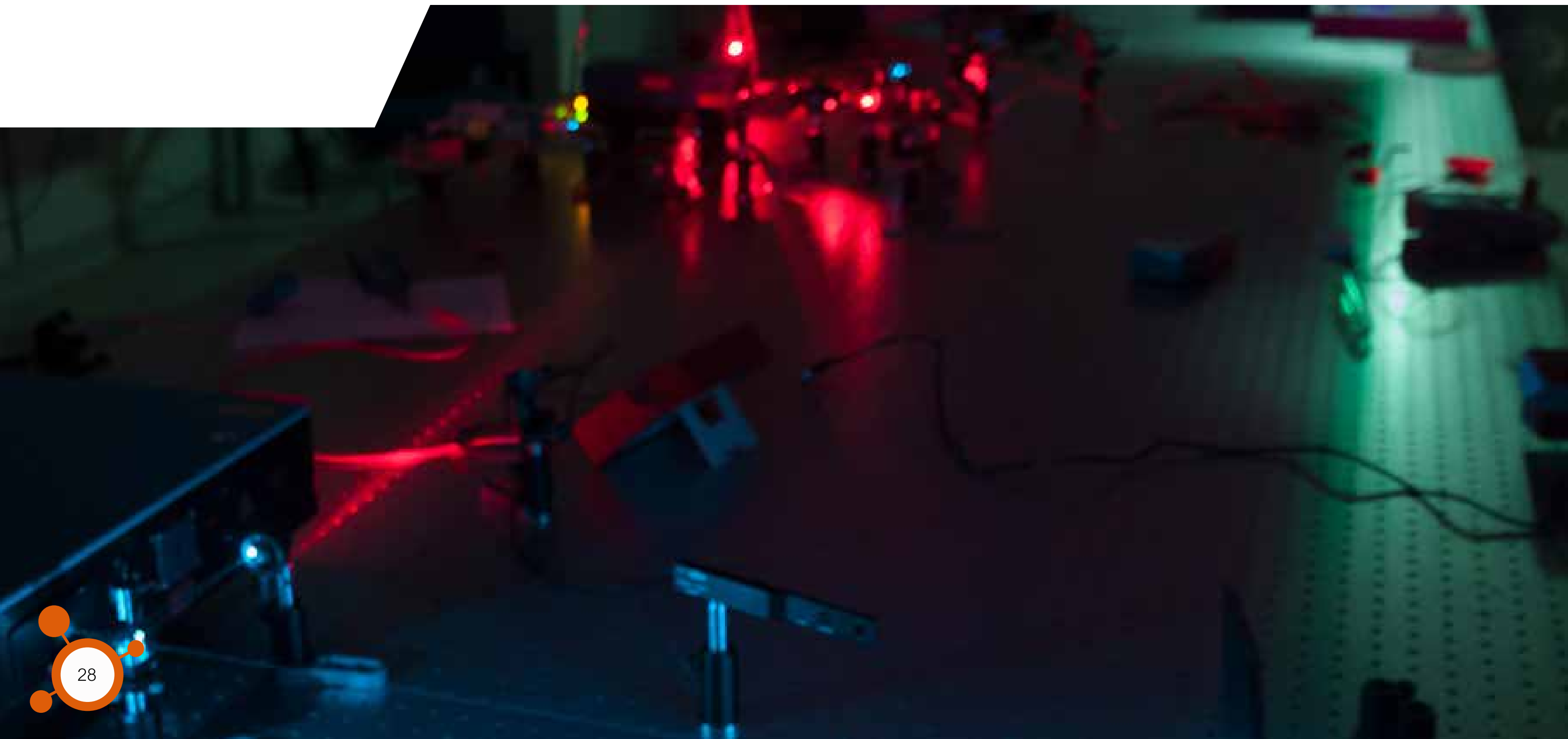
The second project will be a simulation of a condensed matter system. Groups worldwide are studying systems of integer-spin particles (bosons) occupying periodic potentials in a lattice. These systems, described by the Bose–Hubbard model, show behaviour analogous to solid-state systems. For example, researchers have observed cold atoms in an optical lattice transition from a superfluid to a Mott Insulator-like state. The advantage of studying such phenomena in a quantum system is that the parameters can be tweaked, unlike in real materials.

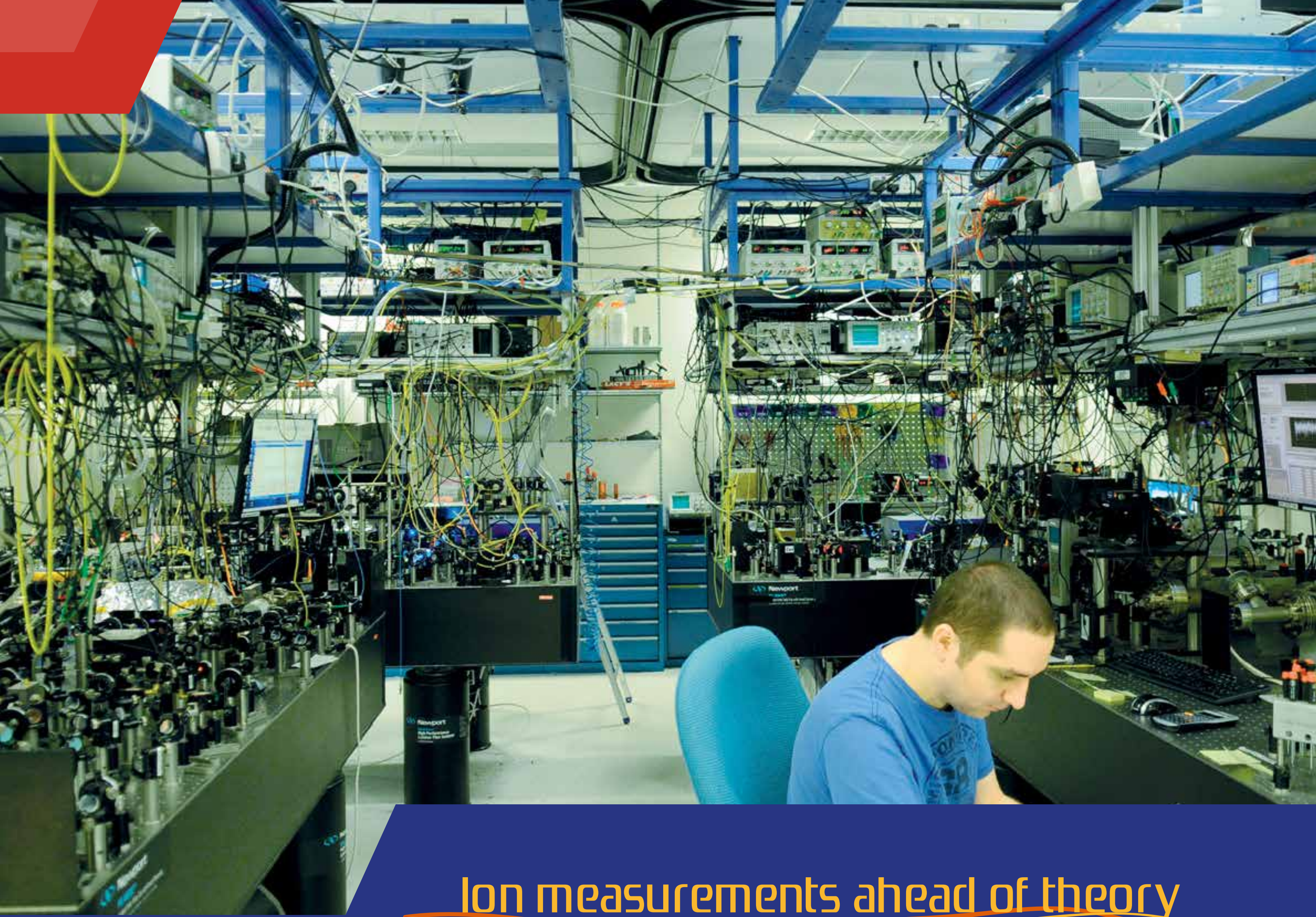
With ions, it is also possible to explore an avenue completely inaccessible to optical lattice systems. The Bose–Hubbard model predicts rich quantum behaviour if the bosons attract each other. It is possible to emulate such a system in an ion trap by manipulating phonons [2], which are propagating states affecting the ions' motion. The phonons can act as repulsive or attractive mass-less bosons. Experimentally, this is implemented using chain of cold ions subject to standing-wave laser fields.

Team efforts

A collective goal of the Centre's ion-trapping groups is to develop miniaturised traps for a new generation of quantum devices. With micro-structured traps the advantage is not only saving space, but also being able to keep the system colder, which reduces coupling of the ions to the environment. This would give quantum states longer lifetimes, and in turn, we hope, make our experiments easier and more precise.

[1] S. Ding and D. Matsukevich, "Quantum logic for control and manipulation of molecular ions using a frequency comb", *New J. Phys.* **14**, 023028 (2012)
[2] T. Dutta, M. Mukherjee and K. Sengupta, "Non-equilibrium phonon dynamics in trapped ion systems", *Phys. Rev. A* **85**, 063401 (2012)





Ion measurements ahead of theory

While the laboratories of Dzimitry and Manas are still filling up with equipment for quantum experiments, the ion-trapping laboratory (pictured above) belonging to Murray Barrett's group is already jam-packed. Murray has been a Principal Investigator with the Centre since it was founded. In 2012, his Microtraps group used their completed ion trap setup to make impressively precise measurements of Barium [1].

The measurements of the 'hyperfine' structure of $137Ba^+$ are accurate beyond all previous measurements; they even exceed the precision of theorists' calculations. "What's important for me is that it's the first demonstration that we can do these types of measurements to this level of precision" says Murray.

These experiments are a stepping stone not only to performing other precision measurements — highly accurate determinations of atomic properties have been important for tests of fundamental physics and in applications such as atomic clocks — but also to using Barium as a component for quantum computing. Having mastered control of a single Barium ion for these experiments, Murray and his team want to try storing quantum bits (qubits) in two Barium ions and applying a logic gate to them.

The hyperfine structure of an atom or ion is the splitting of the electronic energy levels caused by the magnetic field of the nucleus. By measuring this splitting in the energy levels of $137Ba^+$, the team deduced the ion's magnetic dipole moment, electric quadrupole moment and magnetic octupole moment. These moments describe the shape of the nuclear electromagnetic field.

The new dipole and quadrupole measurements reduced 30-fold the uncertainty attached to the previous best experimental values for these quantities. The measurement of the octupole moment of $137Ba^+$ is a first, and it's the most accurately determined octupole moment of any element to date. Achieving such precision meant chasing down every source of uncertainty in the lab.

The experimental results could prove a test for theory, since the measurements' precision now exceeds that of the theoretical predictions. "Theorists who do these calculations can take note of what we're doing," says Murray. "If their calculations don't agree with our results, there's a problem."

[1] Nicholas C. Lewty, Boon Leng Chuah, Radu Cazan, B. K. Sahoo and Murray D. Barrett, "Spectroscopy on a single trapped $137Ba^+$ ion for nuclear magnetic octupole moment determination", *Optics Express* 20, 21379 (2012)

"Our mission is to conduct interdisciplinary theoretical and experimental research in quantum theory and its application to technologies."

2007

Mar The National University of Singapore's proposal for a Research Centre of Excellence (RCE) in quantum information science and technology is approved. Singapore's National Research Foundation and Ministry of Education award $158 million over 10 years to establish the Centre for Quantum Technologies as Singapore's inaugural RCE.

May The creation of CQT is announced to the public.

Dec CQT kicks off officially on 7 December (pictured).

Counting down to CQT's official launch. Ready, steady, go!

2008

Aug Singapore's National Science Award is presented to Antia Lamas-Linares, Valerio Scarani and Christian Kurtsiefer for research testing the nature of quantum reality.

2009

May Murray Barrett's group makes CQT the coolest place on the equator with the creation of a Bose–Einstein Condensate, a quantum form of matter seen near absolute zero temperature.

Aug A long-standing problem in computer science is solved with the proof by Rahul Jain and his collaborators that QIP=PSPACE = IP. 2010 Proc. ACM STOC, pp.573-582

Aug "Information causality" is identified as a possible underlying principle of quantum theory by CQTians Tomasz Paterek, Dagomir Kaszlikowski, Valerio Scarani, Andreas Winter and their collaborators. Nature 461, 1101 (2009)

2010

2010

Mar A Memorandum of Understanding is signed by CQT and the Institute for Quantum Computing at the University of Waterloo, Canada.

Sep "Six Quantum Pieces", a textbook by Valerio Scarani and two NUS high-school students (pictured), is published.

Nov Stephanie Wehner and her collaborator discover a link between two fundamental features of quantum theory: the uncertainty principle limits the theory's non-locality. Science 330, 1072 (2010)

Dec CQT launches the Quantum Immersions programme for writers and artists.

Dec The first conference of the Alliance of Quantum Academia (AquA), a student-run body, is held in Singapore.

2011

Jan Over 300 delegates participate in the 14th Workshop on Quantum Information Processing (QIP 2011), the first big conference hosted by CQT.

Jan An International Review Panel assesses the Centre. "CQT has had an exceptionally strong initial three years of operation," it writes.

Mar CQT expands to the Nanyang Technological University, adopting the lab of Rainer Dumke.

Jun Deleting data can cool computers under certain quantum conditions, find CQTians Vlatko Vedral, Oscar Dahlsten and their colleagues. Nature 474, 61 (2011)

Jun Christian Kurtsiefer and his collaborators help tighten security for quantum key distribution by exposing a practical, hackable weakness in some implementations. Nat. Commun. 2, 349 (2011)

Sep A SGD600,000 optical frequency comb(pictured) is installed as a shared facility to bring increased precision and stability to the labs' lasers.

Nov CQT creates an International Associated Laboratory (LIA) with the French public research organisation CNRS and affiliated research centres.

2012

Jan Joe Fitzsimons and collaborators demonstrate blind quantum computing — a totally secure form of quantum 'cloud' computing. Science 335, 303 (2012)

Feb CQT participates in the 2012 Annual Meeting of the American Association for the Advancement of Science in Vancouver, Canada.

Jul The first graduate (pictured) of the PhD@CQT programme collects his degree.

When foundations

Quantum physics sounds like a collection of troubling and mysterious rules: you cannot predict both the position and momentum of an object with certainty; you cannot predict the individual outcomes of measurements, only the statistics. Aspiring physicists in the 20th Century came to an uneasy truce with these 'limits' on knowledge. They submitted their curiosity to rigorous mental discipline until they learned not to ask questions that seem legitimate but for which nature does not have an answer.

