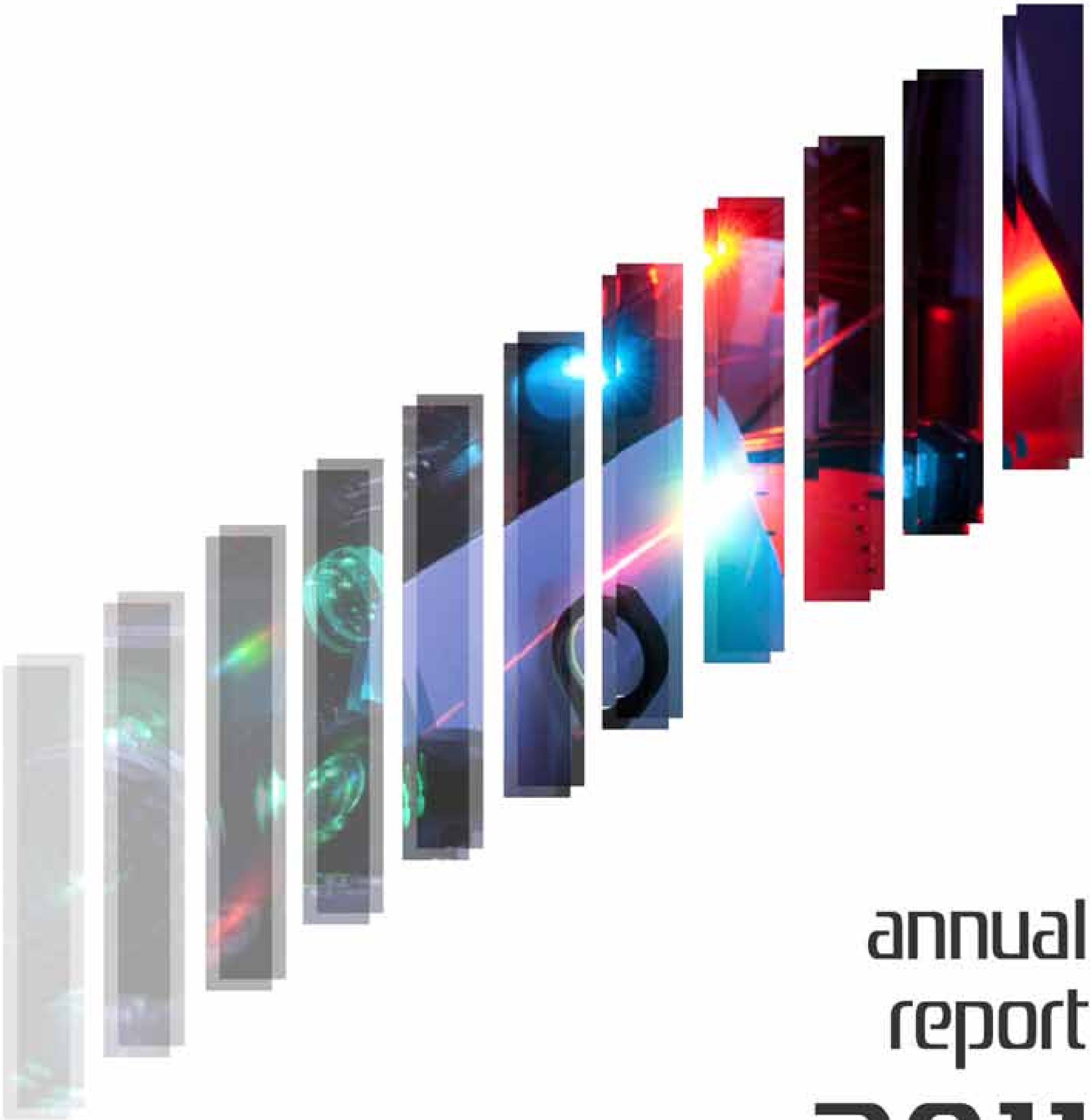
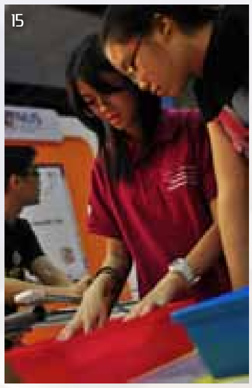
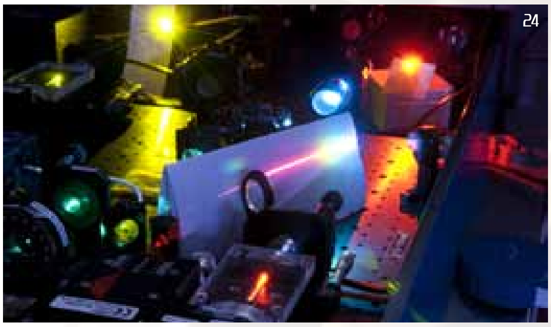
Centre for Quantum Technologies



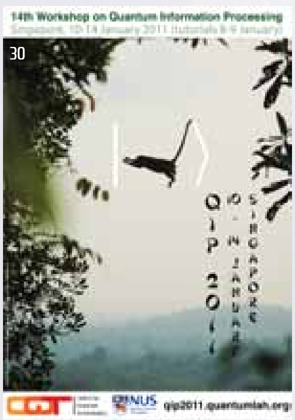
annual report 2011

Contents





▲ On the cover: the optical frequency comb installed in 2011 as a shared facility for CQT's experiments.



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Letter from the Director

No-one could ever say that running CQT is boring. Indeed, if I were to write down some of my daily conversations then, by now, I would have collected enough material for a sizeable best seller. It is amazing how many interesting and talented people we have, and I'm not only talking about their scientific reputations. Want to know the latest on climate change, lock picking, rebels in Bengal, 232-bar pillar valves for diving, or where to find "Hello Kitty" stuff in Taiwan? Do not bother to surf the web, just pop into our Quantum Cafe. Our 219 or so CQTians from 31 countries all over the world form an eclectic mix that is anything but dull. I am glad it is this way. But how do others perceive us?

This year we had the first external review of the Centre. The report of the International Review Panel (see p.16) is very encouraging. We seem to be internationally recognised for the quality of our research and for our truly cosmopolitan, egalitarian, and informal atmosphere. I am happy that the Centre is a place where authorities can be challenged and science is given priority over rules and regulations. Yes, we should be proud with what we have achieved in our first four years but, at the same time, we should put things into perspective and be aware that this is only the beginning. No research institution of any lasting impact and significance was ever established in four years. If we really want to succeed we have to give ourselves a few more years to consolidate, and consolidations are usually much harder than the initial build ups. But hey, we can do it! The first four years have demonstrated this very clearly; there is so much potential in our small community. So, let us buckle up and carry on.

Performance reviews aside, this was an eventful year. We hosted the massive conference QIP 2011 (see p. 30) and a number of excellent colloquia, public events, exhibitions, and school talks. There were days, especially soon after QIP, when the Quantum Cafe had probably the highest concentration of brainpower on the planet. We owe thanks to our Auntie Swee for her exemplary dedication to keeping the place clean, tidy and stocked with coffee to fuel the brains. Her daily efforts have made sure our premises always look presentable and welcoming to the various international delegations passing by.

On the domestic side, Christian and Valerio have been promoted to Professor with tenure at NUS, Kuldip was the recipient of the Commendation Medal (see p.15 for all the awards CQTians picked up this year), Dzmitry and Alex have finally moved into their newly refurbished labs, a frequency comb has been installed (see p. 24), and the sound of drilling and hammering has moved from the second to the sixth floor. As our science knows no borders, we have extended our research facilities to laboratories on the campus of the Nanyang Technological University (see p. 28), where Rainer and his team investigate interactions of superconducting microstructures with atoms.

Throughout the year, our research results filled the pages of many academic journals (see p. 48) and appeared in popular magazines and websites. Most recently a couple of new and pretty abstract ideas, cooked up by the theorists, have found their way to experimental labs. There can be no more joking that our experimentalists want to use our theorists in the same way a drunken man uses lamp-posts, that is, for support rather than illumination. It is such a promising sign. We'll be able to tell you more about this next year.

Many of our researchers and our outreach team, yet again, did an excellent job demonstrating to the world that quantum physics is relevant and that every literate person can appreciate its profound beauty. In the past year we hosted two artists-in-residence (see p. 32) who, inspired by the many world interpretation of quantum theory, turned an empty room into a temporary studio and set up an installation with references to multiple existences. Quantum theory is not exactly easy, but it has been demonstrated at CQT that even high school students can write an excellent textbook introducing the rudiments of quantum theory to their colleagues. To be sure, for this to happen it helps to have Valerio around (see p. 40).

Outreach is part of our mission and we take it very seriously, simply because it is important to explain to the taxpayers that without the curiosity-driven understanding of how atoms behave, how they interact with each other, and how they interact with light, the world we live in would be profoundly different. It is estimated that about 30 per cent of the US gross national product stems from inventions based on quantum physics, from lasers through microprocessors to mobile phones. It is becoming clear that quantum theory is no longer an esoteric topic to be learned in graduate school, but a necessity for many areas of research such as chemistry, communication technologies, engineering, and even biology. So, you see, never confuse quantum physicists with quants. We did not mess up the world, we improved it!

It is difficult to summarise the whole year in few pages but Evon, Daniel, and Jenny, who put this annual report together, managed to capture the essential bits. They have made it both informative and fun to read. I hope you will like it.

CQT people

Governing board

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Director, Singapore Cooperation Enterprise
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Max-Planck Institute of Quantum Optics

Atac Imamoglu
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Institute of Quantum Electronics
ETH Zurich

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University of Waterloo

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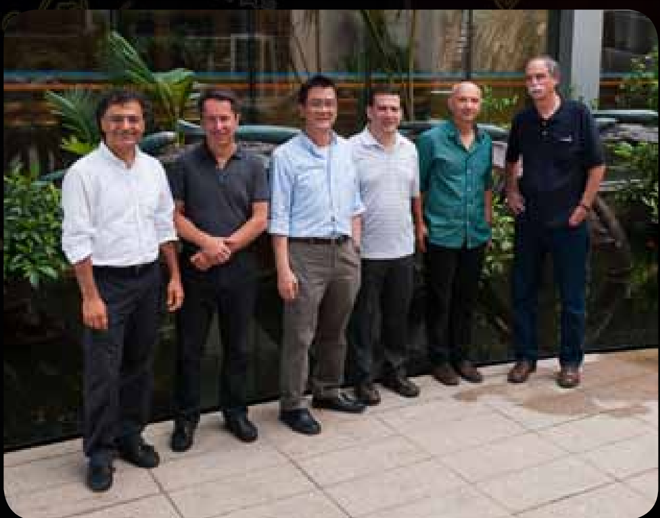
Computer Science Division, College of Engineering
UC Berkeley

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

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



Pictured from left to right are Umesh Vazirani, Ignacio Cirac, Lai Choy Heng, Michele Mosca, Artur Ekert, and Dave Wineland.

Principal Investigators

Computer science

Rahul JAIN

Rahul joined CQT as a PI and NUS as an Assistant Professor in 2008. He had just completed two postdoctoral fellowships: two years at the University of California, Berkeley, United States, followed by two years at the Institute for Quantum Computing at the University of Waterloo, Canada. He obtained his PhD in computer science from the Tata Institute of Fundamental Research, Mumbai, India, in 2003. Rahul's research interests are in the areas of information theory, quantum computation, cryptography, communication complexity, and computational complexity theory. He contributed to the proof that the two classes of mathematical problems QIP and PSPACE are equivalent, resolving a long-standing conjecture in complexity theory.

Hartmut KLAUCK

Hartmut received his PhD from the University of Frankfurt in Germany in 2000. He then held postdoctoral positions at the Centrum Wiskunde Informatica, Amsterdam, the Netherlands; the Institute for Advanced Study in Princeton, New Jersey, United States; and the University of Calgary, Canada, before joining the University of Frankfurt as a Junior Research Group Leader. In 2010 he joined CQT as a PI and Singapore's Nanyang Technological University as an Assistant Professor. His research interests include quantum information, communication complexity, and computational complexity.