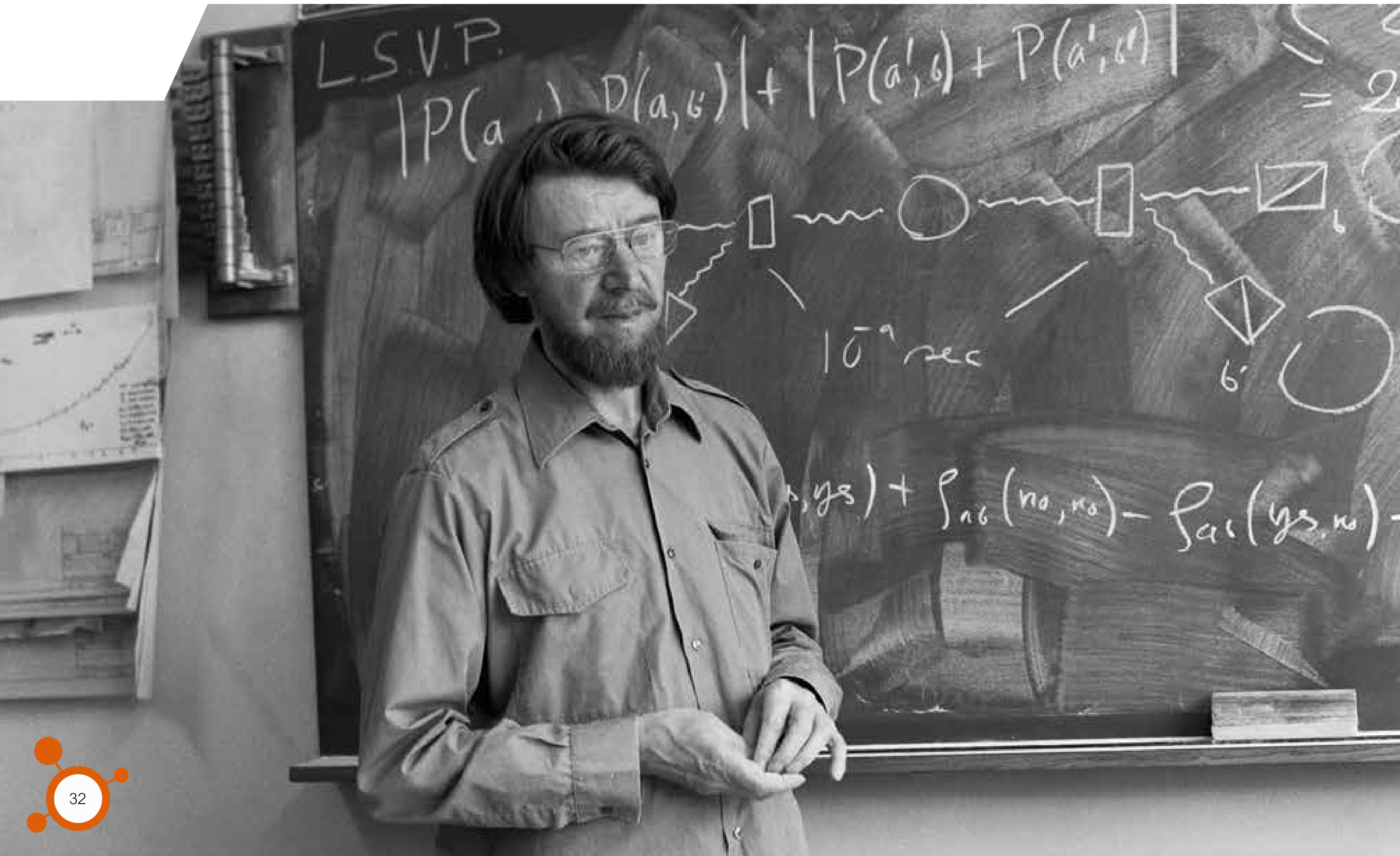
With the emergence of quantum information science, we have learned to do better: the uncertainties are there, but we look for their positive side. "You cannot predict" becomes "there is intrinsic randomness in nature". After a decently exhausting search, I am ready to certify that no philosopher of the past had described nature as behaving in such an intrinsically random but not completely arbitrary way. Physics is better knowledge, not the demise of knowledge.

But there is more: while uncertainty is a source of anxiety, randomness is a very useful resource. Let me share with you a striking example that a colleague mentioned to me: airplanes are nowadays so complex, and are supposed to keep flying in such a variety of unexpected situations, that the software that governs their behavior cannot be tested in a systematic way. What airplane companies do, then, is to test the software with random number generators, hoping that more or less all the situations will be tested sooner or later. The reliability of airplanes testifies that it works: for such tests, I trust a random number generator more than an engineer (although we still need the engineers to assemble the plane and also the random number generators). Randomness is used not only for simulations — industries also consume randomness for security and gaming.

Some of us at CQT are interested in exploring the intrinsic randomness in quantum theory: to consider where quantum randomness will be useful, how to characterize it and what technologies we might use to produce it. It's a remarkably practical place to have ended up, given that one of the central ideas emerged from quietly-received work on the foundations of quantum theory.

Now we can take a step back and ask: what forced physicists to give up certainty… sorry, I was relapsing to pre-quantum-information pessimism. What led physicists to the astounding discovery of intrinsic randomness?

The real history is very long and complex. In the beginning, a visionary physicist called Niels Bohr



PI Valerio Scarani traces the path of Bell's inequalities through his history and the history of physics.

turn to applications

managed to convince the vast majority of his colleagues of the soundness of the do-not-question mental discipline mentioned above. He did not convince Albert Einstein, nor Erwin Schrodinger or Louis De Broglie; but the rage of the chamber debate was overwhelmed by the cheers of success of those who took the new physics and started predicting phenomena without bothering too much about the theory's uncertainties.

The path to confronting quantum uncertainties was opened by John Bell only in 1964. He proposed an experiment that could distinguish between behaviour that was only apparently random (a refuge for those concerned by quantum predictions) and randomness that was intrinsic. The clamor of the computing crowds was still quite loud at that time, and many saw no point in Bell's seemingly philosophical speculation. It took some decades for Bell's ideas to penetrate deeply in the physics community. But in 1982, a series of experiments by Alain Aspect and coworkers used Bell's criterion to prove that quantum randomness is unavoidable.

And yet, more than ten years later, neither Bell nor Aspect were ever mentioned in any of my undergraduate lectures, which were still full of gloomy and mysterious uncertainties. Fortunately, a friend passed me an article in *Physics Today* written by Daniel Greenberger, Michael Horne and Anton Zeilinger on these topics. I got excited and decided I should work in that field, but the complexities of life let me wander for five more years in a desert of nanostructures. Eventually I entered the promised land in 2000 through the group of Nicolas Gisin in Geneva, one of the most enthusiastic promoters of the ideas of Bell. I started working on those topics, getting some results and going to conferences — and there, I got questioned: "Bell? But we know that Aspect's experiments vindicated quantum physics. Why care any longer?" Quantum information science was just booming. My colleagues were discovering the potential applications of entanglement: why bother about Bell's test any further? I had no real answer.

> *"... why bother about Bell's test any further? I had no real answer."*

After these encounters, my perseverance in extending Bell's ideas can be classified as an irrational desire for philosophically intriguing topics. Passion for philosophy is often the death of a scientist. But luckily not for me. Between 2005 and 2007, at the end of a completely improbable sequence of research papers whose titles and content may have sounded pointless to most physicists, a few of us had a flash of the obvious.

It is common knowledge that Bell's criterion is independent of quantum physics: indeed, logically it must be, because it is used to compare quantum physics against Einstein's alternative. What we realised is that, as a consequence, Bell's criterion is also independent of the details of an experiment: independent of whether one uses photons, atoms or electrons; independent of whether one measures position, momentum, polarization or spin. In short, Bell's criterion is 'device-independent'. It can be used to certify that a box generates real randomness without knowing anything of the internal workings of the box! Moreover, Bell's criterion is quantitative: it can tell how much randomness can be generated.

Incidentally, the first device-independent task that we discussed was quantum cryptography; then we had the idea of quantifying entanglement. Two years later the group of Antonio Acin in Barcelona thought to study the generation of randomness, which is probably the most natural task: research, like buses in Singapore, likes to take detours.

Before 2007, most physicists were looking at Bell's criterion as a milestone in our understanding of the world, a topic for smart discussion, maybe a curiosity for museums. That's not bad, not many discoveries achieve even that. But now we know that there is much more to it: it can be used as the ultimate criterion for detecting quantum weirdness… sorry, for the certification of devices based on the unique features of quantum physics.

Since violations of Bell inequalities were first observed in 1982, they have been measured in many laboratories around the world, including here in Singapore using pairs of entangled photons. These experiments, however, have all had to make an assumption to compensate for photons lost in the experiment to detection inefficiencies (the 'detection loophole'): one must assume that the photons detected are representative of all the entangled photons produced. We cannot rely on assumptions if we are trying to guarantee randomness. A loophole-free test of Bell's inequality would be significant in its own right as well as a step towards generating ultimate randomness. Many experimental groups are working hard to get there, among others the group of Christian Kurtsiefer at CQT.

◀ Fundamental ideas developed by John S. Bell, pictured, in the 1960s have unexpectedly led to the prospect of applications today. (Photo courtesy CERN).

The million-dollar fridge

We visit the lab of PI Rainer Dumke to find out what it's for.

CQT has on order a million-dollar fridge — the largest single investment in any piece of research equipment since the Centre was founded.

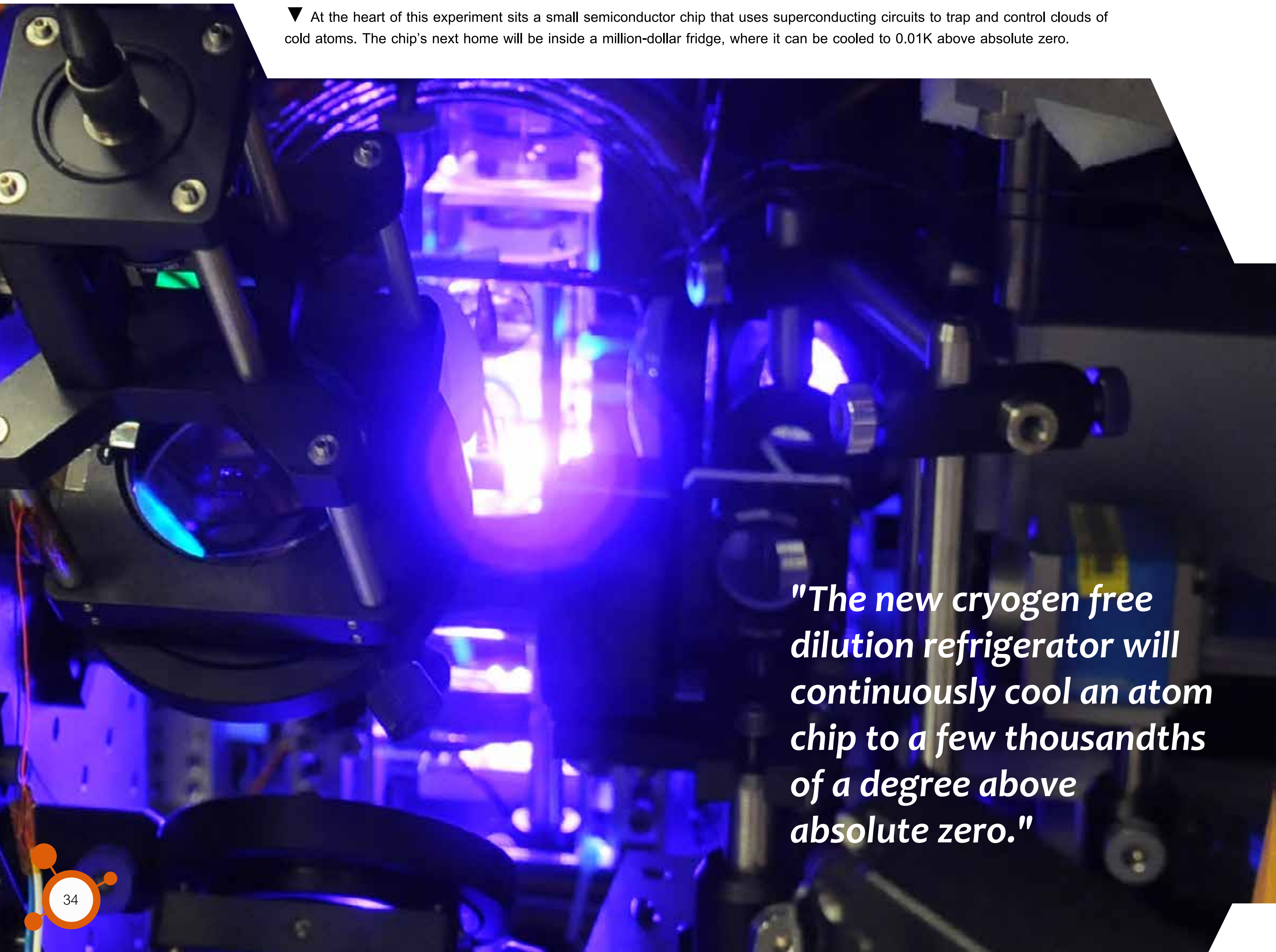
Unlike the conventional lab refrigerator (see graphic, right) that often lurks in University coffee areas, the expensive fridge will be the centrepiece of a brand new laboratory at the Nanyang Technological University (NTU). A team led by Rainer Dumke, CQT Principal Investigator and NTU Assistant Professor, wants the fridge — technically known as a cryogen-free dilution refrigerator — to cool superconducting atom chips and let them interact with clouds of ultra-cold atoms.

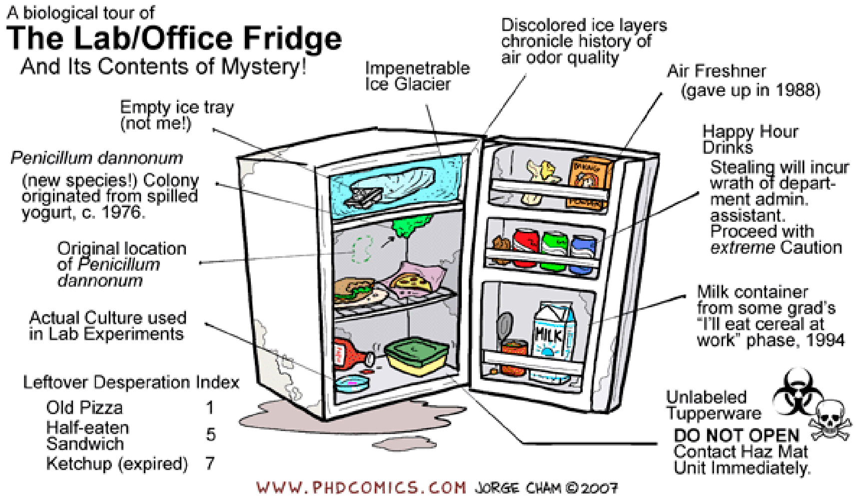
Rainer's group builds semiconductor chips with superconducting circuits drawn on top. They use the magnetic fields generated by vortices in the superconductor to trap and manipulate clouds of cold atoms.