Miklos SANTHA

Miklos joined CQT as a Visiting Research Professor in 2008, in charge of building up the Centre's computer science component. Miklos was born and educated in Budapest, Hungary, and moved to Paris, France, in 1980 to earn a PhD in mathematics. To satisfy his growing interest in computer science, he spent two years at the University of California, Berkeley, United States, and then obtained a Doctorat d'Etat in this field from the Université Paris-Sud, Orsay in 1988. Since 1988 he has been employed by France's Centre National de la Recherche Scientifique, and he is currently head of the Algorithms and Complexity Division of the Laboratoire d'Informatique Algorithmique: Fondements et Applications at the University Paris Diderot. His research interests include quantum computing, randomised algorithms, and complexity theory.

Group Members (led collectively by Rahul, Hartmut, and Miklos)

Senior Research Fellows: Joseph Fitzsimons, Troy Jeffrey Lee. Research Fellows: Thomas Decker, Carlos Antonio Perez Delgado, Matthew Edmund Mckague, Sarvagya Upadhyay. PhD Students: Attila Pereszlenyi, Supartha Podder, Ved Prakash, Penghui Yao. Visiting Research Professor: Mario Szegedy. Visiting Senior Research Fellow: Peter Li Hoyer. Visiting Scholars: Gábor Ivanyos, Iordanis Kerenidis, Ashwin Nayak, Zhang Shengyu.

Stephanie WEHNER

Stephanie came to Singapore in 2010, joining CQT as a PI and NUS as an Assistant Professor. Prior to this, she was a postdoctoral scholar at the California Institute of Technology in Pasadena, United States. Born in Germany, Stephanie moved to the Netherlands in 1997 to work on the practical security of networked systems. Following her growing interest in quantum physics, she obtained her PhD in quantum information in 2008 from the University of Amsterdam. One of her contributions is to show that imperfections in quantum memories, usually regarded as an obstacle, are in fact very useful for cryptography. Her current research interests include quantum correlations, cryptography, and quantum information theory.

Group Member

Research Fellow: Esther Hanggi. Graduate Students: Md. Tanvirul Islam, Corsin Pfister. Honours Student: Nelly Ng Huei Ying. Intern: Deepthi Gopal. Visiting Senior Research Fellow: Fernando Brandao.

Murray BARRETT

Murray joined NUS in 2006. He is an Assistant Professor and has been a PI at CQT since the Centre's founding. Murray received his PhD from the Georgia Institute of Technology in Atlanta, United States, in 2002. His PhD work resulted in the first ever production of a BEC by pure optical means. He then spent two years in Dave Wineland's group at the National Institute of Standards and Technology in Boulder, Colorado, United States, as a postdoc. This work resulted in a number of important demonstrations of entanglement engineering and manipulation, including the first demonstration of teleportation using atomic qubits. He is currently working on integrating micro-traps and cavity QED for quantum information applications.

Group Members

PhD Students: Kyle Arnold, Markus Baden, Nick Lewty. Research Assistants: Andrew Bah Shen Jing, Chuah Boon Leng, Low Lerh Feng, Arpan Roy.

Kai DIECKMANN

Kai started settling in Singapore in 2009, joining CQT as a PI and NUS as a tenured Associate Professor. From 2003, he had been working in Germany in the group of Theodor W. Hänsch at the University of Munich and the Max-Planck Institute for Quantum Optics, Garching, where he began his own research project. He brought to Singapore his experiment on mixed ultra-cold Fermi gases and has started a project to realize fermionic quantum gases in optical lattices. Earlier in his career, Kai obtained his doctoral degree as a Marie Curie fellow at the Institute for Atomic and Molecular Physics in Amsterdam, the Netherlands in 2001. He then joined the group of Wolfgang Ketterle as a postdoctoral fellow at the Massachusetts Institute of Technology in the United States.

Group Members

Research Fellows: Johannes Tomas Gambari, Kanhaiya Pandey, Jimmy Sebastian. PhD Students: Christian Gross, Lam Mun Choong Mark, Sambit Bikas Pal. Research Assistants: Tarun Johri, Thong May Han.

Rainer DUMKE

Rainer is based with his experiments on the campus of the Nanyang Technological University (NTU). He joined CQT as a PI in 2011. His research interests include superconducting atom chips, neutral atom registers and atom interferometry. Rainer started as an Assistant Professor at NTU in 2006. Previously he had worked for one year at the Max Planck research group in Erlangen, Germany, on an indium optical clock, and for two years in the United States at the National Institute of Standards and Technology in Gaithersburg, Maryland, on ultracold molecules with a Feodor Lynn fellowship. Rainer completed his doctorate in 2003 in Hanover, Germany.

Group Members

Research Fellows: Rachele Fermani, Tobias Muller, Mirco Siercke, Zhang Bo. Research Assistants: Mussie Thomas Beian, Oon Fong En.

Björn HESSMO

Björn joined CQT as a PI in 2009 to lead experimental activity on microtraps for neutral atoms. Prior to arriving at CQT, Björn had worked at the Technical University of Vienna, Austria, on atom chips and photonics and at the University of Heidelberg in Germany as a Marie Curie fellow on experimental cold atom physics. He had also been an Assistant Professor at the Royal Institute of Technology in Stockholm. He earned his doctorate in quantum chemistry from Uppsala University, Sweden, in 2000. Bjorn is also an Assistant Professor at NUS.

Group Members

Senior Research Fellow: Joakim Andersson. Research Fellows: Paul Constantine Condylis, Zeynep Nilhan Gurkan, Daniel Sahagun Sanchez. PhD Students: Ritayan Roy, Yik Jinen Johnathan. Research Associate: Aarthi Lavanya Dhanapaul. Research Assistant: Sivakumar s/o Maniam.

Christian KURTSIEFER

Christian led the development of experimental quantum optics in Singapore after joining NUS in 2003. He became a PI at CQT when the Centre was founded in 2007, won Singapore's National Science Award in 2008, and was made a Professor at NUS in 2010. Prior to moving to the equator, Christian worked at the IBM Almaden Research Center in San Jose, California, United States, and the Ludwigs-Maximilians-Universität München in Germany, where he constructed one of the world's best sources of entangled photon. Now the quantum optics group at CQT hosts one of the world's best entangled sources. Christian earned his PhD from the University of Konstanz, Germany in 1997.

Group Members

Senior Research Fellow: Gleb Maslennikov. PhD Students: Syed Abdullah Aljunid, Gurpreet Kaur Gulati, Hou Shun Poh, Siddarth Joshi, Ng Tien Tjuen, Bharath Srivathsan. Research Assistants: Chia Chen Ming, Chng Mei Yuen Brenda, Dao Hoang Lan, Kadir Durak, Tan Peng Kian. Visiting Research Associate Professor: Antia Lamas-Linares. Visiting Scholar: Charles Clark.

Wenhui LI

Born and educated in China, Wenhui worked on experiments with cold Rydberg atoms during her PhD studies at the University of Virginia, United States. After receiving her doctoral degree in 2005, she moved to Randy Hulet's group at Rice University in Houston, Texas, United States, to work on degenerate Fermi gases. She joined CQT as a PI and NUS as an Assistant Professor in 2008. Her current research interests include cold fermionic atoms and cold Rydberg atoms in optical lattices, which are the focus of two experimental laboratories at CQT.

Group Members

Research Assistant: Wang Yibo. PhD Student: Manukumara Manjappa.

Alexander LING

Alex was appointed a PI at CQT and an Assistant Professor at NUS in 2011. He graduated with a PhD in Physics from NUS in 2008. He then moved to the United States to work in the group of Alan Migdall at the National Institute of Standards and Technology in Gaithersburg, Maryland as a postdoc. In July 2010 he returned to join CQT, initially as a Senior Research Fellow. Alex has a background in quantum optics and has previously worked on a wide variety of experiments involving entangled photon generation and manipulation, including quantum key distribution and photonic interfaces with quantum dots. He is looking forward to continuing research work on compact and ultra-bright sources of single photons.

Group Member

Research Fellow: Guo Ruixiang. Research Assistants: William Morong, Subash Ghattadahalli Sachidananda, Tan Yue Chuan. Intern: Rakhitha Chandrasekara.

Dzmitry MATSUKEVICH

A PI at CQT and Assistant Professor at NUS since 2010, Dzmitry is originally from Minsk, Belarus. He received his PhD in 2006 from the Georgia Institute of Technology in Atlanta, Georgia, United States. His graduate research in the group of Alex Kuzmich involved quantum networks with atomic ensembles. He then moved in the US to the University of Michigan in Ann Arbor and later to the University of Maryland in College Park and its Joint Quantum Institute to work in the group of Christopher Monroe. His research interests include quantum optics and trapped ions.

Group Members

PhD Students: Shiqian Ding, Gao Meng.

Dimitris G. ANGELAKIS

Dimitris joined CQT in 2007 initially as a Visiting Assistant Professor and as a PI in 2010. He also holds a tenure position at the Technical University of Crete in Greece. Born and educated in Crete, Dimitris received his PhD in theoretical quantum optics in 2001 from Imperial College, then worked at the University of Cambridge, UK, until moving to Greece in 2008. His research interests lie at the interface of quantum optics, quantum computation and condensed matter physics with an emphasis in photonic quantum simulators, a field which he cofounded in 2007. He was awarded the Valerie Myescrough Prize from the University of London in 2000 and the Quantum Electronics and Photonics Thesis Prize from the UK's Institute of Physics in 2002.

Group Members

Research Fellows: Blas Manuel Rodriguez Lara, Noh Chang Suk, Amit Rai. PhD Student: Huo Mingxia.

Berthold-Georg ENGLERT

Born and educated in Germany, Berge was a postdoc at the University of California, Los Angeles, United States, after receiving his doctorate in 1981. He taught at the University of Munich, Germany, from 1985 to 1995. Berge was then a “physicist at large” until arriving at NUS in 2002, becoming a professor six months later. Berge has made contributions to semiclassical atomic physics, quantum optics, the foundations of quantum physics, and quantum information. His early work on the semiclassical theory of many-fermion systems finds a continuation in his research on ultra-cold atomic fermion gases. He won Singapore’s National Science Award in 2006 and was appointed the NUS Provost Chair in Science for 2009-2012.

Group Members

Research Fellows: Krzysztof Gawryluk, Agnieszka Gorecka, Amir Kalev, Tomasz Karpiuk, Lee Kean Loon, Ng Hui Khoon, Philippe Raynal. PhD Students: Arun, Jibo Dai, Han Rui, Yu-Xin Hu, XiKun Li, Jiangwei Shang, Guangquan Wang, Marta Wolak, Lu Yin. Research Assistant: Len Yink Loong. Visiting Research Professor: George Batrouni.

Dagomir KASZLIKOWSKI

Soon after he received his doctoral degree from the University of Gdansk, Poland, Dagomir joined NUS. That was in 2001. He became a key player in establishing research in quantum theory in Singapore, winning Singapore's National Science Award in 2006. He joined CQT when it was founded in 2007 and was made an Associate Professor in 2009. His research interests are in the foundations of quantum theory and the properties of entanglement, in particular in many-body systems. He contributed to the discovery of “information causality” as a possible underlying principle of quantum mechanics.

Group Members

Research Fellows: Jayendra Nath Bandyopadhyay, Pawel Krzysztof Kurzynski, Tomasz Paterek, Akihito Soeda. PhD Students: Ravishankar Ramanathan, Bobby Tan.

KWEK Leong Chuan

Born and bred in Singapore, Kwek helped initiate research in quantum information in the city-state. As well as being a PI at CQT, he holds two posts at Singapore’s Nanyang Technological University: Deputy Director (Physical Sciences) of the Institute of Advanced Studies and Associate Professor at the National Institute of Education. Kwek was a teacher for eight years before pursuing his doctoral degree at NUS, which he completed in 1999. His current research interests include the foundations of quantum theory and distributed quantum computing. He won Singapore’s National Science Award in 2006. He is also an elected Fellow of the American Association for the Advancement of Science and the Institute of Physics, UK.

Group Members

Senior Research Fellow: Janus Hallelov Wesenberg. Research Fellows: Joonwoo Bae, Hugo Vaughan Cable, Elica Sotirova Kyoseva, Wei Zhaohui. PhD Students: Mingxia Huo, Li Ying, Davit Aghamalyan. Research Assistants: Cui Jian, Dai Li, Lee Chee Kong, Lim Chin Chean. Visiting Research Assoc. Professor: Simon Benjamin.

OH Choo Hiap

Born in Sabah, Malaysia, Choo Hiap was selected under the Colombo Plan to study in New Zealand, where he completed his PhD in 1972. He served at the University of Science of Malaysia from 1972 and joined NUS in 1983. He started his career as a theoretical physicist, specialising in the Yang-Mills gauge fields, particle phenomenology, and integrable models. As the Head of the Physics Department at NUS from 2000 to 2006, he recruited a number of researchers in the field of quantum information who subsequently contributed to forming CQT. In 2006, he received Singapore's National Science Award.

Group Members
Senior Research Fellow: Yu Sixia. Research Fellows: Chen Qing, Lu Xiaoming, Qian Jun, Wu Chunfeng, Zhang Chengjie. PhD Students: Feng Mei, Jiabin You, Liew Ding Yuan. Research Assistants: Huang Jinsong, Su Hongyi, Tong Qingjun, Wang Zhuo, Yang Dabao. Visiting Senior Research Fellows: Chen Jingling, Feng Xun-Li. Visiting Research Fellows: An Junhong, Sun Hui, Yang Wanli, Yi Xuexi, Zhang Qi.

Valerio SCARANI

Valerio joined CQT in 2007 and is a Professor at NUS. He received his PhD in 2000 from Ecole Polytechnique Federale de Lausanne, Switzerland, for experimental research in nanoscience, after which he worked as a theorist in the group of Nicolas Gisin at the University of Geneva, Switzerland. Valerio's research spans from pretty abstract topics in quantum correlations to theoretical assessment of very real experiments. Among his many contributions to outreach, he has written two books, one for a popular audience and the other a textbook for school students. In 2008, he won Singapore's National Science Award.

Group Members
Research Fellows: Jiri Minar, Lana Susan Sheridan. PhD Students: Yimin Wang, Tzyh Haur Yang, Rafael Rabelo, Colin Teo, Le Phuc Thinh, Cai Yu. Research Assistants: Haw Jing Yan, Ho Hui Kiat Melvyn.

Vlatko VEDRAL

Vlatko divides his time between Singapore, where he is a PI at CQT and Professor at NUS, and the UK, where he holds an appointment at the University of Oxford. He obtained his undergraduate and doctoral degrees from Imperial College London, UK, and became a Professor at the University of Leeds, UK, in 2004. Vlatko has made fundamental contributions to the understanding of quantum correlations and their use in information processing. His many awards include the UK's Royal Society Wolfson Research Merit Award in 2007. He has also been active in outreach events, participating in radio and tv shows and writing for newspapers. In 2010, he published a popular book: "Decoding Reality: The Universe as Quantum Information".

Group Members
Research Fellows: Martin Aulbach, Agata Checinska, Oscar Carl Olof Dahlsten, Tristan Farrow, Mile Gu, Libby Heaney, Ho Shen Yong, Kavan Kishore Modi, Mark Simon Williamson, Wonmin Son. PhD Students: Elisabeth Rieper, Giovanni Vacanti. Visiting Senior Research Professor: Rosario Fazio.

Andreas WINTER

Andreas joined CQT as a Visiting Research Professor in 2007. He is also a Professor in Mathematics at the University of Bristol, UK. Andreas joined the University of Bristol after receiving his PhD in mathematics from the University of Bielefeld, Germany, in 1999. He was first a postdoctoral researcher in the Department of Computer Science and then a lecturer in Mathematics before taking up his current post. His research interests cover quantum information theory, discrete mathematics, and statistical physics.

Group Members
Senior Research Fellow: Markus Grassl. Research Fellows: Mafalda Ludovino Almeida, Cedric Beny, Alexandre Monras Blasi, Julien David Degorre, Li Ke, Milan Mosonyi, Ciara Ann Morgan, Angie Qarry, William Henry Rosgen. Visiting Research Associate Professor: Masahito Hayashi. Visiting Research Fellow: Chen Lin.

Exploratory initiatives

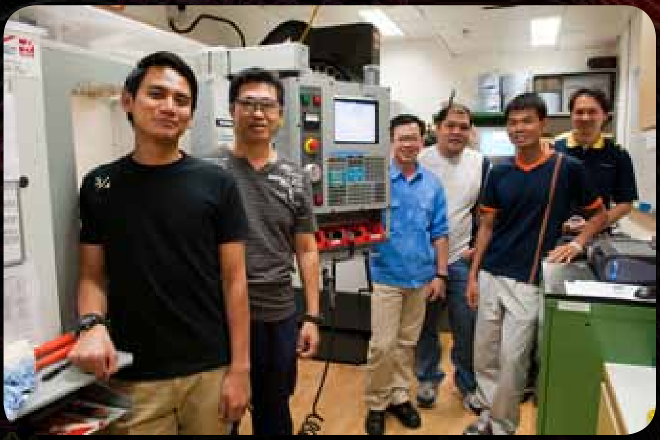
Visiting Research Prof
John Carlos Baez
Giulio Casati
Dieter Hans Jaksch
Erik Torbjorn Sjoqvist

Visiting Research Assoc Prof
David Paul Maxime Wilkowski

Visiting Senior Research Fellow
Tong Dianmin

Research Fellows
Stephen Richard James Franz Clark
Uwe Dorner
Erik Manuel Gauger
Jin Xianmin
Alastair Stuart Kay
Daniel Cavalcanti Santos
Jamie Vicary

Research Assistant
Elnur Hajiyev



Research support

Electronics Workshop Manager
Gan Eng Swee

Mechanical Workshop Manager
Chia Zhi Neng Bob

Mechanical Designer
Yau Yong Sean

Research Engineer
Vladimir Akimov

Research Laboratory Assistant
Kwek Boon Leng Joven

Laboratory Technologists
Mohd Imran Bin Abdol Raman
Lian Chorng Wang
Teo Kok Seng

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Procurement Manager
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Procurement Executive
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Procurement Executive
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Valerie Hoon

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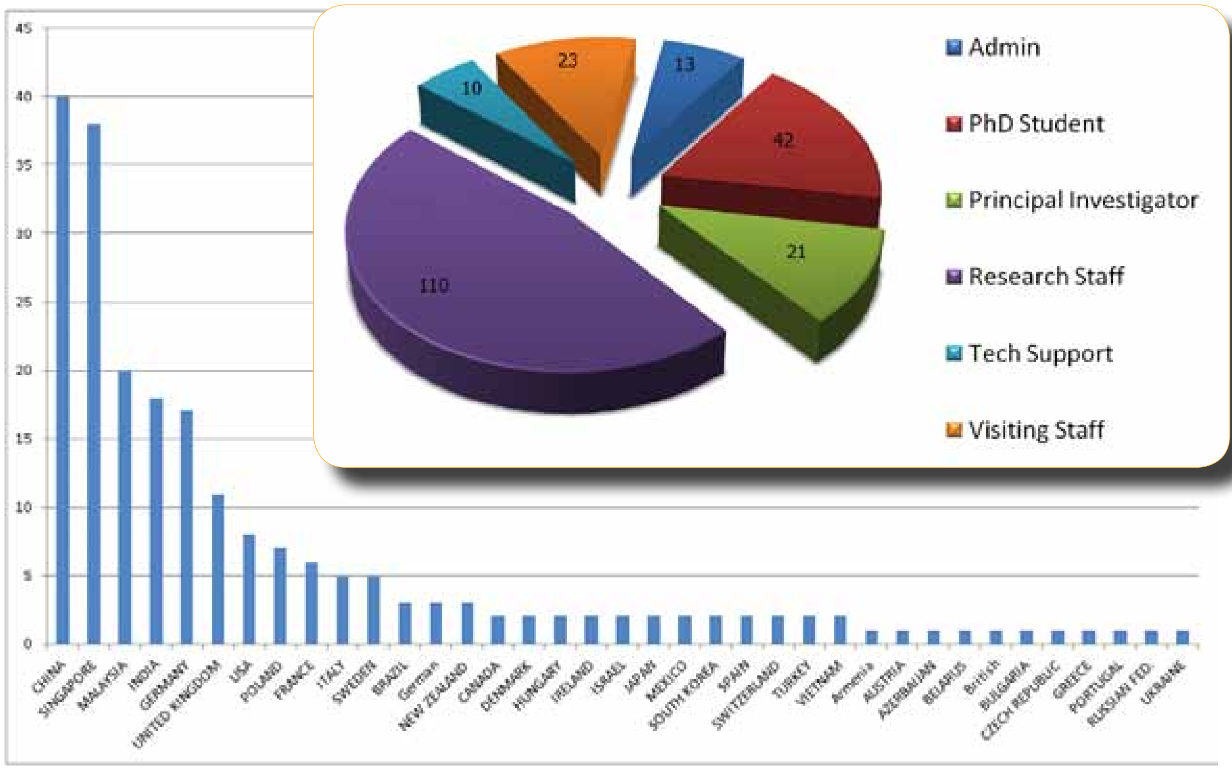
Tan Ai Leng, Irene

Outreach & Media Relations Manager
Jenny Hogan

IT Manager
Darwin Gosal

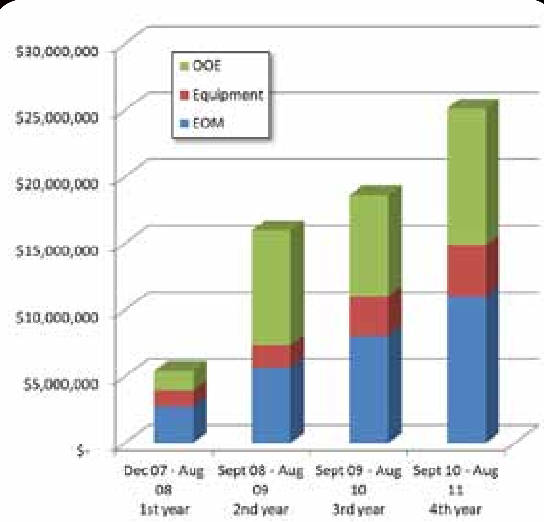
IT Analyst
Lim Jeanbean Ethan

CQT in numbers



Expenditure

Timeline	Manpower (EOM)	Equipment	Other Operating Expediture (OOE)	Total
Dec 07 - Aug 08 1st year	$2,717,874	$1,243,850	$1,457,913	$5,419,637
Sept 08 - Aug 09 2nd year	$5,662,020	$1,686,441	$8,624,033	$15,972,494
Sept 09 - Aug 10 3rd year	$8,041,992	$2,989,894	$7,577,791	$18,609,677
Sept 10 - Aug 11 4th year	$11,020,884	$3,841,551	$10,242,831	$25,105,266
Total	$27,442,770	$9,761,736	$27,902,568	$65,107,074



CQT Support

The Centre for Quantum Technologies is funded by

National Research Foundation

Ministry of Education SINGAPORE

We are hosted by

NUS National University of Singapore

Some of our projects are also supported by

Agency for Science, Technology and Research SINGAPORE

DSO National Laboratories

cnrs dépasser les frontières

Nanyang Technological University

DSTA Defence Science & Technology Agency

Partner Institutions

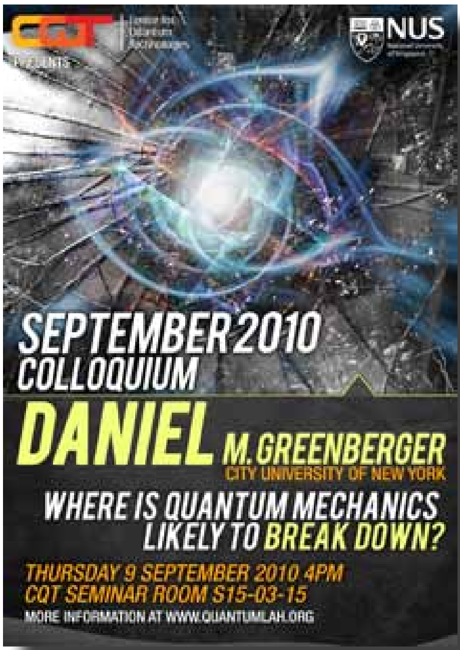
Australian National University
University of New South Wales
Institute of Quantum Computing, University of Waterloo
Centre National de la Recherche Scientifique (CNRS)
Ecole Normale Supérieure de Paris
Institut d'Optique Graduate School
Université de Nice Sophia Antipolis
Université Paris 11
Université Paris Diderot
Université Pierre et Marie Curie
University of Ulm