What the team wants to be able to do is harness the quantum properties of solid state structures as well as the quantum properties of the atoms for applications in quantum information processing.

Quantum bits (qubits) stored in magnetic fields, known as flux qubits, can be manipulated very quickly (GHz speeds) but have short lifetimes, decaying after microseconds. Quantum bits stored in atoms are slower to work with (MHz speeds) but can protect information for seconds. "The idea is to build a hybrid system that combines the advantages of both, getting fast interaction and long storage," says Rainer.

▼ At the heart of this experiment sits a small semiconductor chip that uses superconducting circuits to trap and control clouds of cold atoms. The chip's next home will be inside a million-dollar fridge, where it can be cooled to 0.01K above absolute zero.





To observe quantum effects strongly, the team needs the whole system to be very cold since the vibrations and motion associated with warmth have quantum-eroding effects.

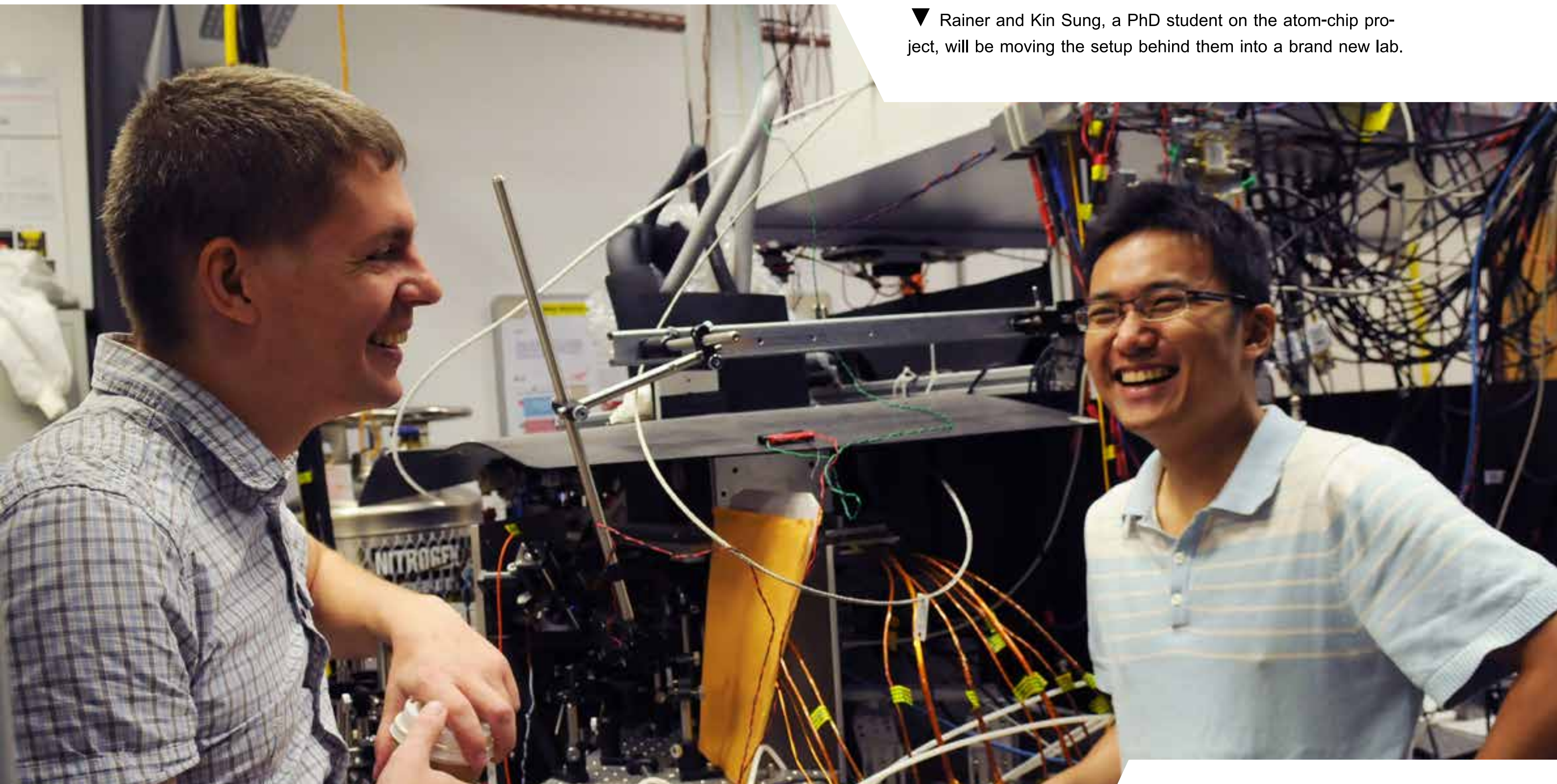
There are clever tricks to cool atoms to nanoKelvin by shining laser light of carefully controlled colour onto them and allowing the hotter atoms to evaporate away, but the same mechanisms cannot be applied to the billions of atoms in the bulk structure of the chip. The new cryogen free dilution refrigerator will continuously cool the chip to a few thousandths of a degree above absolute zero. The fridge will house the chip in an ultra-high vacuum environment and allow ample optical access.

The fridge's cooling mechanism has two parts. The first cooling stage employs a device known as a pulse tube cooler to reach temperatures of a few Kelvin. At this point a dilution fridge can kick in, exploiting cold liquid helium to chill the chip, which is stuck to a cold surface inside the fridge, even further. If the fridge performs according to its specifications, it should be possible to reach 10mK.

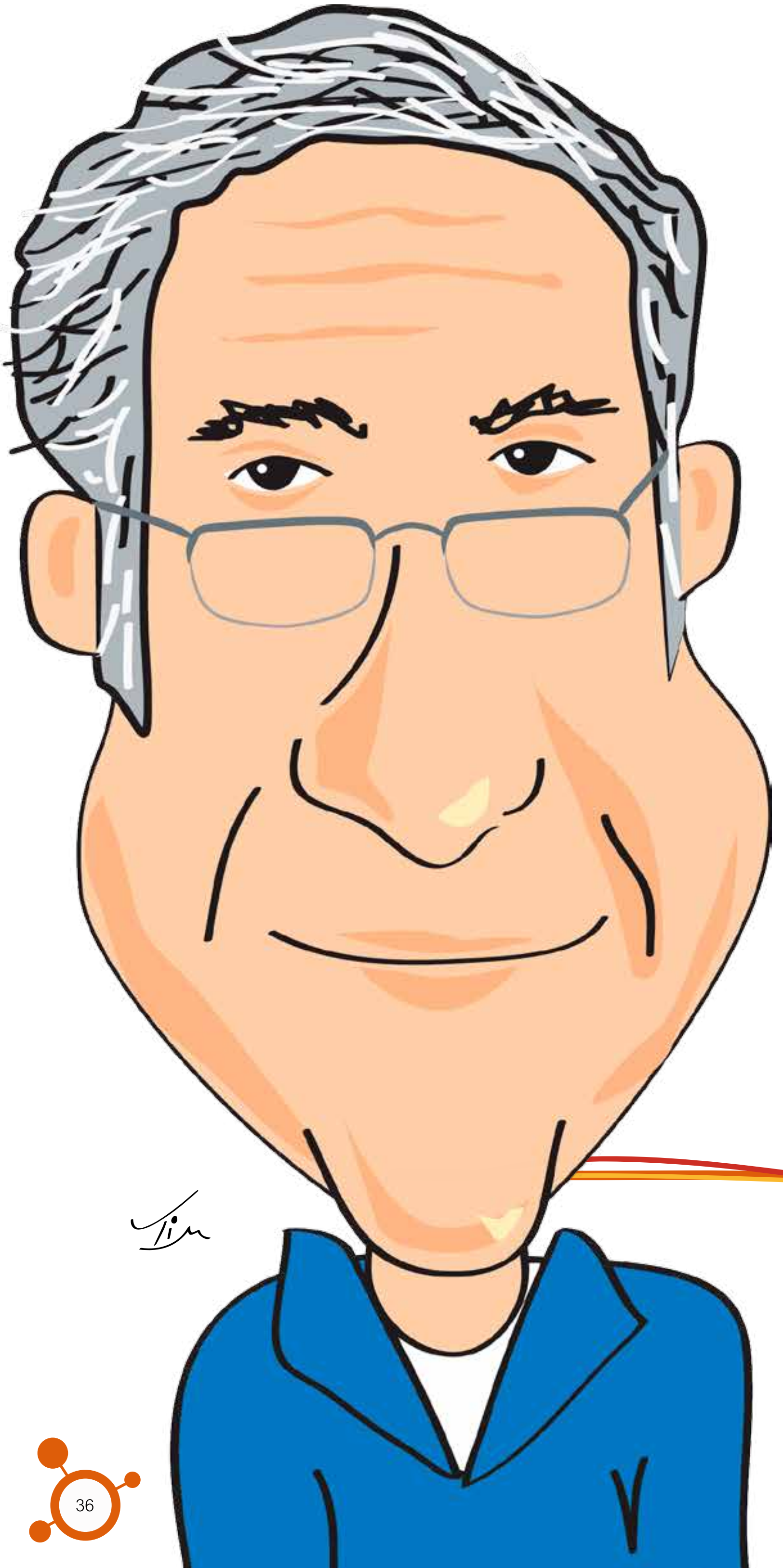
Until now, the team has only been able to explore the quantum properties of the atoms. The chip is cooled only to around 80K so does not behaving too quantumly (though it is cold enough to superconduct). With the ability to cool the whole chip to milliKelvin, the team can start working with flux qubits, too. There are a handful of groups around the world setting up such systems.

Rainer is careful to explain that a full hybrid system for information processing is a long term goal. Intermediate aims include measuring single flux quanta, and using superconducting quantum interference devices (SQUIDS) to measure the magnetic moments of atoms. As he stands in the new laboratory — an empty room, with construction ongoing in the hallways outside — he points out where a crane will be installed. The crane will lift the fridge in and out of the assemblage of equipment to be installed on heavy optics tables. The fridge itself is being constructed to custom specifications by a US-based company, which estimates it will be delivered in October 2013. Experimental physicists have long planning horizons.

▼ Rainer and Kin Sung, a PhD student on the atom-chip project, will be moving the setup behind them into a brand new lab.



Serge Haroche, Chair in Quantum Physics at the College de France and 2012 Nobel Laureate, this year delivered his prestigious College de France lecture series in Singapore. CQT invited him to reflect on his connection with the Singapore quantum research community and on his career.



Why did you become a physicist?

I have always loved math and science and, as for many things one loves, it is hard to rationalise why. If I must give an explanation though, let me say that I was in high school at the time of the first Sputniks and unmanned lunar explorations. I was fascinated by the fact that Newton's law, with some simple math that I could already grasp, could account for the velocity of satellites and of rockets escaping from the Earth's gravitational field. What made me choose atomic physics were encounters with charismatic professors working in this area, at a time when the development of the laser opened extraordinary perspectives for this kind of physics.

What would you pick as the scientific highlights of your career so far?

Observing the decoherence of a quantum field prepared in a state superposition, a system known as a 'Schrödinger cat' was one highlight, as well as the non-destructive detection of photons. These are goals I pursued with my coworkers for many years before experiencing the exhilarating feeling of seeing them realised in the laboratory.

What are your current research goals?

We are presently working on quantum feedback and on quantum Zeno experiments. Feedback procedures adapted to the quantum world are designed to protect microscopic systems from decoherence, which transforms them into entities with mundane classical properties. As for the quantum Zeno experiments, they exploit the fact that the evolution of a quantum system can be frozen if you observe it repeatedly. This effect is named after the famous Greek philosopher who denied the possibility of motion. In quantum physics, the Zeno effect is a consequence of the back action by the measuring apparatus, which always perturbs the observed system. This back action, which is often seen as a limitation, can also be used positively to manipulate quantum systems and to control their states. We have proposed novel ways to do that and now we want to demonstrate them in the laboratory.

As a master experimenter, what skills have been important to your success?

I am leading a research group with outstanding experimenters as colleagues and coworkers. So, my first skill — if you want to call it a skill — is to have been lucky enough to attract these good

Interview: Serge Haroche

people and to have been able to keep such a highly skilled group together over the long time span which is essential for the kind of physics that we are doing. I have always felt that it is important to assign oneself goals which are ambitious enough to motivate your work in the long run, and realistic enough that you can collect intermediate results. Our group has worked in this way, balancing long term projects with easier-to-realise experiments which have provided the bread and butter of our daily life as experimenters. To be successful at this game, you have to be at the same time flexible and determined. Flexible enough to adapt your research goals to the problems you may encounter and determined enough not to give up your long term goals in the face of difficulties.

Do you have any advice for young researchers?

Choose a field and a research topic because you feel excited by it, not merely because it is fashionable. Working in research is difficult and demanding, so you definitely need to feel from the start a passion for what you are doing. And also, do not get discouraged by the amount of things you have to learn to get started in research. As one of my masters told me, in order to make an interesting contribution to research, you need not to know everything, you need only to discover one thing that nobody has known before!

What are you most excited about in the field for the future?

The field of atomic physics and quantum optics has renewed itself time and again since I entered in physics! What we can do now was absolutely beyond imagination at that time. We can manipulate and observe single atoms, cool matter to incredibly low temperatures, explore ultrafast phenomena occurring during less than a single period of a light field oscillation… none of this could have been predicted at the time the first lasers were developed. What I find so exciting about research is precisely this unpredictability. Theoretical advances lead to technological breakthroughs which, in turn, allow us to explore new phenomena which require more theory and so on. This leads us from surprise to surprise, and the excitement comes from the fact that Nature has always more diversity in store for us than we can fathom. So what I am most excited about is the promise that the field will be full of surprises again in the years to come.

How did you make a connection with Singapore?