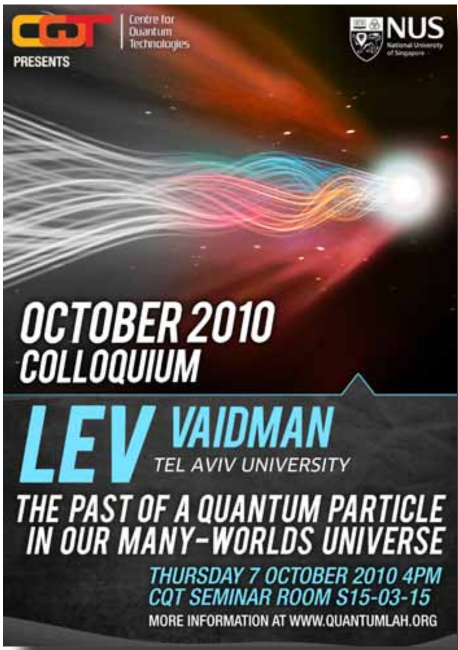
Calendar of events

09-Sep-10	**Colloquium:** Where is Quantum Mechanics Likely to Break Down? Daniel M. Greenberger, City University of New York
07-Oct-10	**Colloquium:** The past of a quantum particle in our many-worlds universe. Lev Vaidman, Tel Aviv University
29-Oct-10	**School Event:** Seminar for JC Teachers
01-Dec-10	**School Event:** Talk by Lana Sheridan on Quantum Cryptography at Nanyang Polytechnic
07-Dec-10	**Colloquium:** CQT Annual Symposium - The Famous, The Bit and The Quantum. Martin Plenio and Mario Szegedy
8-14 Jan-11	**Conference:** The 14th Workshop on Quantum Information Processing — QIP 2011
12-Jan-11	**Public Event:** Talk "Information is Quantum: How physics has helped us understand what information is and what can be done with it" by Charles H. Bennett of IBM Research USA
09-Feb-11	**Colloquium:** Random numbers certified by Bell's Theorem. Antonio Acin, ICFO, Barcelona (Spain)
10-Feb-11	**Colloquium:** Integrated Quantum Photonics. Jeremy O'Brien, University of Bristol
18-Feb-11	**School Event:** Talk by Valerio Scarani at SMJK Heng Ee, Penang, Malaysia
25-Feb-11	**School Event:** Talk by Valerio Scarani "The challenge of Six quantum pieces" in Physics Education seminar, NUS High School
11-Mar-11	**School Event:** Talk by Valerio Scarani at Nanyang Polytechnic
24-Mar-11	**Colloquium:** Dipole-Dipole Interactions in the Frozen Rydberg Gas. Tom Gallagher, University of Virginia, USA
25-Mar-11	**Public Event:** Exhibition at NUS Faculty of Science Open House
9-May - 01-Jul-11	**Public Event:** Artist-in-residence with artists Linda Sim and Dario Lombardi
25-28 May-11	**Workshop:** The 5th Asia-Pacific Workshop on Quantum Information Science
26-May-11	**Colloquium:** Is smell a quantum sense? Luca Turin, BSRC Fleming, Vari, Greece
22-24 Jul-11	**Public Event:** Exhibition at Xperiment 2011, at Suntec Convention Hall
23-Jul-11	**Public Event:** Talk "A first meeting with Bell's experiments: welcome to the wonderful world of quantum physics" by Valerio Scarani at the Singapore Science Festival
29-Jul-11	**Colloquium:** Anderson Localization – looking forward. Boris Altshuler, Columbia University, USA
11-Aug-11	**Colloquium:** Spinor- and Rydberg- Polaritons. Michael Fleischhauer, Universität Kaiserslautern, Germany
12-Aug-11	**School Event:** Talk "From Optics to Quantum Theory" by Kwek Leong Chuan at Deyi Sec School

Visits

28-Sep-10	Charles Day, Senior Editor of Physics Today
08-Oct-10	Pekka Sinervo, Canadian Institute for Advanced Research
08-Oct-10	Sergio M. Alcocer and delegates, Universidad Nacional Autonoma de Mexico
14-Oct-10	Andreas Hemmerich
19-Oct-10	Rivka Carmi and oti Hershkovits, Ben-Gurion University of the Negev (Israel)
05-Jan-11	MOE Academic Research Council
17-Jan-11	Michael Mandelberg, IARPA
02-Feb-11	US Delegation from ASD (R&E), US DoD
17-Feb-11	Gersh "Zvi" Taicher, EchoMedical Systems
15-Mar-11	Quek Tong Boon, MINDEF CDS
31-Mar-11	Delegation from Thurgood Marshall College Fund
9 June-11	Visit by Hwa Chong Students
21-Jul-11	Emmanuel Tsesmelis, CERN


NUS
SEPTEMBER 2010
COLLOQUIUM
DANIEL M.GREENBERGER
CITY UNIVERSITY OF NEW YORK
WHERE IS QUANTUM MECHANICS
LIKELY TO BREAK DOWN?
THURSDAY 9 SEPTEMBER 2010 4PM
CQT SEMINAR ROOM S15-03-15
MORE INFORMATION AT WWW.QUANTUMLAH.ORG


PRESENTS
NUS
OCTOBER 2010
COLLOQUIUM
LEV VAIDMAN
TEL AVIV UNIVERSITY
THE PAST OF A QUANTUM PARTICLE
IN OUR MANY-WORLDS UNIVERSE
THURSDAY 7 OCTOBER 2010 4PM
CQT SEMINAR ROOM S15-03-15
MORE INFORMATION AT WWW.QUANTUMLAH.ORG


NUS
MARTIN Plenio 4PM
Quantum mechanics and noise in biology
MARIO Szegedy 5PM
When local constraints have a global effect
CQT SYMPOSIUM
THE FAMOUS, THE BIT AND THE QUANTUM
TUESDAY, 7 DECEMBER 2010, 4PM
VENUE : NUS KENT RIDGE CAMPUS, UNIVERSITY HALL AUDITORIUM, LEE KONG CHIAN WING
MORE INFORMATION: WWW.QUANTUMLAH.ORG


PRESENTS
NUS
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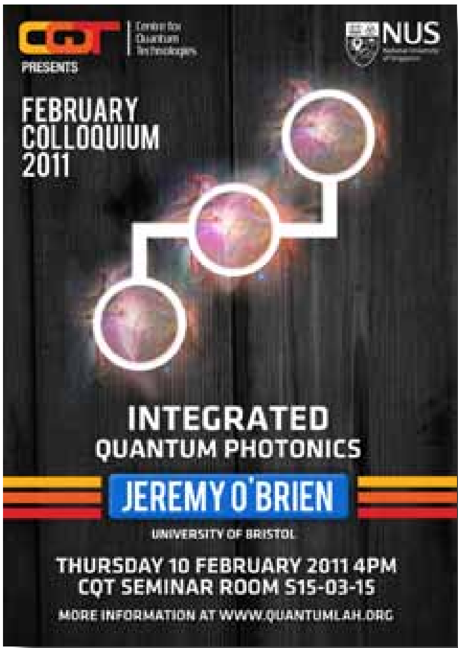
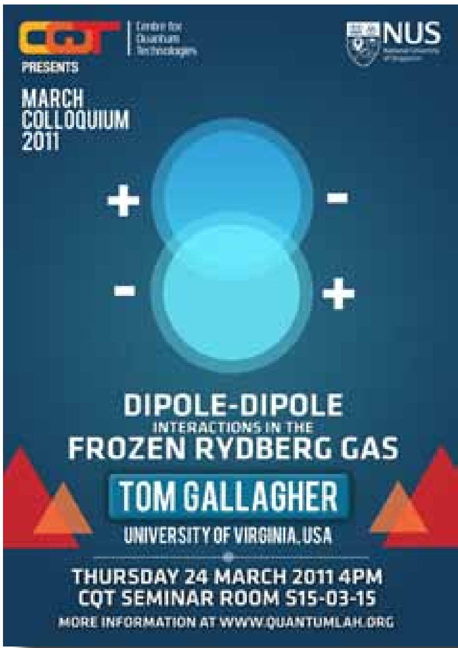
COLLOQUIUM
BELL'S THEOREM
CERTIFIED
7538
RANDOM NUMBERS CERTIFIED
BY BELL'S THEOREM
ANTONIO ACIN
ICFO-THE INSTITUTE OF PHOTONIC SCIENCES - BARCELONA (SPAIN)
WEDNESDAY 9 FEBRUARY 2011 4PM
CQT SEMINAR ROOM S15-03-15
MORE INFORMATION AT WWW.QUANTUMLAH.ORG


PRESENTS
NUS
FEBRUARY
COLLOQUIUM
2011
INTEGRATED
QUANTUM PHOTONICS
JEREMY O'BRIEN
UNIVERSITY OF BRISTOL
THURSDAY 10 FEBRUARY 2011 4PM
CQT SEMINAR ROOM S15-03-15
MORE INFORMATION AT WWW.QUANTUMLAH.ORG


PRESENTS
NUS
MARCH
COLLOQUIUM
2011
DIPOLE-DIPOLE
INTERACTIONS IN THE
FROZEN RYDBERG GAS
TOM GALLAGHER
UNIVERSITY OF VIRGINIA, USA
THURSDAY 24 MARCH 2011 4PM
CQT SEMINAR ROOM S15-03-15
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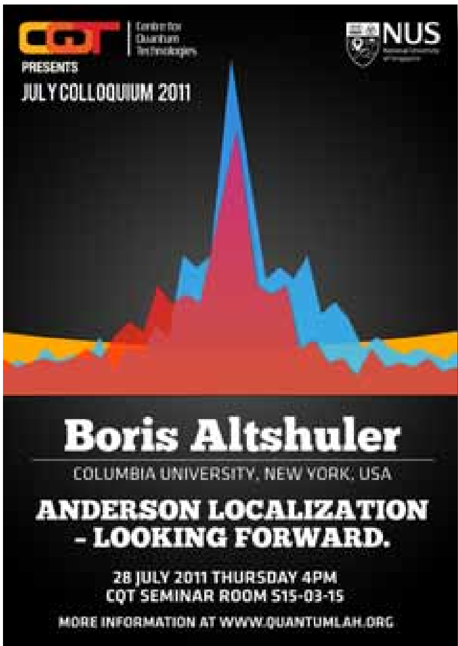
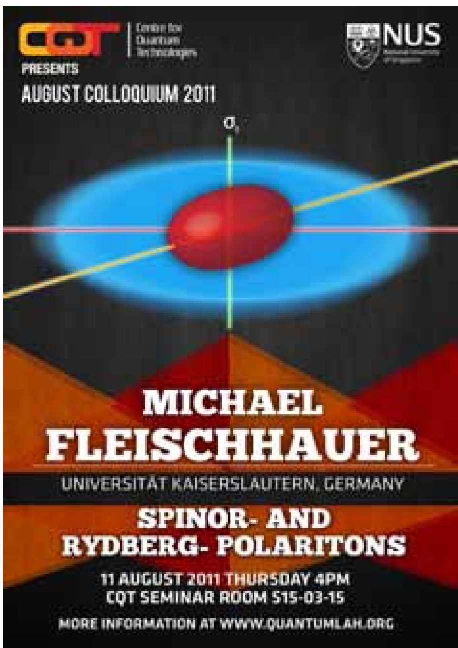
PRESENTS
NUS
MAY COLLOQUIUM 2011
LUCA TURIN
BSRC FLEMING INSTITUTE, VARI, GREECE
Is smell a quantum sense?
26 MAY 2011 THURSDAY 4PM
CQT SEMINAR ROOM S15-03-15
MORE INFORMATION AT WWW.QUANTUMLAH.ORG


PRESENTS
NUS
JULY COLLOQUIUM 2011
Boris Altshuler
COLUMBIA UNIVERSITY, NEW YORK, USA
ANDERSON LOCALIZATION
- LOOKING FORWARD.
28 JULY 2011 THURSDAY 4PM
CQT SEMINAR ROOM S15-03-15
MORE INFORMATION AT WWW.QUANTUMLAH.ORG


PRESENTS
NUS
AUGUST COLLOQUIUM 2011
MICHAEL
FLEISCHHAUER
UNIVERSITÄT KAISERSLAUTERN, GERMANY
SPINOR- AND
RYDBERG- POLARITONS
11 AUGUST 2011 THURSDAY 4PM
CQT SEMINAR ROOM S15-03-15
MORE INFORMATION AT WWW.QUANTUMLAH.ORG

Awards

Christian Kurtsiefer and **Valerio Scarani** have been promoted to Professor with tenure at NUS.

Masahito Hayashi won the 2011 IEEE Information Theory Paper Award.

Kuldip Singh is the recipient of The Commendation Medal 2011, a Singapore National Day Award.

Le Phuc Thinh was among the NUS Outstanding Undergraduate Research Prize (OURP) Winners for AY2010/11.

Vlatko Vedral was awarded the Outstanding Scientist Award 2011 from Faculty of Science, NUS.

Valerio Scarani won the 2010 World Scientific Medal.

Markus Grassl was selected an Outstanding Referee 2011 by the American Physical Society.

Centre for Quantum Technologies achieved Gold Award in the Fire Safety Excellence Award 2011 through the work of **Jessie Ho**, **Ethan Lim** and their team of wardens.

Centre for Quantum Technologies has been awarded Merit Award for the NUS Annual Safety & Health Performance Award 2011 through the efforts of **Murray Barrett**, **Chin Pei Pei** and **Jessie Ho**.

CQT's report cards

How are we doing? The results of CQT's two appraisals in 2011 are encouraging.

The performance of CQT was this year subject to two reviews. The Centre's Scientific Advisory Board (SAB) met with CQT's researchers and students in August, as they have done every year since the Centre's founding, to assess and guide the Centre's direction. The second review was an external assessment by an 'International Review Panel' (IRP) convened by Singapore's Ministry of Education, one of the Centre's funders.

CQT was the first of five Research Centres of Excellence (RCEs) to be established in Singapore. The performance management framework for RCEs calls for the Centres to be reviewed by an IRP every three years. Having turned three in December 2010, CQT faced its first IRP review in January 2011. The Centre was privileged to be assessed by a distinguished panel (see box overleaf).

"In the theoretical and physical aspects of quantum information processing CQT is singular given its breath of interests. It is without any doubt among the top ten departments around the world in each individual subject."

Report on CQT by IRP, January 2011

As well as considering the science and performance of the Centre in an international context, the IRP also reviewed CQT's success in meeting Singapore's vision for RCEs to contribute to the local research landscape (see box: The vision: Singapore's Research Centres of Excellence).

So, how are we doing? CQT was pleased to receive encouraging reports in both reviews. In the assessment by the IRP, three results were singled out as examples of achievements by the Centre to date: a conclusive experimental test of an alternative-to-quantum-theory model developed by Nobel prize-winner Anthony Leggett, the proof by computer scientists that two classes of mathematical problem are equivalent (QIP=PSPACE), and the discovery of 'information causality' as a possible underlying principle of quantum mechanics. These results have been described in the Centre's 2008, 2009 and 2010 Annual Reports, respectively. The review reports were also helpful in identifying areas where the Centre can strengthen its existing activities and new research topics that may complement current directions. Here we present some excerpts.

CQT's global reputation

Singapore is known as the "little red dot" for the way it sometimes appears on maps, a small dot off the tip of Malaysia. That dot has earned a place on the global map of research in quantum technologies, according to the IRP.

The IRP report says "CQT has had an exceptionally strong initial three years of operation and has put Singapore on the map of this exciting and potentially important area of science and technology".

The SAB also commented on CQT's strengthening reputation "as one of the reference research centers in quantum science around the world".

The quantum dot is also attracting people. The IRP noted that "All major players in the international community now see a visit to the CQT as being an important part of their travel plans". Visitors welcomed to CQT in 2010–2011 are listed on p. 48.

▼ *CQT visitor Michael Brooks (left) and CQT Principal Investigator Vlatko Vedral, thoughtful during the SAB week.*

The vision: Singapore's Research Centres of Excellence

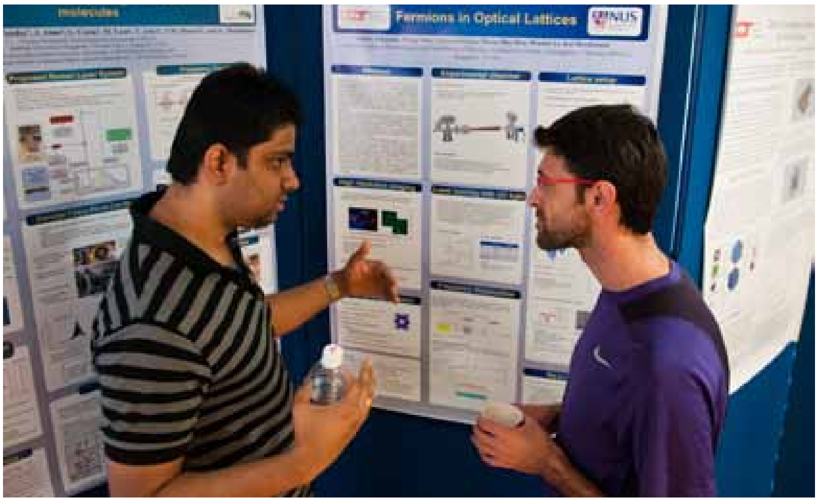
The vision is for RCEs to conduct world-class investigator-led research with a global impact, focusing on areas aligned with the long-term strategic interests of Singapore. It will serve to attract top academic research talent and retain them in Singapore.

At the same time, RCEs will engender interest in research among local students, and encourage more to pursue research careers. RCEs will catalyse the development of local universities into research-intensive universities and will enhance their international standing.

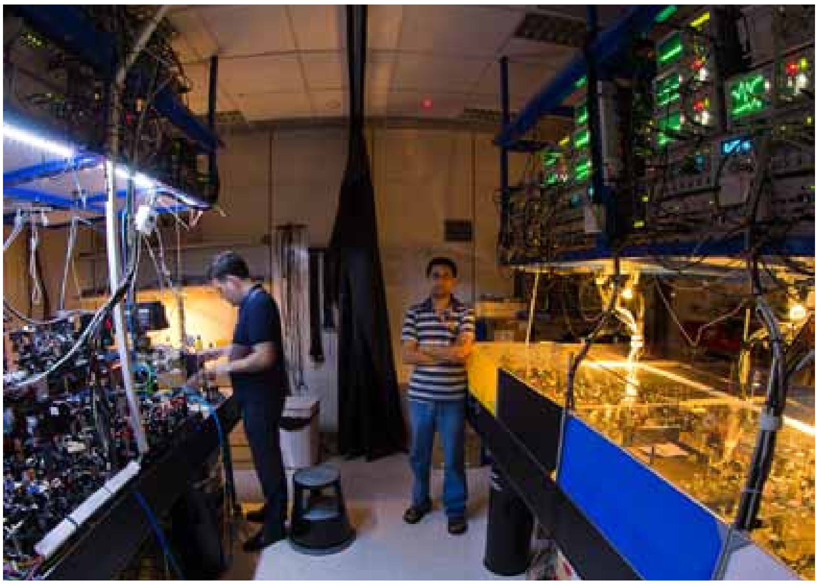
Source: National Research Foundation, www.nrf.gov.sg

CQT's local impact

The vision for Singapore's RCEs includes that they should benefit their host universities. CQT shares many ties with the National University of Singapore beyond its physical location on the NUS campus: for example, Principal Investigators hold joint appointments, graduate degrees are awarded by NUS, and CQT talks and colloquia are open to NUS faculty and students. The IRP felt that CQT "has had a major influence on the reputation of NUS for world leading science. NUS has benefited by the hire of first rank scientists, the visits of leading scientists in the world, the improvement in the quality of students and PostDocs, and the excellent outreach activities carried out at CQT."



▲ *During a poster session organised for the review visits, CQT researchers Jimmy Sebastian (left) and Paul Condylis (right) took the opportunity to learn more about each other's work.*



▲ *CQT has eight experimental Principal Investigators leading laboratories.*

▼ *To head research groups takes management skills as well as scientific vision.*

Focus on experiments

CQT brings together computer scientists and quantum physicists from theoretical and experimental backgrounds. The SAB noted in its report last year that CQT's experimental groups have been in general less visible than its theoretical groups during the experiments' build-up phase – most of the experiments are new to Singapore since CQT's founding. Both the IRP and SAB reports provided updates on CQT's experimental progress.

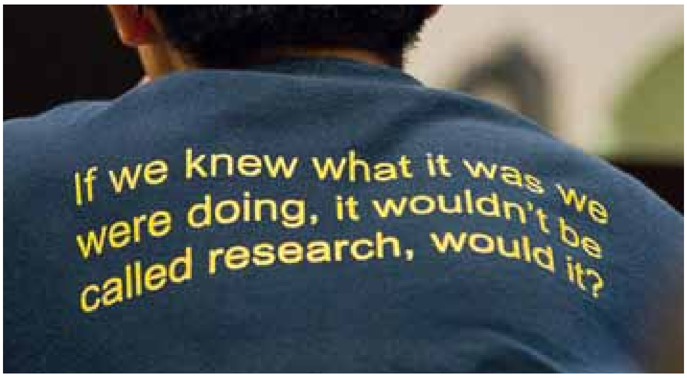
The experimental PIs have established a research infrastructure "which is at the highest international level, without being extravagant", according to the IRP. The IRP also commented that the experimental PIs "have formed an excellent team with hard-working spirit".

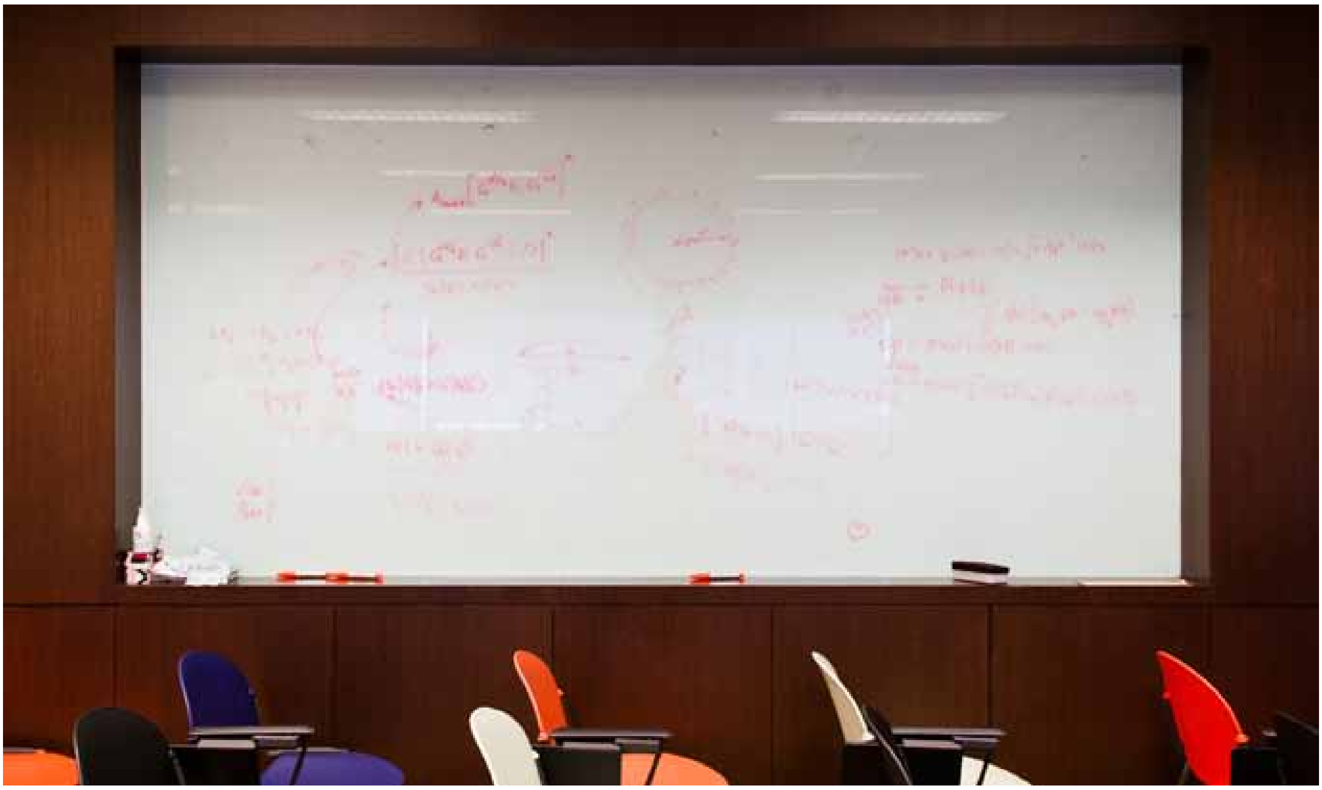
Having so many experiments under one roof — "a super-critical number", as the SAB report says — "can be a definite strength for the Centre, because although the projects are scientifically distinct, many of the techniques are common to multiple experiments".