My first visit was about three years ago. I was invited to give a general audience conference sponsored by the French embassy here. The initiative came from my colleague Christian Miniatura, who manages the cooperative program between CQT and the French national research organization, CNRS (see p. 17). So far I've been back twice more; this year I gave a College de France lecture series. Since my first visit, I have been struck by the strong commitment of the Singapore society to education and to science. There is in this small country a strong belief that developing scientific research helps to build a better future.

One thing you are likely to have noticed on your visits to Singapore is how much people here love their food. Do you have a favourite Singapore dish or place to eat…?

I love the mix of cuisines you find in Singapore, with a special fondness for Chinese cooking. My wife and I have enjoyed very tasty dim sums in a small restaurant off Market Street in Chinatown where mostly local people were patrons. I unfortunately misplaced the card of the restaurant and forgot its name. I don't think this is the place for an advertisement anyway…

Postdoc power

Research fellows make up the largest segment of CQT's research staff, numbering 84 total. Here we meet a few of them.

Ng Hui Khoon

CQT Research Fellow from April 2010
Berge Englert's group

It's amazing how quickly CQT has grown. I should know. My first contact with CQT was in fact with its predecessor, the Quantum Information Technologies (QIT) group, or the fondly nicknamed "quantum lah". This was in early 2004, when I was back home in Singapore after completing my undergrad studies overseas. For half a year, I interned in the QIT lab in Berge Englert's group.

Back then, the QIT lab physically comprised only a room for the theory group, adjoined to a lab for experiments, altogether about the size of CQT's Quantum Cafe and seminar room today. The experimental group comprised the sum total of two scientists, Christian Kurstiefer (still here) and Antia Linares-Lamas. Alex Ling was a student then, not yet the satellite-building miniaturization expert and Principal Investigator he is today. And my office, as a lowly research assistant, was a tiny cubicle stuffed in a boring room.

I went to Caltech in the US for my PhD studies. By the time I returned to Singapore in late 2009, the QIT lab had undergone a miraculous transformation. Backed by generous funding, CQT occupied almost an entire building and was attracting top researchers from all over the world to Singapore.

Thankfully, Berge didn't mind inviting me back to his group as a postdoc. Two years down the road, I still marvel at how CQT is such a conducive environment for research, with its colourful and varied blend of characters. Within Berge's group alone, I have had the opportunity to learn about and work on atomic physics, quantum optics and state estimation, and even dabble a little in disorder and localization physics. Equally rewarding is the chance to work with students, who constantly surprise me with their creativity and keep me on my toes with their questions.

Troy Lee

CQT Senior Research Fellow from September 2010
Computer Science group

When I was a kid, I dreamed of becoming a physicist and traveling the world doing research. After getting a PhD in Amsterdam, postdocs have taken me to Paris, New York, and now Singapore...but, alas, the physicist thing didn't work out. Well, perhaps being a computer scientist in a centre for quantum information is a close second.

The computer science group at CQT is well stocked in my favourite subjects of quantum query complexity and communication complexity, and I hang out with physicists much more than I am used to.

While nearly anywhere else in the world showing a "strong direct product theorem" would get you strange looks, here it is something it seems everybody is doing (see p. 22). A strong direct product theorem says there is no better way to solve k independent instances of a problem than running k times in parallel the best algorithm for one instance. This year we showed this is true for quantum query algorithms.

Besides my bread and butter research, the broader reach of the centre has led me to try some new things, like writing for a blog (check out quantumblah.org) and distracting the CQT workshop from their real work to build soap bubble computers for public demos such as at the Singapore Xperiment science festival. Soap bubbles naturally try to minimize their surface area, and we can use this property to try to solve other optimization problems like finding the minimum length of cable needed to connect a set of cities in a network. We used this demo to get people thinking about the physics underlying computation and to introduce the complexity classes P and NP. But mostly the bubbles were a big hit with the kids.

Paul Condylis

CQT Research Fellow from May 2010
Bjorn Hessmo's group

I arrived in Singapore in 2010 from Crete, Greece. It was quite a contrast: moving from the mountains of Crete to the skyscrapers of Singapore, swapping the market for the deli and the taverna for the food court. The transition was made easy, though, by the friendly atmosphere into which I stepped. In many ways CQT is a mirror for Singapore itself, with a dynamic group of people from a mixture of backgrounds all working together.

In the experiment I work on, we trap atoms below tiny wires imprinted on a microchip. These tiny wires make magnetic potential energy surfaces upon which the atoms move around, are contained and can be manipulated. They are like the test tubes of modern physics, where we hope to discover more about the quantum world. We use the magnetic fields to confine the atoms into a single one-dimensional chain. At very low energies our bosonic atoms, which like to clump together, start to behave like fermions, which repel one another. This intriguing behaviour is technically challenging to observe because it involves the detection of only a few hundred atoms or less. For this reason, I also conduct research to advance imaging systems.

'Technically challenging' for our experiment applies to lots of things, not least that we're building a whole new experiment to cool and trap rubidium atoms. This is one of my favourite parts of working in a physics laboratory. The tasks are varied, from designing the vacuum system to bolting it together, from implementing the laser system to modelling the proposed experiment, and finally to doing new physics, collecting and analysing data. Mostly what an experimental physicist does is problem solving, and with such a rich and dynamic set of problems to solve, a new lab is paradise.

Our students are the future

The Centre for Quantum Technologies is committed to training the next generation of scientists. It attracts talented students from around the world (see graphic) to undertake PhD studies, offering top-class education in a vibrant environment. CQT also accepts undergraduates and students pursuing Masters-level degrees at their home university for short internships.

Earn a PhD@CQT

CQT aims to produce high-caliber graduates in the exciting and growing interdisciplinary field of quantum technologies, which encompasses research in experimental and theoretical quantum physics and computer science. Students receive multidisciplinary training with a focus in science, engineering or computing. The PhD@CQT programme will train at least 80 PhD students over 10 years. The inaugural intake was in August 2008 after the Centre was founded at the end of 2007. There are currently over 50 students in the PhD programme. Students under the PhD@CQT programme receive a generous scholarship, plus allowances for travel and other expenses. Principal Investigators at CQT also supervise students funded by other sources, such as the NUS Faculty of Science or NUS Graduate School for Integrative Sciences and Engineering. All doctoral degrees are awarded by the National University of Singapore, consistently ranked among the leading universities in the world.

Internships

For students contemplating a career in research, CQT offers internships. These are particularly suited to students between the 4th and 5th year of an undergraduate degree or between the 1st and 2nd year of an MSc. They are available in CQT's experimental, theoretical and computer science groups. Students are invited to apply for placements to be undertaken in 2013 (dates flexible). Follow up applications by successful interns to the PhD@CQT programme will be given high priority. More information on the student programme and a description of how to apply are available on the CQT website: www.quantumlah.org.

Congratulations to our first graduates!

This year CQT proudly congratulated the first students to graduate from the PhD@CQT programme. Arun, supervised by Berge Englert, successfully defended his thesis on "Hybrid Quantum Computation". Elisabeth Rieper, supervised by Vlatko Vedral, was awarded her degree for research on "Quantum Coherence in Biological System". More will soon follow. We wish the programme's alumni every success in their careers.

What our students say

Han Rui

CQT PhD Student
Berge Englert's Group

"Project-wise, we have a lot of freedom to choose what we want to do. Since the Centre has a lot of people doing different things, we can try different directions."

Markus Baden

CQT PhD Student
Murray Barrett's Group

"At CQT you feel that you are part of more than just your group. Whether you have problems in the lab, questions about courses or just want to go for food and drinks after work, there is always someone you can ask just down the hall."

Elisabeth Rieper

CQT PhD Graduate
Vlatko Vedral's Group

"CQT has a never-ending flow of visitors, which is great for making new contacts and staying in touch with the world. Some visitors also give guest lectures, which is a great opportunity to learn."

Where our students come from

Le Phuc Thinh
CQT PhD Student
Valerio Scarani's Group

"CQT offers a friendly yet stimulating research environment."

Colin Teo
CQT PhD Student
Valerio Scarani's Group

"We are given many opportunities to attend conferences which is helpful not only to deepen our understanding of our field but also to develop our careers."

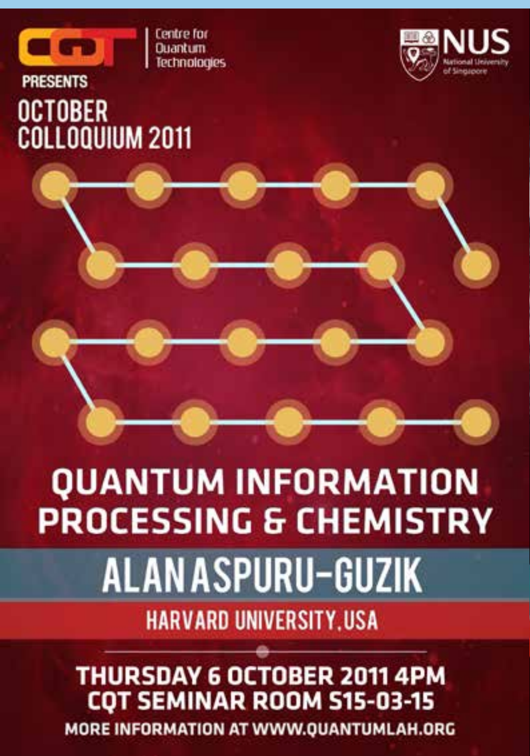
Michael Kalenikin
CQT Intern
from ETH Zurich
Christian Kurtsiefer's Group

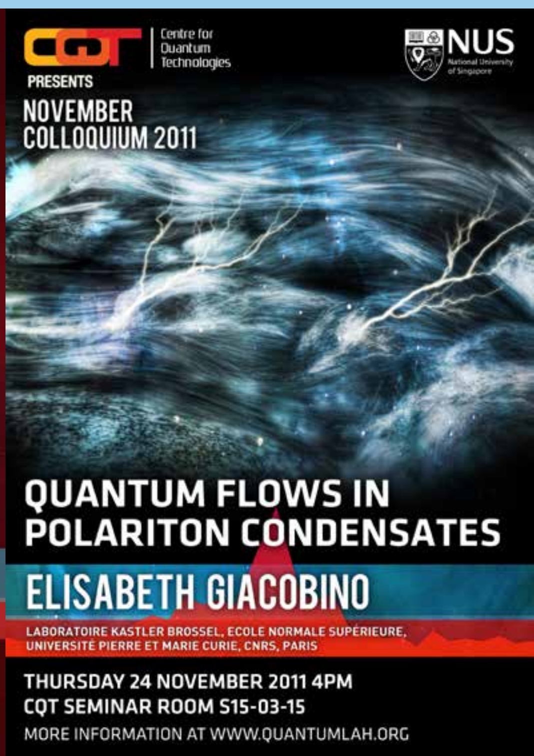
"From day one, people have been happy and eager to lead me deeper into a research field I find profoundly fascinating. I have been introduced to a very open-minded and hands-on approach to science."

Events

Colloquia

06.10.2011	Quantum Information Processing and Chemistry, Alán Aspuru-Guzik, Harvard University, USA
24.11.2011	Quantum flows in polariton condensates, Elisabeth Giacobino, Laboratoire Kastler Brossel, Ecole Normale Supérieure, Université Pierre et Marie Curie, CNRS
07.12.2011	Controlling and Exploring Quantum Gases at the Single Atom Level, Immanuel Bloch, Max-Planck-Institut für Quantenoptik
07.12.2011	Position-based Cryptography, Harry Buhrman, Centrum Wiskunde & Informatica (CWI) & University of Amsterdam
07.12.2011	Probabilities Versus Amplitudes, John Baez, University of California, Riverside & CQT, NUS
12.01.2012	Quantum Theory of the Classical, Wojciech Zurek, Los Alamos National Laboratory, USA
12.01.2012	Experimental Quantum Error Correction, Raymond Laflamme, IQC, Waterloo, Canada
09.02.2012	Carbon Spintronics, Guido Burkard,University of Konstanz, Germany
08.03.2012	Breaking the bounds of quantum thermodynamics, Gershon Kurizki, Weizmann Institute of Science, Israel
24.05.2012	Simulating quantum transport with atoms and light, Philippe Bouyer, Laboratoire Charles Fabry, France
26.07.2012	Doing small systems: Fluctuation relations and the arrow of time, Peter Hanggi, University of Augsburg, Germany
02.08.2012	The evasive cheshire cat: How to detect fractional statistics, Yuval Gefen, Weizmann Institute of Science, Israel