Both reports pointed out that hiring excellent PhD students and Postdocs was an outstanding challenge for experimental groups. "…in most cases, the student and postdoc support does not appear to be sufficient to make rapid progress on all the projects proposed," wrote the SAB. The IRP recommended that experimental PIs "consider setting up a way to mutually discuss each other's projects critically".

Being interdisciplinary

That experimentalists and theorists collaborate is one of the goals of CQT. The IRP described the potential for research that exploits the synergy of quantum theory, quantum experimentation and computer science "as a continuing and crucial asset" for the Centre, adding that "CQT should explore ways to harness this advantage to differentiate itself from its competitors". The SAB noted that CQT Principal Investigator Stephanie Wehner, whose hiring was anticipated to help bridge the different research areas, "has been successful beyond expectations". The SAB has recommended making another such bridging hire.





▼ *In December 2010, CQT hosted a conference for graduate students in quantum research.*

The graduate programme

CQT and its graduate programme are just old enough for some of its first PhD students to be finishing their studies. The SAB remarked that of the eight or so students in this situation, "some have already received good job offers, which is encouraging". The SAB said "We reiterate that the quality of the PhD students is crucial to achieving the highest level of excellence pursued by CQT." In the context of there being a pipeline of talent for CQT in Singapore, the IRP said "the fact that exceptional NUS undergraduates are being attracted to CQT is clearly a crucial and much to be encouraged development".

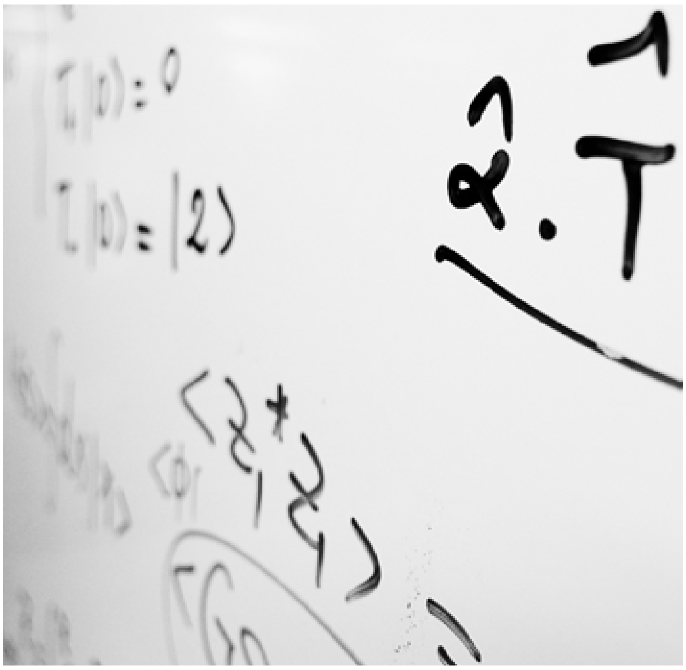
Both reviews had recommendations for the graduate programme itself. The IRP advised the Centre make sure "there is a wide range of flexibility in the coursework. Attending workshops and summer-schools, as well as soft-skill courses (e.g. presentation skills) should find sufficient acceptance in the modules." The SAB has recommended offering additional specialised modules on quantum information topics.

Technology impact

What is the potential for development of the "quantum technologies" CQT is named for? This was a topic considered by the IRP only. In its report, the IRP wrote it was "convinced that the core vision for the centre was soundly based on the need to embed quantum effects in future generations of technology". The IRP also "reflected on how it would be possible for the CQT to take the maximum value to Singapore through commercialization".

The Centre's current experimental efforts centre around ions, atoms and photons, and the IRP noted that the testing and demonstration of fundamental concepts in such systems "is crucial for the understanding and developments of quantum technology". It also identified the project of Alexander Ling, appointed a CQT Principal Investigator in 2011, as being where "the link to technological projects with direct potential for commercialization is most visible". He is working to develop a satellite-based entanglement source (see article on p. 20). The IRP described his project as "a very cleverly spotted niche with huge potential".

▲ *Designing a quantum experiment to go into space involves many technological challenges.*



▼ *Pictured from left to right are Charles Clark, Keith Burnett, Artur Ekert, Ignacio Cirac, Tilman Esslinger, Andrew Chi-Chih Yao and Amy Wang.*

The IRP also said the Centre should consider widening its experimental basis to include quantum systems such as nanomechanical oscillators, nano-resonators, and superconducting qubits, noting "this would give additional opportunities for exploitation of technologies". Research in superconducting systems has recently been introduced to CQT through a partnership with Singapore's Nanyang Technological University and joint-appointment there of a new Principal Investigator, Rainer Dumke (see article, p. 28).

Other research directions the IRP report highlighted as having potential applications are quantum simulation, quantum precision measurement, and quantum cryptography. "The CQT is perfectly positioned to take a leading role in these domains," the IRP report concluded. ■

Members of the International Review Panel for CQT, 2011

Keith Burnett
Vice-Chancellor, University of Sheffield,
United Kingdom

Ignacio Cirac
Director, Theoretical Division,
Max Planck Institute of Quantum Optics,
Garching, Germany

Tilman Esslinger
Professor, Department of Physics,
ETH Zurich, Switzerland

Andrew Chi-Chih Yao
Dean and Professor,
Institute for Interdisciplinary Information Sciences,
Tsinghua University, Beijing, China

For members of CQT's Scientific Advisory Board, see p. 4.

CQT eyes orbit for next experiment

*CQT Principal Investigator **Alexander Ling** and **Daniel Oi** from the University of Strathclyde, UK, are collaborating to put an optical entanglement experiment into low Earth orbit. In this article, they describe the motivations and challenges.*

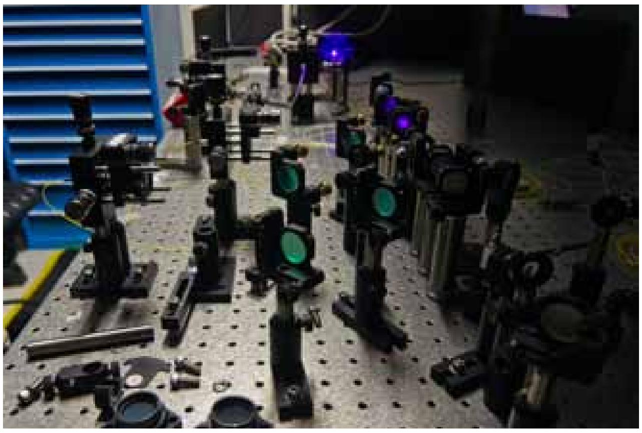
Quantum theory has survived all challenges so far: the pioneering experiments of Alain Aspect demonstrated quantum correlations violating classical predictions, and experiments have tested quantum entanglement – the "spooky action at a distance" that so disturbed Einstein – over ever greater separation. But these experiments have all been Earth-bound. Isn't it time to test quantum theory in space? Science is driven by unexpected discoveries, discoveries often made at the limits of our understanding or in extreme physical environments. Going into space will stretch our tests of quantum theory, from observing entanglement over even longer distances to exploring relativistic effects.

We need not, however, expect the unexpected. Our proposal to put an optical entanglement experiment (see Fig. 1) into low Earth orbit is also motivated by a practical vision. Quantum entanglement forms the basis of the rapidly developing field of quantum technologies, especially quantum cryptography and communication. Long-distance quantum communication networks may rely upon a constellation of satellites carrying sources of entangled photons which would be distributed to ground stations. In this context, demonstrating entanglement in space is the first rung on the ladder to a world-spanning quantum internet.

Space missions are costly

Getting into space is not easy or cheap. The commercial launch of a geosynchronous communications satellite, for example, costs on the order of US$100 million. Building and running the satellite may add twice that much. For most academic organizations, these costs are out of reach. To address the need for more affordable access to space, California Polytechnic State University and Stanford University in Palo Alto launched the "CubeSat" initiative in 1999. There are now over 40 universities involved in developing CubeSats for educational and scientific purposes.

The CubeSat concept is to have small, standardised modules that ride into orbit piggy-backed on commercial satellite launches. Each "1U" module is a cube measuring 10cm to a side and up to 1kg in mass, with components consuming no more than 1.5W of power, and they are deployed in groups of three. Commercial satellite launches are fairly regular so it is not too difficult to book a seat.



▲ *Figure 1: This is a prototype entanglement source and state analyser. To send the experiment into space, it needs to be shrunk to a fraction of its current size. Our current plans require the experiment to fit entirely within a 10cm x 10cm x 3cm slice, have a mass less than 300g and consume only a few watts of power.*

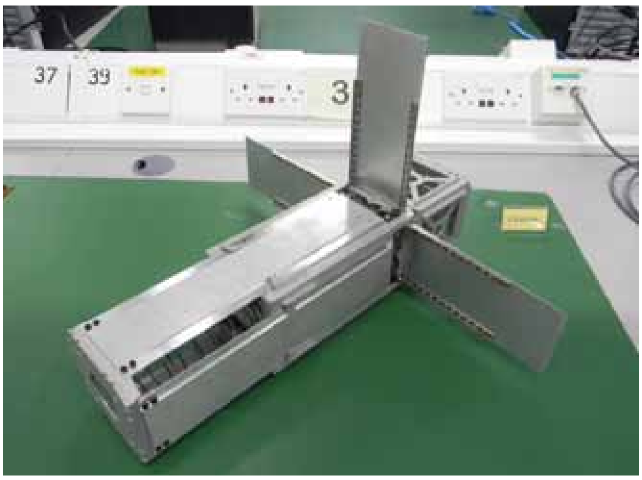
Hitching a ride into space means that launch costs are three to four orders of magnitude less for a CubeSat than for a conventional satellite. The small size and standardized specifications of the CubeSat help cut development time to months and costs to a few tens of thousands of dollars, from the years and tens of millions of dollars that might be invested otherwise. There are other sources of savings, too. CubeSats spend only a short time in orbit, months to a few years, so conventional off-the-shelf components can be used instead of specialist space-rated equipment.

Both NUS and the Nanyang Technological University (NTU) have engineering programmes to build and improve CubeSats. At the moment, CQT is working closely with NTU's Satellite Research Centre to incorporate a quantum science payload into the Velox-I satellite (see Fig. 2), which may be launched in 2013. Current plans allocate CQT a 300 gram, 3cm-thick section of one CubeSat module.

Technology challenges

We propose to build and operate a source of polarization-entangled photon pairs in low earth orbit. The source should generate maximally entangled Bell states (1/sqrt(2) (HV + VH)) via spontaneous parametric down conversion, and hold the necessary diagnostic equipment to check that the photon pairs are entangled.

Several factors make CubeSats ideal platforms for our quantum experiments, including the fact that the cost and development challenges are appropriate for our medium-sized research group.

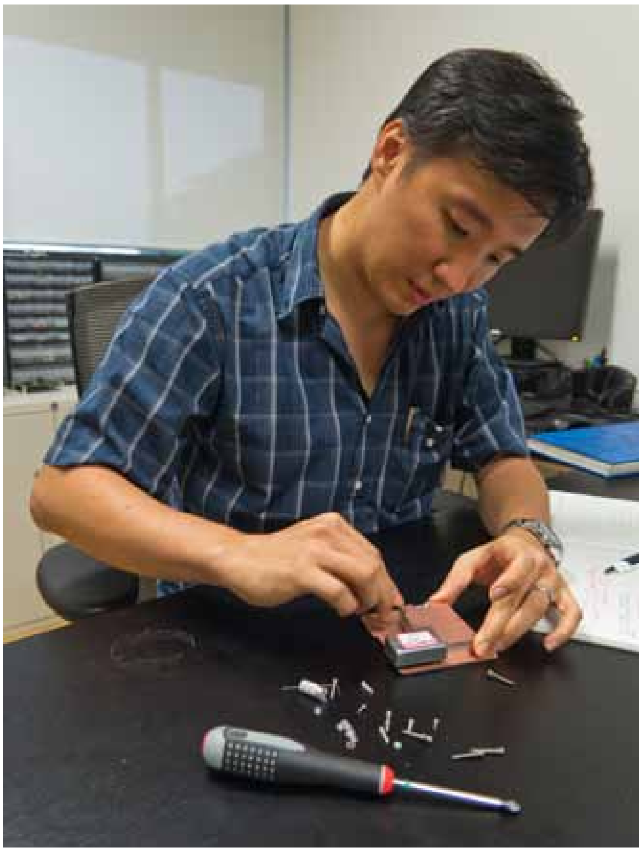


◀ *Figure 2: CQT is teaming up with the Satellite Research Centre at Nanyang Technical University, which plans to launch the 3U Velox-I (pictured). This a 3U CubeSat, the size of three 1U CubeSats, that will separate into a 2U and 1U section to test communication technologies between the free-flying sub-units. The CQT experiment will occupy a 3cm-thick section of the 1U unit located above the solar panel holders.*

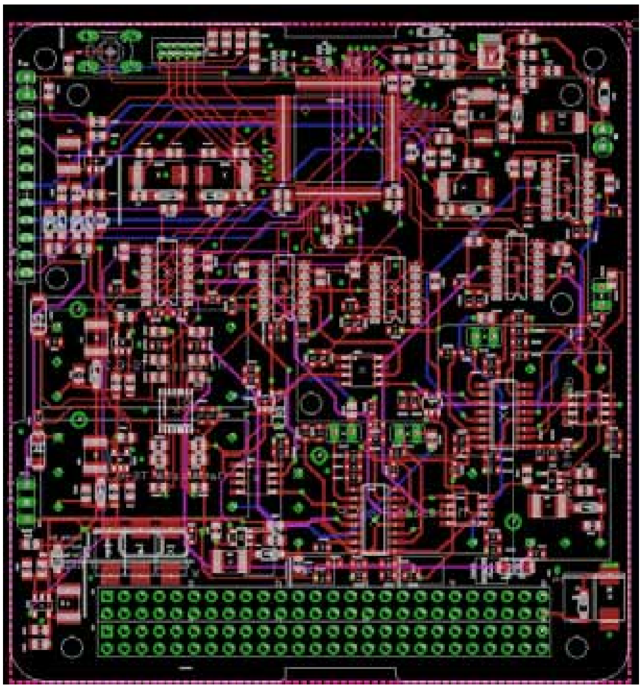
It is immensely challenging to compress an experiment that would typically fill a lab into a volume the size of a small shoebox. Previous efforts at CQT to shrink and demonstrate in the field optical bench-sized experiments have given us a head start thinking about design. And thanks to the miniaturisation and mass production of electronic and optical components, items we need such as lasers and photon detectors are inexpensive. However, size is not the only constraint.

While it is technically feasible to compress the electronic circuits of existing lab equipment, we have to re-examine the components to solve the problem of power consumption. For example, typical single-photon detector circuits require a stable temperature of -15C for operation – significantly below room temperature, and below the temperature of an object in orbit in the glare of the Sun. In the lab we can use thermoelectric coolers, but each cooler consumes about 1W of electrical power. The CubeSat, relying on batteries powered by photo-voltaic panels, only has 1.5W available for continuous operation.

The CubeSat environment also presents challenges unique to space, such as radiation exposure and temperature fluctuations over the orbital cycle. Due to mass and cost constraints, little radiation shielding is built into CubeSats. As a result, they often follow low orbits where Earth's magnetic field still provides some protection from charged particles. A typical orbit is 90 minutes. Heat management over the rapid temperature swings as the satellite revolves through night and day is a huge challenge, especially for our quantum experiment since single-photon detector count rates are highly dependent on temperature. There is also waste heat to manage. A software model of the quantum optics payload is being planned to study heat transfer issues.



▲ *Alex Ling tackles the delicate job of assembling a prototype CubeSat scientific payload.*



▲ *Figure 3: Engineering Model, Version 1.0. The electronics board layout conforms to the PC104 board standard for CubeSats and holds circuits for a laser diode driver, power supplies for four single-photon detectors and associated detection circuitry, temperature sensors and microcontrollers for running the experiment. The next version will include liquid crystal drivers and memory chips.*

Timeline for CQT's CubeSat

To meet a launch date of 2013, the CQT team faces a number of deadlines. We need to build and test engineering models (see Fig. 3) to ensure that the payload will meet the specifications for mass, volume, and power, at the same time being robust enough to withstand the shock and vibration of launch. We should hit the first milestone in late August 2011: a demonstration that all the necessary instrumentation can fit inside the payload volume. If all goes well, a full engineering model that incorporates a source of correlated photons will be ready by the end of this year. By August 2012 we will need a final "qualification model" to test against launch conditions and simulated temperature fluctuations. We also hope to test our payload in a low-pressure environment right at the edge of space by sending it up on a weather balloon. The CQT team is negotiating with several organizations to perform these tests. ■

How the idea launched

I was at a conference in Glasgow to celebrate the 40th Anniversary of the Apollo moon landings. Over a pint of real ale, I was talking to Professor Colin McInnes, director of the Advanced Space Concepts Laboratory at Strathclyde University. He mentioned CubeSats, tiny spacecraft which hitch a lift on conventional satellite launches, as an exciting development in opening access to space. In describing my work on quantum information, I realised the opportunity that easy and inexpensive access to space would represent for experiments to test quantum theory beyond previous limits. Here, I thought, was a way of doing things faster and cheaper than hitherto proposed space missions to test fundamental physics.

Daniel Oi

Small is beautiful

Miniaturised cold atom experiments could lead to beautiful science and robust technologies, writes CQT's **Björn Hessmo**.

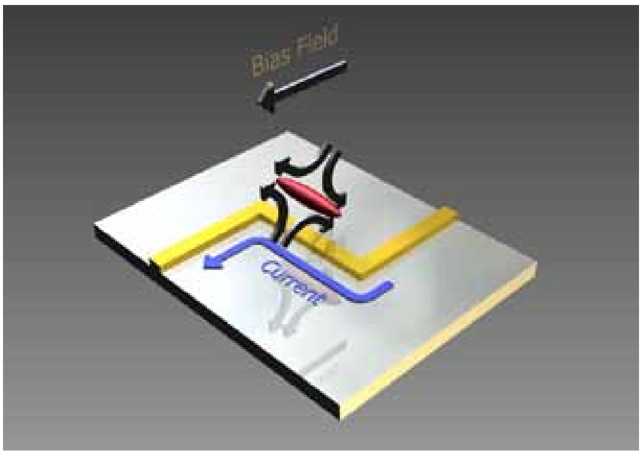
Microfabrication is one of the backbone technologies for the global economy. We have microfabrication to thank for the availability today of vast numbers of robust electronic devices at low cost. Modern computers contain billions, if not trillions of miniaturized components. Miniaturization has made a significant impact in other fields, too. In optical technologies, chip-scale devices are used in high-speed communication networks. In chemistry, researchers have miniaturized experiments into devices known as a 'lab-on-a-chip'. A chemist's chip, combining optical and electrical components such as heaters, pumps, and spectroscopic setups, can parallelise experiments at low cost.

The miniaturization trend shows up in physics too. In my group at CQT, we aim to miniaturize physics experiments with cold atoms. Today, most cold atom experiments are carried out with bulky components: vacuum chambers, magnetic coils and optical elements that sprawl across a table, together filling up a room. There is for sure plenty of scope to make things smaller. We are using microfabrication techniques to build miniaturized versions of atomic physics devices on a chip. The devices will interact with atoms located just next to the chip surface.

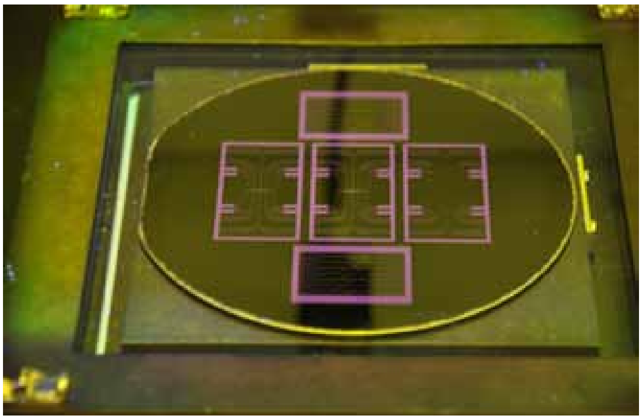
Our efforts are not directed towards producing inexpensive electronics for the consumer market, or to parallelise chemical analysis. So what is the advantage of miniaturization in our case? The advantage is that several physical properties scale very favourably with decreased feature sizes. These favourable scaling laws should allow us to test aspects of thermodynamics and quantum mechanics in a miniaturized setup more robustly than would be possible in other implementations.

Magnetic microtraps

To experiment on cold atoms, we must first contain them. The magnetic trap is the workhorse for cold atom physics. In such traps, atomic states with a positive Zeeman shift (states where the ground state energy increases with increasing magnetic field) are pulled towards magnetic field minima. Tight confinement of the atoms is achieved by having high magnetic field gradients.



▲ *Figure 1: A one-dimensional magnetic trap on a chip formed by sending a current through a z-shaped wire mounted on a substrate. Just above the chip, the magnetic field from the wire is cancelled out by adding an external bias field. The atoms are trapped at the magnetic field minimum.*



▲ *Figure 2: A silicon wafer during lithography. A mask containing the desired pattern has been placed above a silicon wafer coated with photoresist. UV light exposes the resist in the unmasked sections. This particular wafer contains three "atom chips" and two test structures for calibration.*

When currents are passed through thin wires mounted at the surface of a chip, it is possible to create very tight magnetic traps for atoms located just above the surface. The magnetic field from a current-carrying wire scales inversely proportionally to the distance to the wire (Biot-Savart's law), but the gradient scales inversely proportionally to the distance squared. This feature makes it appealing to work as close as possible to the current-carrying wire, where the gradients are maximized. A very high gradient can be realized close to a chip-mounted current carrying wire.

When you have strong confinement of atoms in the trap, the trapped atoms oscillate at high frequencies. This underpins one of our science goals — to explore the limits of validity of the Born-Oppenheimer approximation. The Born-Oppenheimer approximation is used for calculating the energy level of molecules, and it works well for molecular systems, in which the time scales for electronic and nuclear motion are decoupled. In our system, the cold atom spins are analogous to the molecular electrons and the atoms' physical position to the nuclear motion. However, the spin dynamics is not completely decoupled from the spatial motion when the atoms are set oscillating. We can also tune the coupling. In this way, we can explore physics beyond the commonly-used approximation, for example implementing Mead-Berry potentials.

In these chip traps it is also possible to realize one-dimensional quantum gases by confining the atoms very tightly in the direction perpendicular to the wire and very loosely in the parallel direction (see Fig. 1). We wish to use the one-dimensional gas to test a few theoretical tools from quantum information theory, for example the computing capabilities of matrix product states. One dimensional quantum gases also have exotic thermodynamic properties and exhibit interesting quantum correlations.

As well as working on equipment to support our miniaturized experiments, my group is currently testing chip designs and fabrication procedures. The chips should create stable traps. For this, it is important to have smooth wires that support high current densities. The high current densities prevent the atoms from crashing on the surface; the smooth wires are essential to generate a trapping potential with minimal noise.

Microfabrication

So how does one proceed to build an efficient chip trap? Silicon has been used to manufacture electronics components for decades. Today single crystals of almost arbitrary dimensions can be made. The price for a wafer of 100mm diameter that is atomically smooth is only a few dollars. This material is extremely well understood, and a wide range of tools are available to process silicon – some of which we have in CQT's labs.

Nearly all fabrication processes consist of three major steps: optical photolithography, deposition, and etching. The microelectronics industry can pattern chips by photolithography to have features only 32nm wide lines. The chemistry around the deposition and etching of such small features is a well-protected secret of the companies that manufacture your CPUs and memory circuits. Fortunately, it is still possible to build amazing components with the nonindustrial fabrication tools available to us. We can fabricate devices on the micrometer scale. This is fine enough for most miniaturized atomic physics experiments.

For the patterning step by photolithography, we coat a silicon wafer with a commercially available photosensitive film. Then we expose the film through a mask to a regular UV-lamp. The mask defines the pattern of wires we want to create (see Fig. 2). The exposed sections of photoresist can then be etched away, leaving the silicon wafer exposed where the wires should be and covered by film elsewhere.