Centre for Quantum Technologies
NUS National University of Singapore
JANUARY COLLOQUIA
2012
WOJCIECH ZUREK
LOS ALAMOS NATIONAL LABORATORY, USA
4 PM
QUANTUM THEORY OF THE CLASSICAL
RAYMOND LAFLAMME
IQC, WATERLOO, CANADA
5 30 PM
EXPERIMENTAL QUANTUM ERROR CORRECTION
12 JANUARY 2012 THURSDAY CQT SEMINAR ROOM S15-03-15
MORE INFORMATION AT WWW.QUANTUMLAH.ORG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FEBRUARY COLLOQUIUM 2012
CARBON SPINTRONICS
GUIDO BURKARD
DEPARTMENT OF PHYSICS, UNIVERSITY OF KONSTANZ, GERMANY
THURSDAY 9 FEBRUARY 2012 4PM
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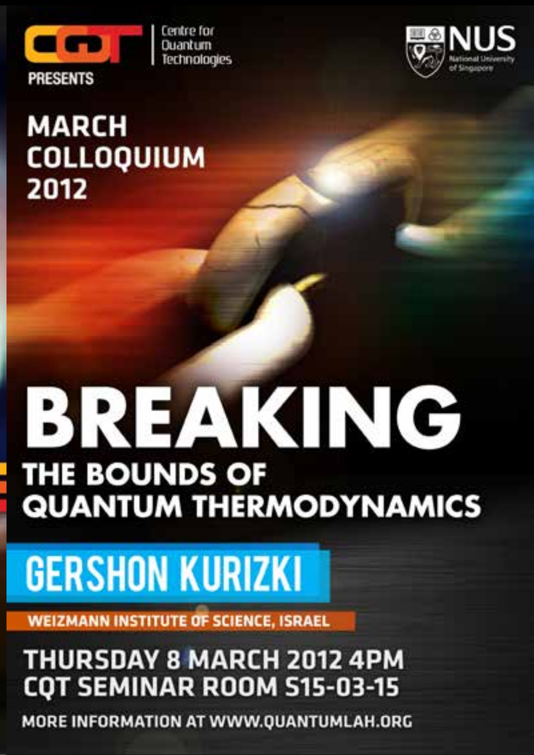
Centre for Quantum Technologies
PRESENTS
NUS National University of Singapore
MARCH COLLOQUIUM 2012
BREAKING
THE BOUNDS OF QUANTUM THERMODYNAMICS
GERSHON KURIZKI
WEIZMANN INSTITUTE OF SCIENCE, ISRAEL
THURSDAY 8 MARCH 2012 4PM
CQT SEMINAR ROOM S15-03-15
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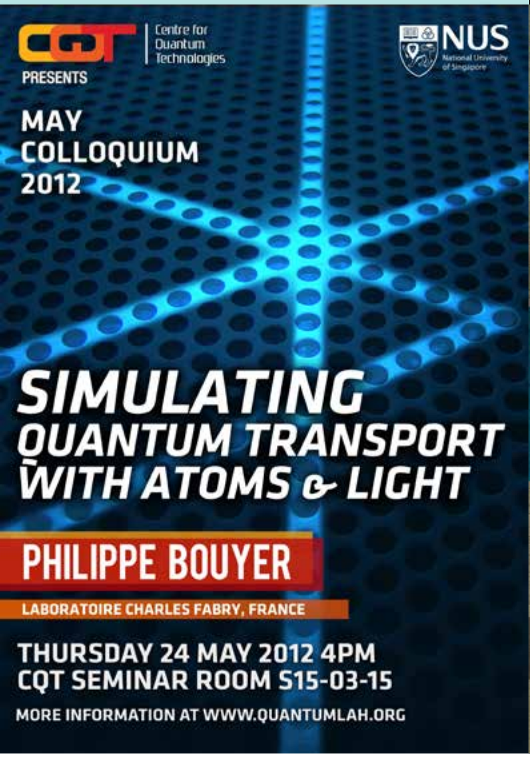
Centre for Quantum Technologies
PRESENTS
NUS National University of Singapore
MAY COLLOQUIUM 2012
SIMULATING QUANTUM TRANSPORT WITH ATOMS & LIGHT
PHILIPPE BOUYER
LABORATOIRE CHARLES FABRY, FRANCE
THURSDAY 24 MAY 2012 4PM
CQT SEMINAR ROOM S15-03-15
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Centre for Quantum Technologies
PRESENTS
NUS National University of Singapore
JULY COLLOQUIUM 2012
DOING SMALL SYSTEMS:
FLUCTUATION RELATIONS & THE ARROW OF TIME
PETER HANGGI
UNIVERSITY OF AUGSBURG
THURSDAY 26 JULY 2012 4PM
CQT SEMINAR ROOM S15-03-15
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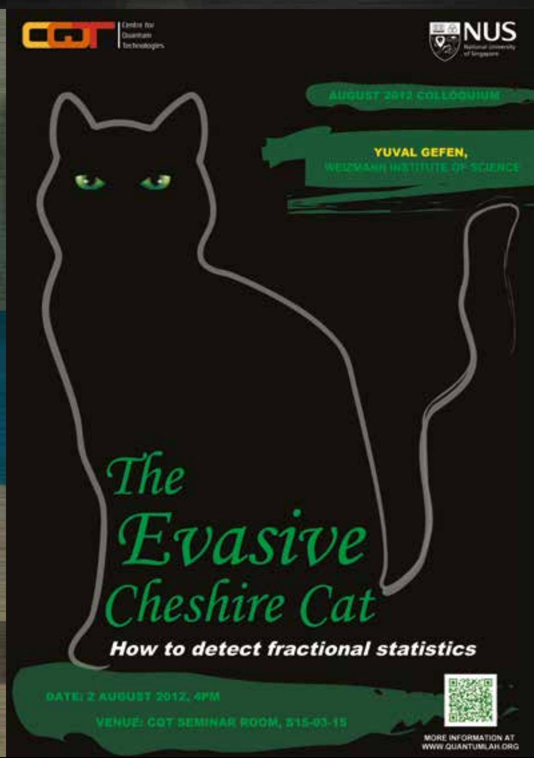
NUS
AUGUST 2012 COLLOQUIUM
YUVAL GEFEN,
WEIZMANN INSTITUTE OF SCIENCE
The Evasive Cheshire Cat
How to detect fractional statistics
DATE: 2 AUGUST 2012, 4PM
VENUE: CQT SEMINAR ROOM, S15-03-15
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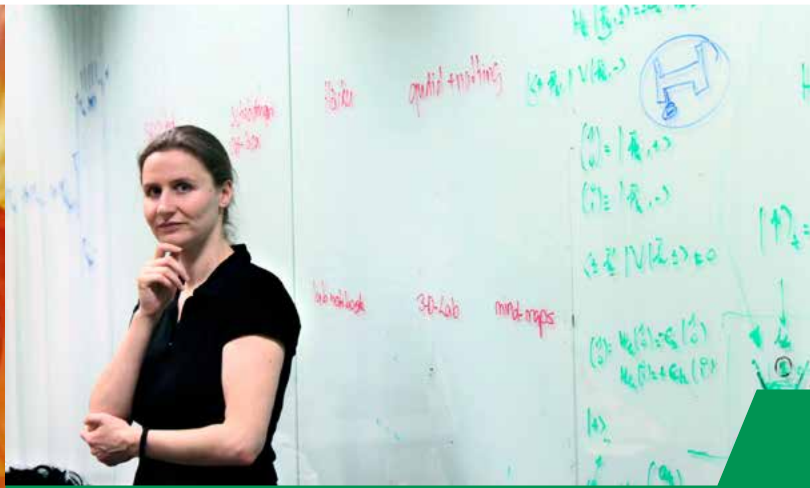


▲ Artist Grit Ruhland from Germany spent a month at CQT through the NUS 2012 Arts/Science Residency Programme.

◀ The fabric and light sculpture pictured left was created by Momo Lu Yin, a PhD student, and artist Madhura Nayak, participants in Grit's collaborative 'Cabinet of Curiosities' project. The sculpture is inspired by cold atoms trapped in optical lattices.

▼ Michael Brooks gave a talk at the Singapore Science Centre, "When Scientists do Extraordinary Things", to an audience of over 100 people.

Awards

Lai Choy Heng was awarded a National Day Award 2012, the Long Service Medal.

Nelly Ng Huei Ying, an intern who has since joined CQT's research staff, was named a Koh Boon Hwee Scholar and won the Shell Eastern Petroleum Gold Medal cum Cash Award on graduating from Nanyang Technological University.

Valerio Scarani was awarded the NUS Provost's Chair 2012 for his research into various aspects of quantum cryptography, in particular the device independent protocols, which push secret communication to its limits.

Rahul Jain won the NUS Young Researcher Award 2012 for his "breakthrough contributions to our understanding of proofs and computation". Rahul is one of only three faculty to receive the Young Researcher Award 2012.

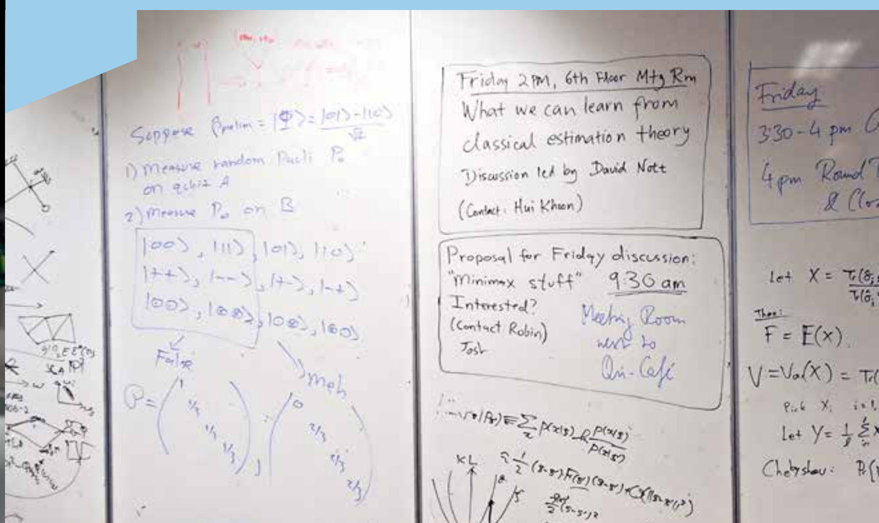
Swee Yee Wee, known to CQTians as Auntie, received the inaugural "CQTian of the Year" award in 2011.

Outreach

13 Oct – 16 Dec 11	George Musser, an editor with Scientific American, spent two months at CQT as a writer-in-residence to work on a popular science book. He also gave a public talk and did a Q&A session with students enrolled in the NUS–ANU MSc in Science Communication.
25 Oct 11	Christian Kurtsiefer and Valerio Scarani are mentioned in a feature in *New Scientist* on quantum hackers.
14 Dec 11	CQT offered a three-hour quantum workshop for 30 students participating in the NUS Science Focus event—a three-day programme organised by NUS and MOE for JC1 students.
18 Jan 12	Public Talk: "Photon, Atom and Neutron: How Quantum Mechanics cracked the Nuclear Code" by Charles Clark at NUS University Hall Auditorium
16-20 Feb 12	CQT participated in the annual meeting of the American Association for the Advancement of Science (AAAS), held in Vancouver, Canada.
4 Feb 12	"Thinker, diver, pilot, code-breaker": a profile of CQT's Director Artur Ekert is published in Singapore's *TODAY* newspaper.
29 Mar 12	Science café by Valerio Scarani at a Chinatown Bar.
25 Mar – 22 Apr 12	CQT hosted artist Grit Ruhland from Germany for one month under the NUS 2012 Arts/Science Residency Programme.
26 May and 2 Jun 12	CQT researchers ran hands-on activities for NUS science alumni days.
7 Jun 12	Alexander Ling presented at CQT to 30 secondary school students from the Singapore Space Academy.
1 Jul 12	CQT participated by invitation of NRF in Singapore-led events at the 2012 Lindau Nobel Laureate meeting in Germany, which brings together Nobel prize-winning scientists and young researchers.
11 Jul 12	Students in Singapore to compete in the International Biology Olympiad visited CQT.
29 Aug 12	Public Talk: "When Scientists do Extraordinary Things", by Michael Brooks at Singapore Science Centre.

Workshops

28 Nov – 2 Dec 11	Workshop of Quantum Tomography 2011
12 – 14 Dec 11	AtomChip Workshop at Pangkil Island, Indonesia
9 – 13 Jan 12	Quantum Discord Workshop 2012
21 May – 8 Jun 12	Singapore School of Physics – Strong Light-Matter Coupling: from atoms to solid-state systems



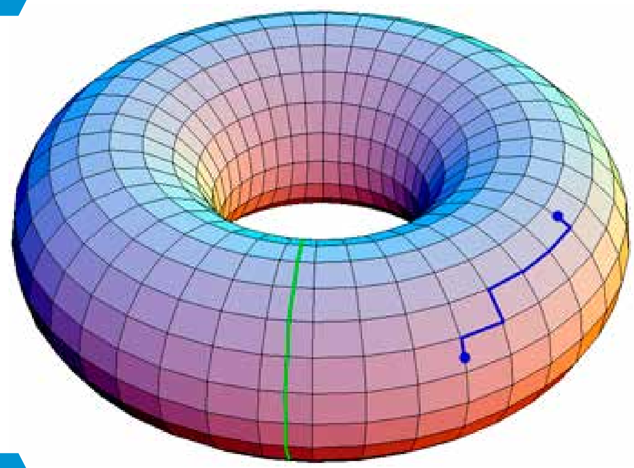
Imperfections could massively improve quantum hard drives

The last thing you'd expect to be useful in a computer's hard drive is structural flaws, but Research Fellow Alastair Kay of CQT and the University of Oxford, UK, has quantified how imperfections in a quantum hard drive could help prevent delicate quantum data from accumulating errors.

Classical computer hard drives store information safely for long times without any power. Searching for a comparable way to achieve passive, stable quantum data storage has previously led researchers to propose 'toric codes'. These systems for encoding quantum data store information in the global properties of groups of qubits rather than individual qubits, such that single isolated errors cannot destroy it directly. Unfortunately, localised errors can grow into logical errors through the intrinsic interactions of the system, causing the memory to fail.

In condensed matter systems, impurities often curtail dynamical properties such as electrical and thermal conduction, a phenomenon known as Anderson localisation. Alastair explored the idea that Anderson localisation could control error propagation in a quantum memory implementing a toric code, with structural flaws acting like impurities. For a two-dimensional code disturbed by a magnetic field, he calculated that inducing Anderson localisation would (almost always) give an exponential increase in the quantum data lifetime — from scaling as log(N) to scaling as N^c (c being some constant).

Mathematically, the result is derived by mapping the two-dimensional memory system into a one-dimensional Ising model and using Lieb–Robinson bounds. The theoretical analysis is backed up with simulations of a 3-million-qubit toric code.



The Capabilities of a Perturbed Toric Code as a Quantum Memory
A. Kay, Phys. Rev. Lett. 107, 270502 (2012)

A direct product theorem for bounded-round public-coin randomized communication complexity
R. Jain, A. Pereszlenyi, P. Yao
Proc. IEEE FOCS (2012)

A short proof of the Quantum Substate Theorem
R. Jain, A. Nayak
IEEE Transactions on Information Theory, (2012)

Adiabatic quantum simulators
Biamonte, JD, Bergholm, V., Whitfield, J.D., J. Fitzsimons, Aspuru-Guzik, A.
AIP Advances 1, 022126, (2011)

All entangled pure states violate a single Bell
S.X. Yu, Q. Chen, C.J. Zhang, C H Lai, C.H. Oh
Phys. Rev. Lett. 109, 120402, (2012)

Almost All Quantum States Have Low Entropy Rates for Any Coupling to the Environment
A. Hutter, S. Wehner
Phys. Rev. Lett. 108, 070501, (2012)

An efficient quantum algorithm for the hidden subgroup problem in nil-2 groups
G. Ivanyos, Luc Sanselme, M. Santha
Algorithmica 62, 480-498, (2012)

Bell nonlocality in conventional and topological quantum phase
D.L. Deng, C.F. Wu, J. Chen, S J Gu, S.X. Yu, C.H. Oh
Phys. Rev. A 86, 032305, (2012)

Bell tests for continuous variable systems using hybrid measurements and heralded amplifiers
J.B. Brask, N. Brunner, D. Cavalcanti, A. Leverrier
Phys. Rev. A 85, 042116, (2012)

Calibrating an interferometric laser frequency stabilization to megahertz precision
J. F. S. Brachmann, T. Kinder, K. Dieckmann
Applied Optics 51, 5517, (2012)

Capturing long range correlations in two-dimensional quantum lattice systems using correlator product states
S. Al-Assam, S. Clark, C. J. Foot, D. Jaksch
Phys. Rev. B 84, 205108, (2011)

Categorical Tensor Network States
J. D. Biamonte, S. Clark, D. Jaksch
AIP Advances 1, 042172, (2011)

Coherent Backscattering of Ultracold Matter Waves: Momentum Space Signatures
N. Cherroret, T. Karpiuk, C. A. Müller, B. Gremaud, C. Miniatura
Phys. Rev. A (R) 85, 011604, (2012)

Coherent cavity networks with complete connectivity
E. Kyoseva, Almut Beige, L.C. Kwek
New J. Phys. 14, 023023, (2012)

Composition-Dependent Structural and Electronic Properties of alpha-(Si1-xCx)(3)N-4
Xu M., Xu S., Duan M.Y., Jiang N, Li H.S., L.C. Kwek
J. Phys. Chem. C 115, 2448, (2011)

Computing Extensions of Linear Codes using a Greedy Algorithm
M. Grassl, S. Han
Proceedings of ISIT, 1573-1577, (2012)

Condensate deformation and quantum depletion of Bose-Einstein condensates in external potentials
C. A. Müller, C. Gaul
New J. Phys., 14 075025, (2012)

Converting zitterbewegung oscillation to directed motion
Q. Zhang, J B Gong, C.H. Oh
Europhys. Lett. 96, 10004, (2011)

Correlation/Communication complexity of generating bipartite states
R. Jain, Y. Shi, Z.H. Wei, S. Zhang
ACM SIAM SODA, (2012)

Detecting multipartite classical states and their resemblances
L. Chen, Eric Chitambar, K. Modi, G. Vacanti
Phys. Rev. A 83, 020101(R), (2011)

Device-independent certification of entangled measurements
R. Rabelo, M. Ho, D. Cavalcanti, N. Brunner, V. Scarani
Phys. Rev. Lett. 107, 050502, (2011)

Dimer, trimer and Fulde-Ferrell-Larkin-Ovchinnikov liquids in mass- and spin-imbalanced trapped binary mixtures in one dimension
M. Dalmonte, K. Dieckmann, T. Roscilde, C. Hartl, A. E. Feiguin, U. Schollwock, F. Heidrich-Meisner
Phys. Rev. A 85, 063608, (2012)

CQT researchers and their collaborators published 122 papers in peer-reviewed places from September 2011 to August 2012. Papers are listed here alphabetically by title, with descriptions of selected results adapted from highlights published on CQT's website.

Substate theorem

New approaches to proving the ten-year-old quantum substate theorem have raised interest thanks to the theorem's wide impact. The theorem had already found applications including evaluating privacy trade-offs in communication protocols and studying message compression in classical and quantum communication. For researchers who make use of the quantum substate theorem, the new proofs that CQT Principal Investigator Rahul Jain describes as "much simpler and more intuitive" than the original, are welcome.

The quantum substate theorem was originally formulated and proven by Rahul and two other colleagues in 2002. The theorem connects two important measures of a pair of quantum states — the relative entropy and smooth relative min entropy. These measures quantify the similarity of, or in the language of quantum mechanics, the distance between, two quantum states.

The smooth relative min entropy indicates whether it is possible to express one of the two quantum states as a 'large' substate of the other — a useful trick in calculations — but the relative entropy is often the easier to calculate. The quantum substate theorem showed that the relative entropy is an upper bound to the smooth relative min entropy (times the smoothness parameter epsilon). The theorem therefore clarifies which cases can be expressed as nice substates.

There are two new proofs: one is based on minimax duality, the other on semi-definite programming duality. This new work also slightly improves the bound.

A short proof of the quantum substate theorem, Rahul Jain and Ashwin Nayak, IEEE. Trans. Inf. Theory doi:10.1109/TIT.2012.2184522 (2012)

Phase change

An upside-down way of looking at the connection between physics and information led CQT researchers and their collaborators to results offering insight for quantum computation.

Researchers know that when quantum matter shifts from one state to another, there is often a signature in an informational measure, such as entanglement. This has led to quantum information theory being used to study the physical properties of quantum phase transitions. But as the team points out in this paper, the reverse — the question of how physical phase transitions influence informational properties — is less studied.

"We look past the physical properties of the different phases and ask, 'Could different phases have different capacities to process information as well?' The answer turns out to be yes" says Mile Gu, a CQT Research Fellow.

The team looked at a simplified model of matter known as an Ising model, which can adopt different magnetic phases. The researchers analysed how the entropy of the model's paramagnetic and ferromagnetic phases change when an external magnetic field is applied, and found in the simplest case that the ferromagnetic phase has a capacity to exhibit quantum effects that the paramagnetic phase does not. The researchers suggest the approach could be applied to studying a form of quantum computation known as 'adiabatic', in which the computation is implemented by applying external influences to quantum matter and the result deduced from its end state.

Quantum phases with differing computational power, J. Cui, M. Gu, L. C. Kwek, M. F. Santos, H. Fan and V. Vedral, Nature Commun. 3, 812 (2012)

Dipole-Dipole coupled double Rydberg molecules
M. Kiffner, Hyunwook Park, W. Li, T. Gallagher
Phys. Rev. A (R) 86, 031401(R), (2012)

Does ignorance of the whole imply ignorance of the parts? Large violations of non-contextuality in quantum theory
T. Vidick, S. Wehner
Phys. Rev. Lett. 107, 030402, (2011)

Dynamical fluctuations in classical adiabatic processes: General description and their implications
Q. Zhang, J B Gong, C.H. Oh
Ann. Phys. 327, 1202-1213, (2012)

Dynamics of quantum discord in a quantum critical environment
Z J Xi, X. Lu, Z Sun, Y M Li
J. Phys. B: At. Mol. Opt. Phys. 44, 215501, (2011)

Dynamics of quantum light in integrated nonlinear waveguide arrays and generation of robust continuous variable entanglement
A. Rai, D.G. Angelakis
Phys. Rev. A 85, 052330, (2012)

Emergent Spin Liquids in the Hubbard Model on the Anisotropic Honeycomb Lattice
G. Wang, Mark O. Goerbig, C. Miniatura, B. Gremaud
Europhys. Lett. 95, 47013, (2011)

Encoding Universal Computation in the Ground States of Ising Lattices
M. Gu, A. Perales
Phys. Rev. E 86, 011116, (2012)

Entanglement distribution over the subsystems and its invariance
Q.J. Tong, J H An, H G Luo, C.H. Oh
Quantum Information and Computation 11, 0874, (2011)

Entangling Macroscopic Diamonds at Room Temperature
K. C. Lee, M. R. Sprague, B. J. Sussman, J. Nunn, N. K. Langford, X.M. Jin, T. Champion, P. Michelberger, K. F. Reim, D. England, D. Jaksch, I. A. Walmsley
Science 334 ,1253-1256, (2011)

Equilibrium and Disorder-induced behavior in Quantum Light-Matter Systems
E. Mascarenhas, L. Heaney, M. C. O. Aguiar, M.F. Santos
New J. Phys. 14, 043033, (2012)

Excitation energy transfer in light-harvesting systems: effect of the initial state
B Cui, X. Yi, C.H. Oh
J. Phys. B: At. Mol. Opt. Phys. 45, 085501, (2012)

Experimental Demonstration of Blind Quantum Computing
S. Barz, E. Kashefi, A. Broadbent, J. Fitzsimons, A. Zeilinger, P.Walther
Science 335, 303-308, (2012)

Experimental implementation of a codeword-stabilized quantum code
J. Zhang, M. Grassl, B. Zeng, R. Laflamme
Phys. Rev. A 85, 062312, (2012)

Experimental proposal for symmetric minimal two-qubit state tomography
A. Kalev, J.W. Shang, B.-G. Englert
Phys. Rev. A 85, 052115, (2012)

Experimentally faking the violation of Bell
I. Gerhardt, Q. Liu, A. Lamas-Linares, J. Skaar, V. Scarani, V. Makarov, C. Kurtsiefer
Phys. Rev. Lett. 107, 170404, (2011)

Fabrication of Glass Micro-Cavities for Cavity QED Experiments
A. Roy, M.D. Barrett
Applied Physics Letters 99, 171112, (2011)

Fully Distrustful Quantum Cryptography
J. Silman, A. Chailloux, N. Aharon, I. Kerenidis, S. Pironio, S. Massar
Phys. Rev. Lett. 106, 220501, (2011)

Geometric measure of quantum discord for superpositions of Dicke states
X L Yin, Z J Xi, X. Lu, Z Sun, X G Wang
J. Phys. B: At. Mol. Opt. Phys. 44, 245502, (2011)

Growth specificity of vertical ZnO nanorods on patterned seeded substrates through integrated chemical process
P. Suresh Kumar, S. M. Maniam, J. Sundaramurthy, J. Arokiaraj, D. Mangalaraj, D. Rajarathnam, M.P. Srinivasan, L.K. Jian
Materials Chemistry and Physics 133, 126-134, (2012)

Faking Bell

When it comes to pitting quantum theory against classical notions of the world, there's one experiment that physicists say can make a clear distinction: a test of Bell's inequalities. But CQT researchers with collaborators from Norway managed to fake quantum results using classical physics in such a test, reminding scientists to be cautious about the assumptions in their experiments.

Bell inequalities measure the strength of correlations between two particles, or how much their behaviours are coordinated. Quantum physics allows stronger correlations than classical physics, and this shows up in experiments as a violation of the inequality. In the experiment at CQT, a typical apparatus for measuring Bell violations by pairs of photons was cheated using bright pulses of light to manipulate the output of single-photon detectors. The researchers had previously used a similar trick to eavesdrop on quantum key distribution.

The deception worked by exploiting what's known as the 'detection loophole', which arises from an assumption made to account for inefficiencies in photon detection. In this case the exploitation was deliberate, but researchers also want to perform a loophole-free Bell test to remove the fine-print from their tests of nature's quantum behaviour.

The paper was highlighted as an Editor's Suggestion in *Physical Review Letters* and was covered by media including *Physics Today* and *Nature* news.

Experimentally faking the violation of Bell's inequalities, I. Gerhardt, Q. Liu, A. Lamas-Linares, J. Skaar, V. Scarani, V. Makarov and C. Kurtsiefer, Phys. Rev. Lett. 107, 170404 (2011)

Hierarchy of measurement-induced Fisher information for composite states
X. Lu, S L Luo, C.H. Oh
Phys. Rev. A 86, 022342, (2012)

High threshold distributed quantum computing with three-qubit nodes
Y. Li, S. Benjamin
New J. Phys. 14, 093008, (2012)

Holographic Storage of Biphoton Entanglement
Han-Ning Dai, H. Zhang, Sheng-Jun Yang, Tian-Ming Zhao, J. Rui, You-Jin Deng, L. Li, S. Chen, Xiao-Hui Bao, X.M. Jin, B. Zhao, Jian-Wei Pan
Phys. Rev. Lett. 108, 210501, (2012)

In situ determination of Zeeman content of collective atomic memories
S. D. Jenkins, Y. O. Dudin, R. Zhao, D. Matsukevich, A. Kuzmich, T. A. B. Kennedy
J. Phys. B: At. Mol. Opt. Phys. 45, 124006, (2012)

Incomplete quantum state estimation: a comprehensive study
Y.S.Teo, B. Stoklasa, B.-G. Englert, J. Rehacek, Z. Hradil
Phys. Rev. A 85, 042317, (2012)

Information Causality and Extremal Tripartite Correlations
T.H. Yang, D. Cavalcanti, M. Almeida, Z.W. Teo, V. Scarani
New J. Phys. 14, 013061, (2012)

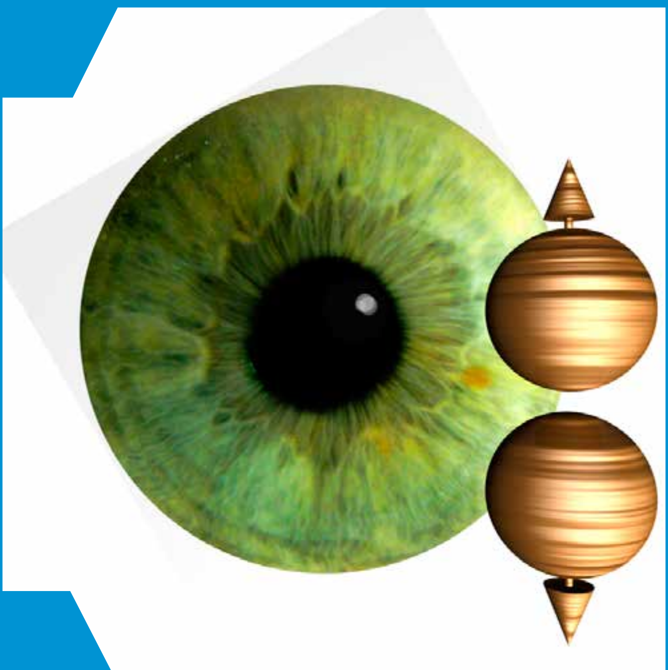
Irreducible multiqutrit correlations in Greenberger-Horne-Zeilinger-type states
F L Zhang, J. Chen
Phys. Rev. A 84, 062328, (2011)

Knowledge and ignorance in incomplete quantum state tomography
Y. S. Teo, H. Zhu, B.-G. Englert, J. Rehacek, Z. Hradil
Phys. Rev. Lett. 107, 020404, (2011)

Localization behavior of Dirac particles in disordered graphene superlattices
Q Zhao, J Gong, C. A. Müller
Phys. Rev. B 85, 104201, (2012)

Localization of solitons: linear response of the mean-field ground state to weak external potentials
C. A. Müller
Appl. Phys. B 102, 459, (2011)

In search of certainty about superpositions



Tests of the 'Leggett–Garg inequality' on photons and other systems have helped to confirm one of the stranger predictions of quantum theory: that objects can be in two or more mutually exclusive conditions at the same time. An experiment carried out by a team of 12 researchers including two affiliated with CQT represents the first 'ideal negative result' implementation, as originally proposed by Tony Leggett and Anupam Garg in 1985.

The idea behind a 'negative result measurement' is to infer the state of a system indirectly, by looking for it but not seeing or finding it. It is one way round the main challenge in testing the Leggett–Garg inequality. Because the test involves looking at how a system evolves in time, the experiment must be performed such that the results can't be dismissed as influenced by the measurement. Previous tests have tried approaches such as making very gentle 'weak' measurements.

As well as being of philosophical interest, the experiment demonstrated tools for the precise manipulation and readout of a quantum system that could be applied in quantum technologies. The group looked at an ensemble of phosphorous impurities in a crystal of purified silicon. Using one electron per impurity to indirectly examine each phosphorous nucleus, the team were able to expose quantum superpositions in the nuclei's spin (akin to the spins being magnetic compass needles pointing both up and down at once).

Violation of a Leggett–Garg inequality with ideal non-invasive measurements, G. C. Knee, S. Simmons, E. M. Gauger, J. J. L. Morton, H. Riemann, N. V. Abrosimov, P. Becker, H.-J. Pohl, K. M. Itoh, M. L. W. Thewalt, G. A. D. Briggs and S. C. Benjamin, Nature Commun. 3, 606 (2012)

Long distance two-party quantum cryptography made simple
I. Kerenidis, S. Wehner
Quantum Information Processing 12, 0448-0460, (2012)

Long-distance entanglement generation with scalable and robust two-dimensional quantum network
Y. Li, D. Cavalcanti, L.C. Kwek
Phys. Rev. A 85, 062330, (2012)

Mapping coherence in measurement via full quantum tomography of a hybrid optical detector
L. Zhang, Hendrik B. Coldenstrodt-Ronge, A. Datta, G. Puentes, Jeff S. Lundeen, X.M. Jin, B. J. Smith, M. B. Plenio, I. A. Walmsley
Nature Photonics 6, 364–368, (2012)

Metastability in Spin-Polarized Fermi Gases
Y. A. Liao, M. Revelle, T. Paprotta, A. S. C. Rittner, W. Li, G. B. Partridge, R. G. Hulet
Phys. Rev. Lett. 107, 145305, (2011)

Micromotion in trapped atom-ion systems
Le Huy Nguyen, A. Kalev, M.D. Barrett, B.-G. Englert
Phys. Rev. A 85, 052718, (2012)

Multicopy and stochastic transformation of multipartite pure states
L. Chen, M. Hayashi
Phys. Rev. A 83, 022331, (2011)

Necessary and sufficient condition for saturating the upper bound of quantum discord
Z J Xi, X. Lu, X G Wang, Y M Li
Phys. Rev. A 85, 032109, (2012)

New Binary Codes From Extended Goppa Codes
M. Tomlinson, M. Jibril, C. Tjhai, M. Grassl, Mohammed Zaki Ahmed
Designs, Codes and Cryptography, (2012)

New Constructions of Codes for Asymmetric Channels via Concatenation
M. Grassl, P. Shor, G. Smith, J. Smolin, B. Zeng
Proceedings of ISIT, 1573-1577, (2012)

Non-equilibrium phonon dynamics in trapped ion systems
T. Dutta, M. Mukherjee, K. Sengupta
Phys. Rev. A 85, 063401, (2012)

Nonlocality is transitive
S. Coretti, E. Hänggi, S. Wolf
Phys. Rev. Lett. 107, 100402, (2011)

Nonlocality tests enhanced by a third observer
D. Cavalcanti, R. Rabelo, V. Scarani
Phys. Rev. Lett. 108, 040402, (2012)

Observing the Operational Significance of Discord Consumption
M. Gu, Helen M. Chrzanowski, Syed M. Assad, T. Symul, K. Modi, T. C. Ralph, V. Vedral, P.K. Lam
NaNature Physics 8, 671–675 (2012)

On the hitting times of quantum versus random walks
F. Magniez, A. Nayak, P. Richter, M. Santha
Algorithmica 63, 98-116, (2012)

One-sided Device-Independent Quantum Key Distribution: Security, feasability and the connection with steering
C. Branciard, E. G. Cavalcanti, S. P. Walborn, V. Scarani, H. M. Wiseman
Phys. Rev. A 85, 010301, (2012)

Optimal bounds for quantum bit commitment
Andre Chailloux, I. Kerenidis
Proc. IEEE FOCS (2011)

Optimal irreversible stimulated emission
D. Valente, Y. Li, J. P. Poizat, J. M. Gérard, L.C. Kwek, M.F. Santos, A. Auffèves
New J. Phys. 14, 083029, (2012)

Pairing in population imbalanced Fermion systems
M. Wolak, V. G. Rousseau, G. Batrouni
Computer Physics Communications 182, 2021, (2011)

Perfect Quantum Routing in Regular Spin Networks
Peter J. Pemberton-Ross, A. Kay
Phys. Rev. Lett. 106, 020503, (2011)

Photon Production from the Vacuum Close to the Superradiant Transition: Linking the Dynamical Casimir Effect to the Kibble-Zurek Mechanism
G. Vacanti, S. Pugnetti, N. Didier, M. Paternostro, G. Massimo Palma, R. Fazio, V. Vedral
Phys. Rev. Lett. 108, 093603, (2012)

Practical Implementation and Error Bound of Integer-Type Algorithm for Higher-Order Differential Equations
Fuminori Sakaguchi, M. Hayashi
Numerical Functional Analysis and Optimization 32, 1316-1364, (2011)

Dance like a neutrino

The dance of neutrino particles oscillating between their three flavours can be recreated in the quantum states of three trapped ions, according to a proposal by three CQT theorists. Lasers acting on the ions will create interactions mimicking those in neutrinos.

Neutrinos are pesky things to study: they barely interact with matter and have a very tiny mass. Experiments to study them typically use vast detectors to capture neutrinos produced in the Sun or in particle accelerators. Physicists would like more precise measurements than such experiments have so far yielded since neutrino behaviour could provide a first glimpse of physics beyond the current Standard Model.

The CQT theorists hope to collaborate with experimentalists to realise their 'quantum simulation' using existing techniques. The long-standing idea of using a controllable, tunable quantum system in the lab to simulate the complicated behaviour of another quantum system is increasingly being put into practice — for example, in 2010 a very fast jittering predicted to occur for relativistic particles known as *Zitterbewegung*, never before seen, was simulated in a trapped ion.

Neutrino oscillations in standard theory are easily calculated, however, the CQT researchers say the simulator could prove useful in exploring more exotic models of neutrino behaviour. The new scheme could also inspire simulations of other types of particles that come in families of three such as quarks, the nucleons that form protons and neutrons.

Quantum simulation of neutrino oscillations with trapped ions, C. Noh, B. M Rodríguez-Lara and D. G Angelakis, New J. Phys. 14, 033028 (2012)

Ultra-fast circuit QED

CQT researchers and their collaborators in Spain invented a scheme to get ultrafast performance from one of the most promising technologies for quantum-powered computations and simulations.

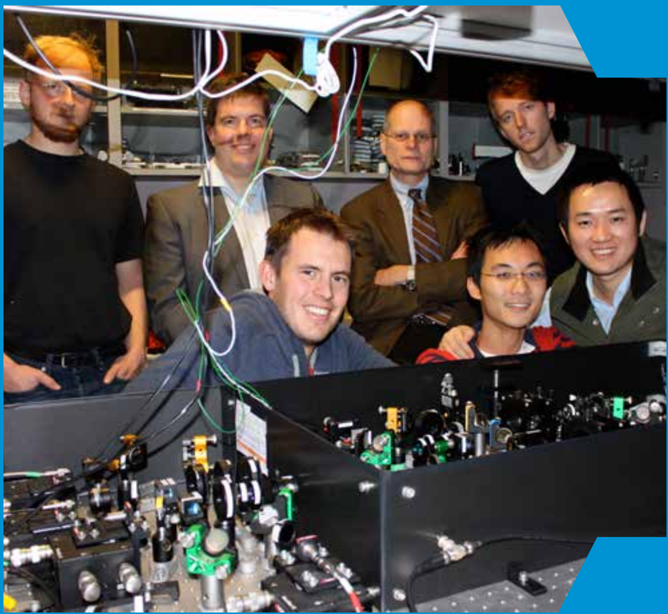
The scheme is for the technology known as circuit QED, which has already been used for the demonstration of quantum-information processing tasks. One of the attractions of circuit QED schemes is that they involve all-electronic structures that are controllable and potentially simple to scale.

The researchers' proposal takes advantage of the recent experimental discovery of the 'ultrastrong coupling' regime in circuit QED (first announced in two papers in 2010). In an earlier paper, the researchers had shown that the accuracy of existing logic gate schemes for circuit QED would decrease significantly in the ultrastrong regime. As a follow-up, they designed a two-qubit 'CPHASE' gate specifically for this regime that uses a modified qubit architecture — a particular arrangement of SQUID rings. The researchers estimate that operation times would be improved from tens of nanoseconds in existing proposals to less than a nanosecond. Information stored in circuit QED qubits is expected to decohere after a few microseconds, making it important to do gate operations quickly.

Yimin, a CQT PhD student, initiated this project after presenting in CQT's Journal Club the 2010 experimental papers on ultrastrong coupling.

Ultrafast Quantum Gates in Circuit QED, G. Romero, D. Ballester, Y. M. Wang, V. Scarani and E. Solano, Phys. Rev. Lett. 108, 120501 (2012); arXiv:1109.1305

Diamonds entangled at room temperature



Entangling Macroscopic Diamonds at Room Temperature, K. C. Lee, M. R. Sprague, B. J. Sussman, J. Nunn, N. K. Langford, X.-M. Jin, T. Champion, P. Michelberger, K. F. Reim, D. England, D. Jaksch and I. A. Walmsley, Science 334, 1253 (2011)

Quantum physics doesn't only describe the antics of tiny particles. Two diamond crystals were entangled in a shared quantum state in experiments at the UK's University of Oxford, led by a 12-strong team that included two researchers affiliated with CQT. The feat was published in *Science* and reported widely in the media.

The researchers estimate that approximately one nanocarat (10^{-9} carats) in one diamond was entangled with one nanocarat in another diamond located 15 cm away. Though minuscule by romantic standards, a nanocarat contains approximately 10^{16} carbon atoms and would be large enough to see by eye.

To create and detect the entanglement, which lasted only picoseconds (10^{-12} seconds), the team used an optical setup exploiting femtosecond (10^{-15} second) laser pulses.

It is the first demonstration of quantum effects in the bulk properties of diamond, and the group has conceived schemes to scale up such effects into fast, high-capacity quantum memory chips. Diamond is considered a promising material for quantum technologies. However, for now, the result stands out most as an observation of quantum phenomena in a solid, everyday object at room temperature.

"This work pushes the boundary of the quantum manipulation of massive objects in ambient environment conditions," said Xian-Min Jin, a CQT-Oxford Research Fellow, "it offers a glimpse into the transition between the quantum and classical realms".

Birds' eyes

Two CQT-affiliated researchers who contributed to calculations suggesting European robins' magnetic sense may involve a long-lived quantum state have returned to the topic. Quantum longevity is interesting to quantum physicists seeking to study and manipulate quantum states in the lab — but the result also piqued the physicists' interest for its biological implications.

Exactly how birds detect magnetic fields is poorly understood. A popular model holds that the mechanism is part of the visual system, involving an unidentified magnetoreceptor molecule that is excited by light to form a 'radical pair'. The external magnetic field would determine what proportion of the excited molecules end up in a 'spin-triplet' versus a 'spin-singlet' state.

Typically the radical pair model is thought to conclude in chemistry: for example, the triplet state may decay in a different way to the singlet state, with detection of the field via the resulting chemical products. The team's alternate hypothesis is that the birds see the cumulative electric field of the triplet states (the singlet state creates no field), which could directly disrupt the light-sensing components of the retina. This mechanism would provide a biological motivation for a long-lived quantum state.

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Phys. Rev. X 1, 021022, (2011)

Quantum discord as resource for remote state preparation
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Computing from noise

The process known as spontaneous emission that was previously seen as creating unhelpful noise in quantum data can be harnessed not only to protect the data, but even to compute, according to research initiated by one of CQT's long-term visitors, Marcelo Franca Santos.

The finding offers a new strategy for building quantum-information processing devices, which Marcelo and his collaborators have explored in three papers. Marcelo returned to his permanent position at the Universidade Federal de Minas Gerais (UFMG) in Belo Horizonte, Brazil after completing his 14-month sabbatical at CQT in March 2011.

Spontaneous emission is when a system suddenly spits out a photon, transferring to a lower energy state. In a typical qubit scheme, a higher-energy state encodes a '1' and a lower-energy state a '0'. This means that spontaneous emission flips a bit from 1 to 0. Repeated over many bits, this turns data into junk.

To get round this, the researchers proposed a three-level qubit scheme, in which photons from the two possible spontaneous emissions are indistinguishable. Clever ways of detecting these photons can protect the qubit and even implement logic gates. Experiments are planned.

"The sabbatical in CQT was the most productive year I have had in ages, and visiting my friends and collaborators in the Centre has become one of the greatest pleasures of my scientific and personal life," says Marcelo.

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Speed limit

CQT's Esther Hänggi and her collaborators at ETH Zurich in Switzerland discovered how to rule out rival explanations for experimental results interpreted as quantum. The work deals with 'non-local' correlations between systems — the coordinated behaviour of remote quantum systems that Einstein called "spooky action at a distance".

Quantum theory predicts that non-local correlations are instant, but because experiments can only be carried out over finite distances and measurements done with finite speed, they cannot test 'instantly' exactly. Instead, experiments set a limit on how quickly signals would have needed to travel for one system to have communicated with the other during the course of the experiment. This limit has already been pushed above light speed, the universal speed limit set by special relativity, but physicists would prefer to rule out the possibility of superluminal but finite-speed 'hidden' communication too.

Considering correlations between three parties, Esther and her collaborators find an example state that could rule out theoretically that finite-but-faster-than-light speed communication mediate non-local correlations. The catch is that the state is not quantum. They considered non-local correlations in general, and quantum physics represents a special set of such states.

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P. Rudolfsson, E. Sjoqvist
Quantum Information and Computation,12 119 , (2012)

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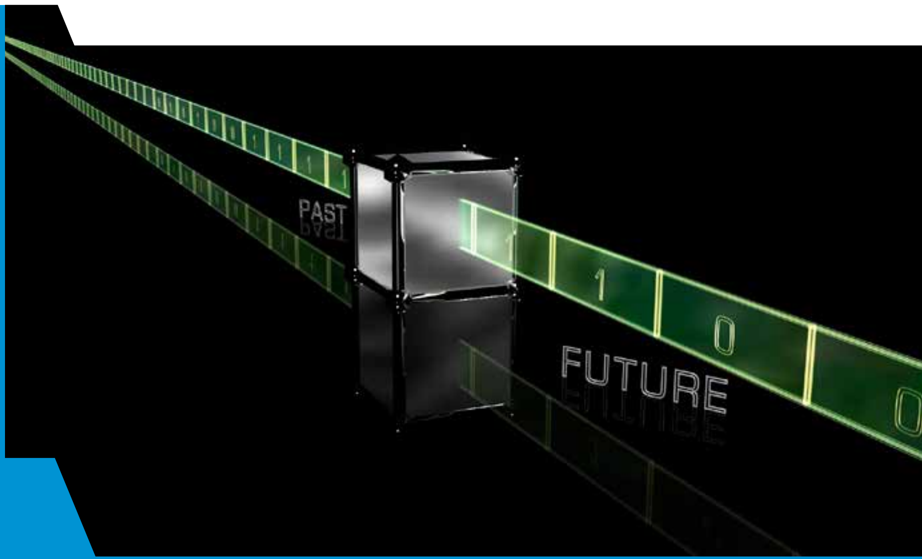

By analysing how much information is needed to predict the future, CQT researchers and their collaborators discovered that a Matrix-like simulation of reality would require less memory on a quantum computer than on a classical computer. Their work also hints at a way to investigate whether a deeper theory lies beneath quantum theory.

The researchers considered the simulation of 'stochastic' processes, where there are several possible outcomes to a given procedure, each occurring with a calculable probability. Many phenomena, from stock market movements to the diffusion of gases, can be modelled as stochastic processes. The amount of information transferred inherently in any stochastic process is known as the excess entropy. Theoretically, this sets the lowest amount of information needed to simulate the process. In reality, however, classical simulations of stochastic processes require more storage than this.

For a particular stochastic process — a perturbed coin — the researchers showed that a quantum simulation came closer to the ideal information-storage requirement than a classical simulation, but still had to store more information than the process would seem to need. That suggests quantum theory might not yet be optimised. "What's fascinating to us is that there is still a gap. It makes you think, maybe here's a way of thinking about a theory beyond quantum physics," says author and CQT PI Vlatko Vedral.

Quantum mechanics can reduce the complexity of classical models, M. Gu, K. Wiesner, E. Rieper and V. Vedral, Nature Commun., 3, 762 (2012)

How quantum physics could make the "matrix" more efficient

Why is the moon's behaviour different to that of a quantum particle? CQT PI Dagomir Kaszlikowski and his group came up with a new approach to explaining how the macroscopic classical world emerges from the strange quantum behaviour of its microscopic constituents.

Conventionally, quantum physicists point to 'decoherence' as the destroyer of quantum properties. The idea of decoherence is that interactions with the surroundings gradually wash the quantumness out of a system — a process that would happen much faster for a large object containing many interacting particles than for small systems.

"Interestingly, our explanation for how the classical world arises from the quantum world does not invoke decoherence or any of the other mechanisms proposed before," Dag wrote in a blog post about the work for the magazine *Scientific American*. Instead, his group argues, it comes down to what's observable statistically for large numbers of particles. They show that macroscopic variables are always 'local realistic' even when the underlying states have the quantum property of being non-local. Quantum non-locality disappears for objects big enough to contain roughly the Avogadro number of atoms — the number of atoms you'd expect in a few grams of matter.

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Nature Communications 3, 606, (2012)

The quantum cloud

Perfectly secure 'cloud' computing can be achieved with quantum computers, according to research by an international team including CQT Senior Research Fellow Joseph Fitzsimons.

The team built a quantum computer that performed computations for a client while remaining 'blind' to the data input, processing and output. This experiment was performed in Vienna, Austria, and implemented a scheme that Joe and his collaborators first described in 2009.

Blind quantum computing combines the power of quantum computing with the security of quantum cryptography. Quantum computers are expected to outperform classical computers on many tasks; quantum cryptography offers communication with security guaranteed by physics.

In the scheme, a user sends to a remote quantum computer (a server) data encoded in qubits and instructions for processing it. The server carries out the instructions, which describe measurements to perform on the qubits, and sends back the results, but the server cannot decipher the data or determine the net outcome of the calculation. The 'blindness' arises because the user tailors each instruction to the particular state of each qubit, which is only known by the user.

The experiment was performed with data encoded in photons. The researchers carried out two quantum algorithms, each using four qubits, in the blind way. They also individually demonstrated the required building blocks for implementing such blind computation on a larger scale.

The work was published in *Science* and highlighted there with a Perspective article. It also received widespread media coverage.

Demonstration of Blind Quantum Computing, Stefanie Barz, Elham Kashefi, Anne Broadbent, Joseph F. Fitzsimons, Anton Zeilinger, Philip Walther, Science 335, 303 (2012)

Seeing nuclei

Atomic force microscopes (AFMs) can already map the surface of materials atom by atom by detecting the distribution of electric charge, but even more could be learned from probes that can see the magnetic field of atom's nuclei. Measuring individual nuclear fields would more precisely locate atoms and help to distinguish one type of atom from another. Researchers at CQT and the University of Oxford, UK, proposed a device that could achieve the required sensitivity.

The proposed magnetic sensor consists of a diamond containing an NV centre attached to the tip of an atomic force microscope. NV centres are where a nitrogen atom appears in the diamond's carbon structure next to a missing carbon atom. Protected by the surrounding diamond, the NV centre has a long-lived quantum state that can be used to sense magnetic fields. Such sensors are in development.

The CQT–Oxford team came up with the idea to enhance the device's sensitivity: an 'amplifier' spin system sits on the surface of the diamond, where it is close to the target atoms. They calculate that the combined system is 100 to 1000 times more sensitive than the NV centre alone, and that the sensor could resolve the magnetic field of individual protons measured from a distance of one nanometer.

The paper in *Physical Review Letters* was highlighted as an "Editor's Suggestion" and featured in the online magazine *Physics*.

Proposed Spin Amplification for Magnetic Sensors Employing Crystal Defects, M. Schaffry, E. M. Gauger, J. J. L. Morton and S. C. Benjamin, Phys. Rev. Lett. 107, 207210 (2011)

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Australian National University

Sophie Laplante
Université Paris-Sud

Wayne Lawton
Mahidol University

Lay Nam Chang
Virginia Tech Blacksburg

Su-Yong Lee
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Gerd Leuchs
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Li Ke
NIST

Bo Li
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Nankai University

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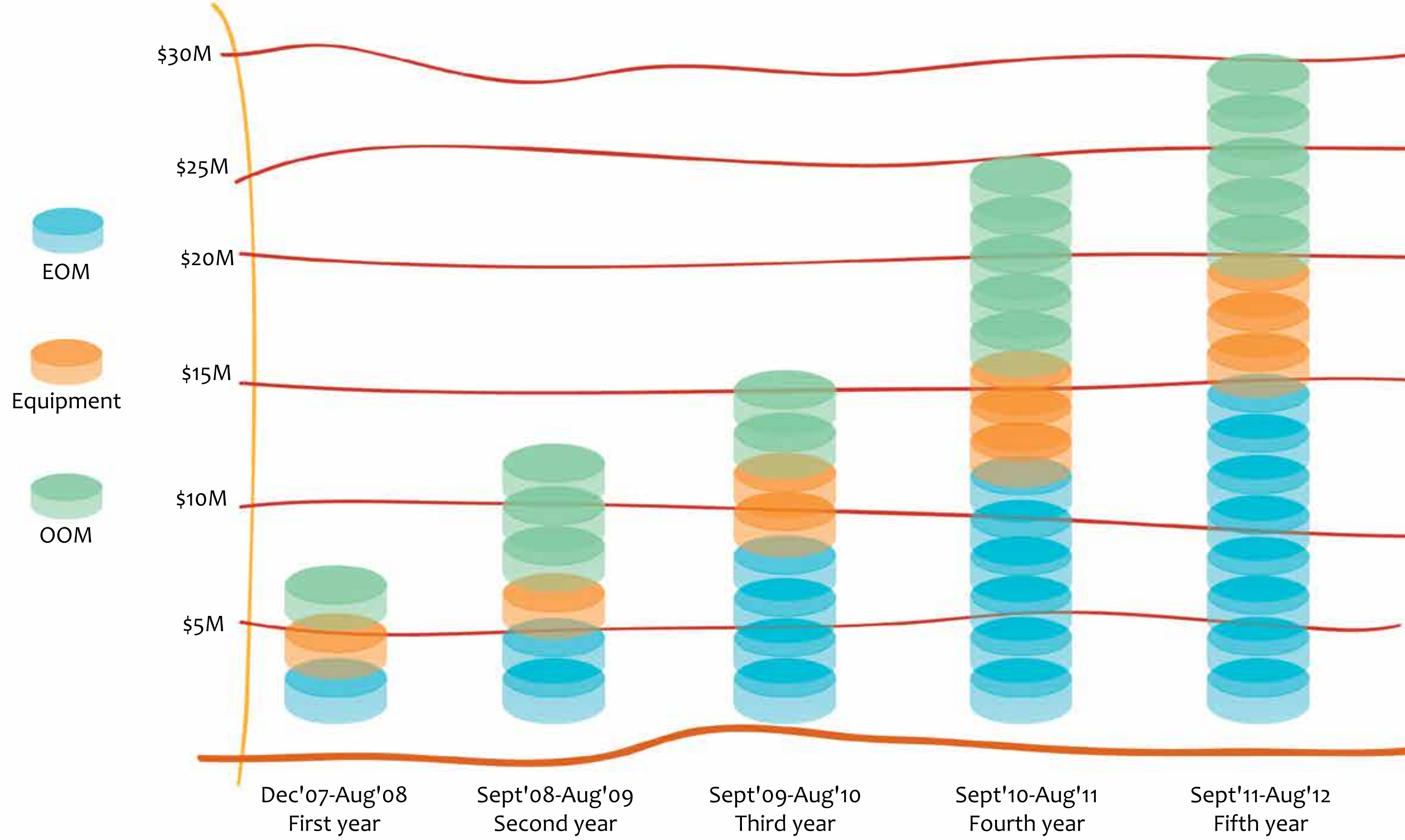
We spent some money



	Manpower (EOM)	Equipment	Other Operating Expenditure (OOM)	Total
Dec'07-Aug'08 First year	$2,717,874	$1,243,850	$1,457,913	$5,419,637
Sept'08-Aug'09 Second year	$5,662,020	$1,686,441	$8,624,033	$15,972,494
Sept'09-Aug'10 Third year	$8,041,992	$2,989,894	$7,577,791	$18,609,677
Sept'10-Aug'11 Fourth year	$11,020,884	$3,841,551	$10,242,831	$25,105,266
Sept'11-Aug'12 Fifth year	$14,080,766.76	$4,893,010	$11,455,527	$30,429,304
Total	$41,523,537	$14,654,746	$39,358,095	$95,536,378

We are supported by

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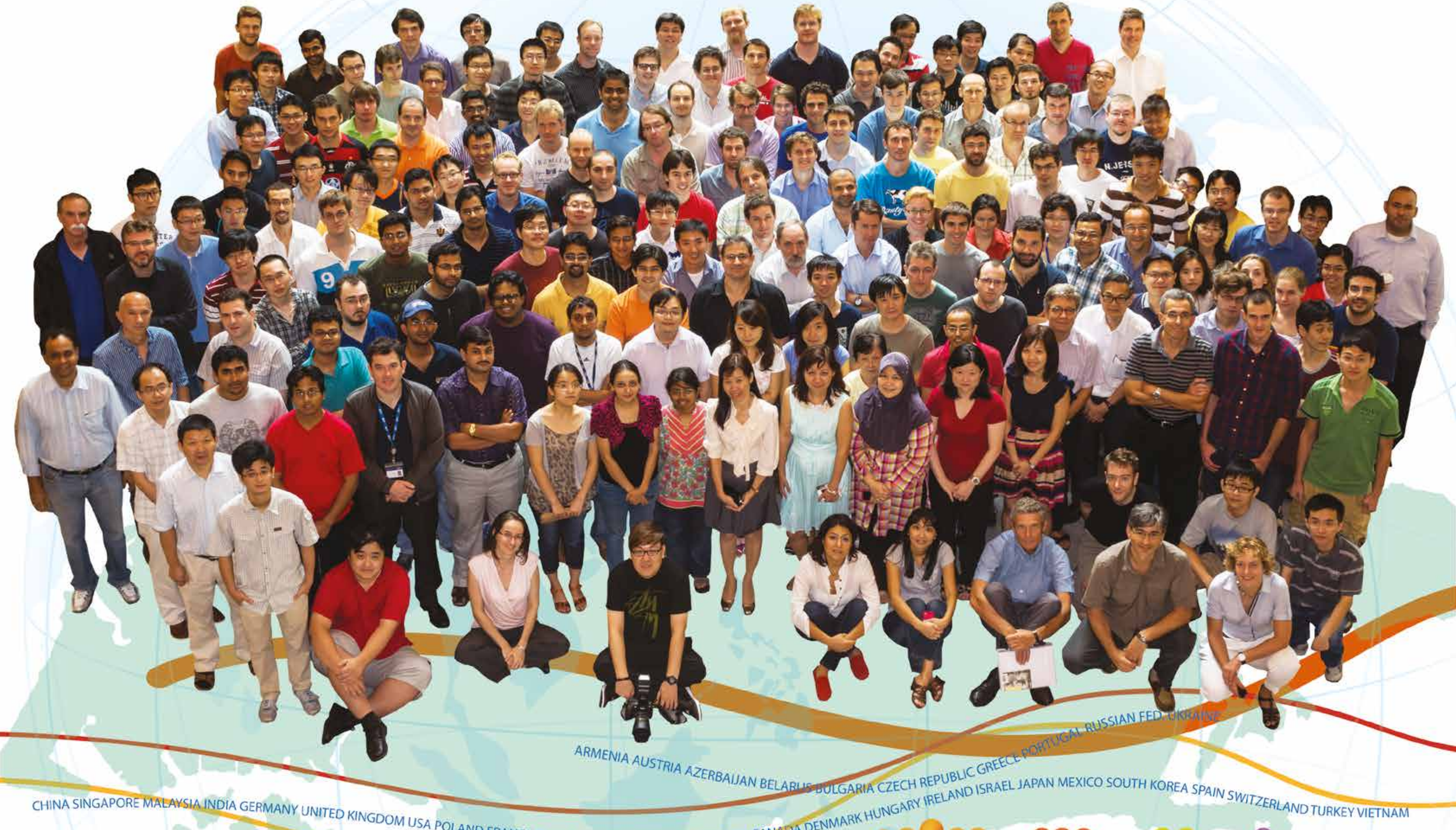
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CQTians


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23
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16
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10
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