In the next step, a metal layer is deposited on the wafer. This is usually done by evaporating metal from a crucible containing the desired metal. This covers both the resist and the silicon with the metal. When the resist is removed, one obtains a silicon surface with the metallic pattern on top of it – in our case, we end up with the conductive wires that will generate our magnetic trap.

▲ *Figure 3: (Top) Don't try this at home! (Bottom) A diamond-coated silicon wafer is boiled in potassium hydroxide to remove the silicon. When the silicon is removed, we are left with wires supported by a diamond film.*

▲ *Diamonds are not only decorative. Diamond is the hardest known material and has the highest known thermal conductivity, giving it a role in many technologies.*

Diamond substrates

As mentioned, for a good trap we need the wires to carry high currents, which will lead to heat generation. To prevent the small wires from burning, it is important to remove this heat as efficiently as possible. Unfortunately silicon has quite poor thermal conductivity. An ideal substrate would be diamond, which has the highest thermal conductivity of all known materials. The thermal conductivity of diamond is about five times higher than for copper.

Diamond is not as good as silicon for the patterning steps, but we can combine the best of both materials. After we have made our silicon atom chip, we grow a layer of diamond on the surface using a setup not that different to an oversized light bulb. The silicon substrate is placed near a filament which heats to around 900°C a surrounding atmosphere containing hydrogen and a small amount of methane. Under these conditions, diamond starts to form on the substrate – a process known as chemical vapour deposition.

Using chemical vapour deposition, it is possible to encapsulate the thin wires inside a highly thermally conductive diamond film. When a wire with cross-section 5 micrometres by 2 micrometres is in contact with diamond it can carry one Ampere of current. That is equivalent to running a small town on a regular electrical cable connected to a domestic power plug! In Fig. 3 you can see how we remove the silicon from the wire encapsulated in diamond.

Quantum-optics-on-a-chip

On the technological side, we also want to follow the path of the lab-on-the-chip community in incorporating different kinds of devices on one chip. A particularly interesting possibility is to interface the atoms with micro-optical elements to investigate light-matter interactions. When optical components are miniaturized it becomes possible to focus light to smaller spot sizes, using near-field optics. As a result, the atoms experience higher light intensities. These systems allow you to measure elusive van der Waals forces and interactions with surface plasmons. Using integrated optics it is also possible to realize very efficient atom detectors that allow you to perform quantum optical experiments on a single atom level.

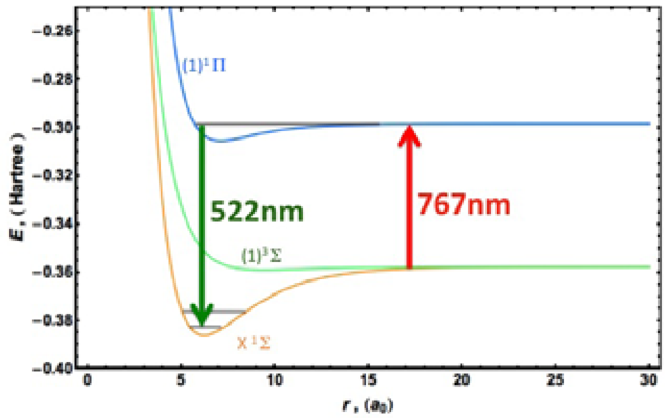
As this article suggests, robust engineering of classical components is crucial for building future quantum technologies. These technologies and tools are most likely to appear also in future non-quantum technologies, such as classical electronics enhanced by the heat management offered by diamond films. ■

CQT lasers get new taskmaster

Investment in S$600,000 frequency comb brings new optical precision to CQT's experimental labs.

It is sometimes said that shopping is a national sport in Singapore, and the experimentalists setting up new labs at CQT have had lots of shopping to do. In addition to the usual lenses, lasers and microcontrollers, this year's purchases have included a big-ticket item: equipment worth over S$600,000 that will act as a 'boss' for lasers in CQT's experimental labs, keeping each laser's output to a tightly-defined and stable frequency of light.

The equipment — an optical frequency comb and related elements — will improve some existing experiments and make new ones possible. For example, in CQT's Quantum Matter lab headed by Principal Investigator Kai Dieckmann, the comb will be used to implement a cooling scheme for ultra-cold molecules known as stimulated rapid adiabatic passage (STIRAP). "Not every laser cooling lab has a frequency comb. It makes you able to compete with the best," says Johannes Gambari, a Research Fellow in Kai's group. Johannes manages the comb setup, which has been installed on CQT's ground level as a shared facility.



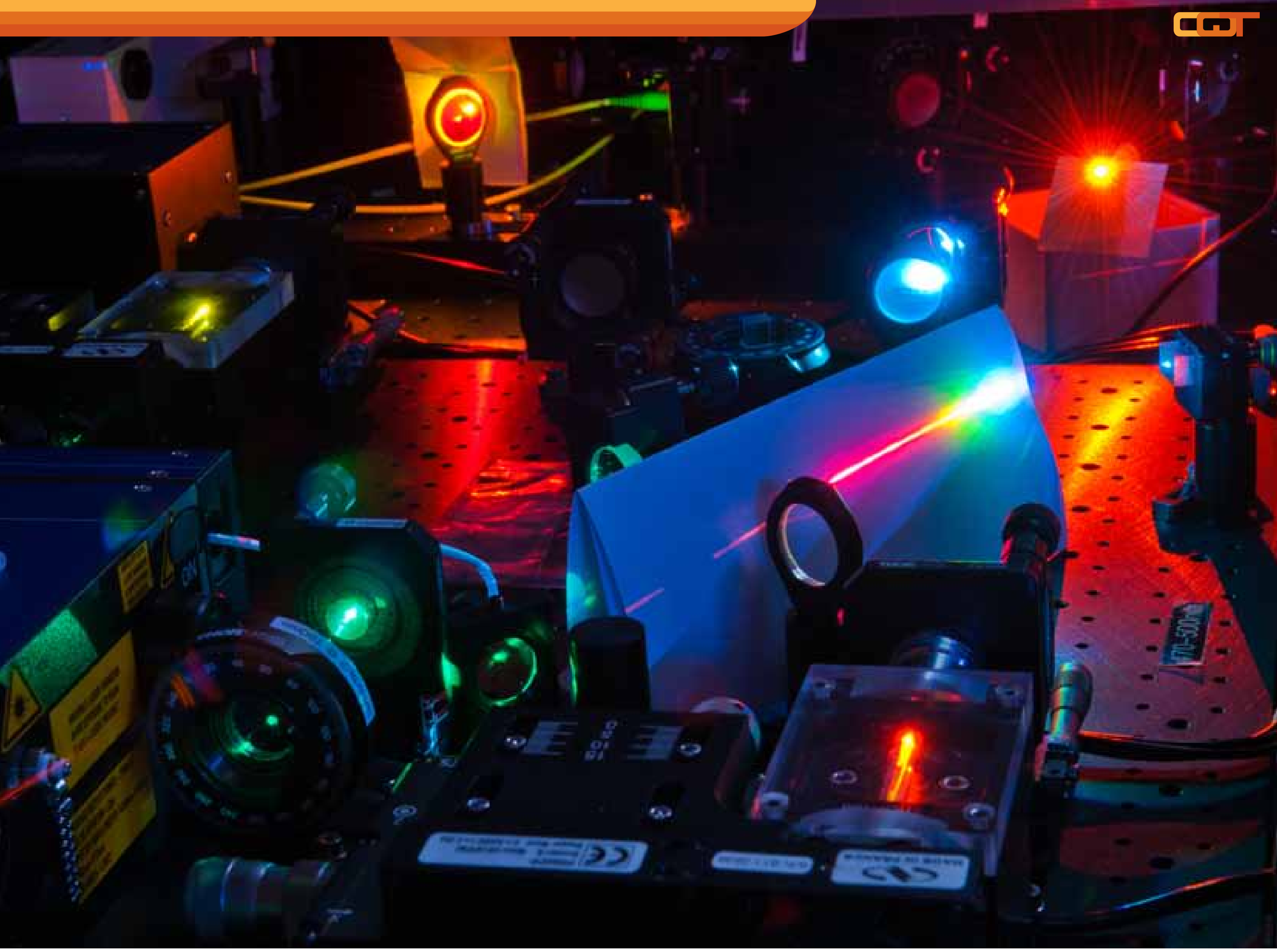
▲ *Figure 1: Creating ultra-cold molecules by stimulated adiabatic rapid passage (STIRAP), as the quantum matter group hopes to do with Lithium and Potassium, will require lasers driving two transitions. These move the molecules into their ground state via an electronic excited state. The figure plots the ground ($X^1\Sigma$) and excited ($1^{(1)}\Pi$) states for Li-K molecules, showing the Morse potential — the potential energy of the molecule's electrons as a function of the separation of the atoms. The figure also shows the laser wavelengths the group will use to implement STIRAP. These wavelengths are equivalent to frequencies of the order of 10^{11} KHz. For the scheme to work, the frequencies must be stabilized to within roughly 1KHz.*

▲ *Time to unpack and assemble. The frequency comb and other equipment, purchased from Menlo Systems in Germany, arrived on a Singapore Airlines flight in July 2011.*

CQT labs use lasers to manipulate, measure and contain quantum systems comprising atoms, as well as in experiments exploring the quantum behaviour of light. Experiments are typically designed to operate at specific frequencies of light, corresponding, for example, to the transition of an atom between two energy levels. Checking and stabilizing the output of a laser to match the frequencies required is a technical challenge the new facility will solve. The planned STIRAP-based cooling is a case in point: for this to work, two transitions need to be driven by a pair of lasers that have relative frequencies defined to kHz precision (see Fig. 1), something the comb enables.

A frequency comb is also known as a 'super continuum source' of light, meaning that it produces light across a broad range of frequencies. This 'rainbow' of light (see picture) is generated from a 70-femtosecond pulsed laser broadened by honey-comb hollow optical fibre. Viewed up close, the rainbow is not continuous but looks like a comb: it comprises millions of needles spaced by frequency intervals of 250MHz. The spacing between the needles is controlled with very high accuracy, making the comb an ultra-stable tool for frequency measurements.

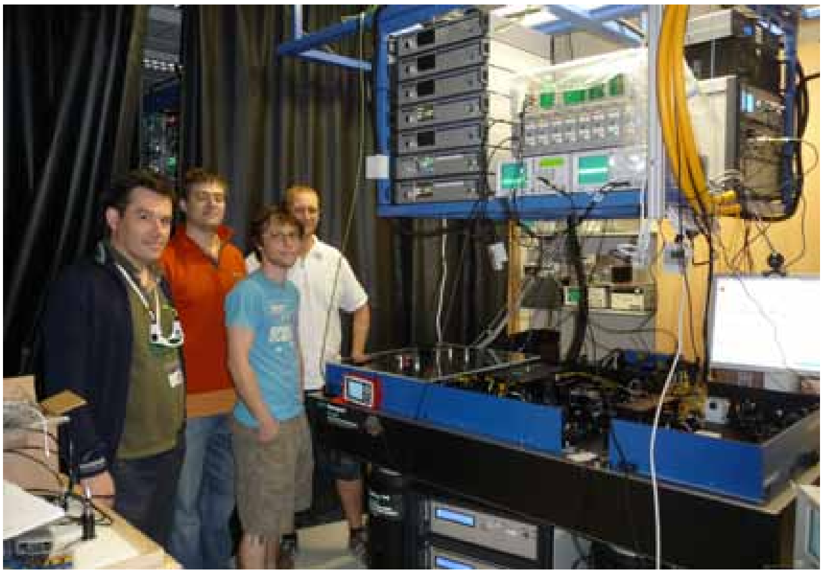
The needles of the comb function like the markings on a ruler. To perform a frequency measurement, laser light is compared against the comb and the 'number' of the closest needle noted. The light's frequency is then measured with respect to that needle, a procedure that is quick and accurate. Optical frequencies are the highest frequencies that can be measured; optical electromagnetic waves oscillate around



▲ *The rainbow of light produced by the frequency comb is made of millions of sharply-defined lines of colour.*

1,000,000,000,000,000 times per second. In this sense, the frequency comb is the fastest counter existing. As a result of knowing the laser's frequency in near real-time, it is possible to implement a stabilizing feedback loop, 'locking' the laser frequency to the needle frequency.

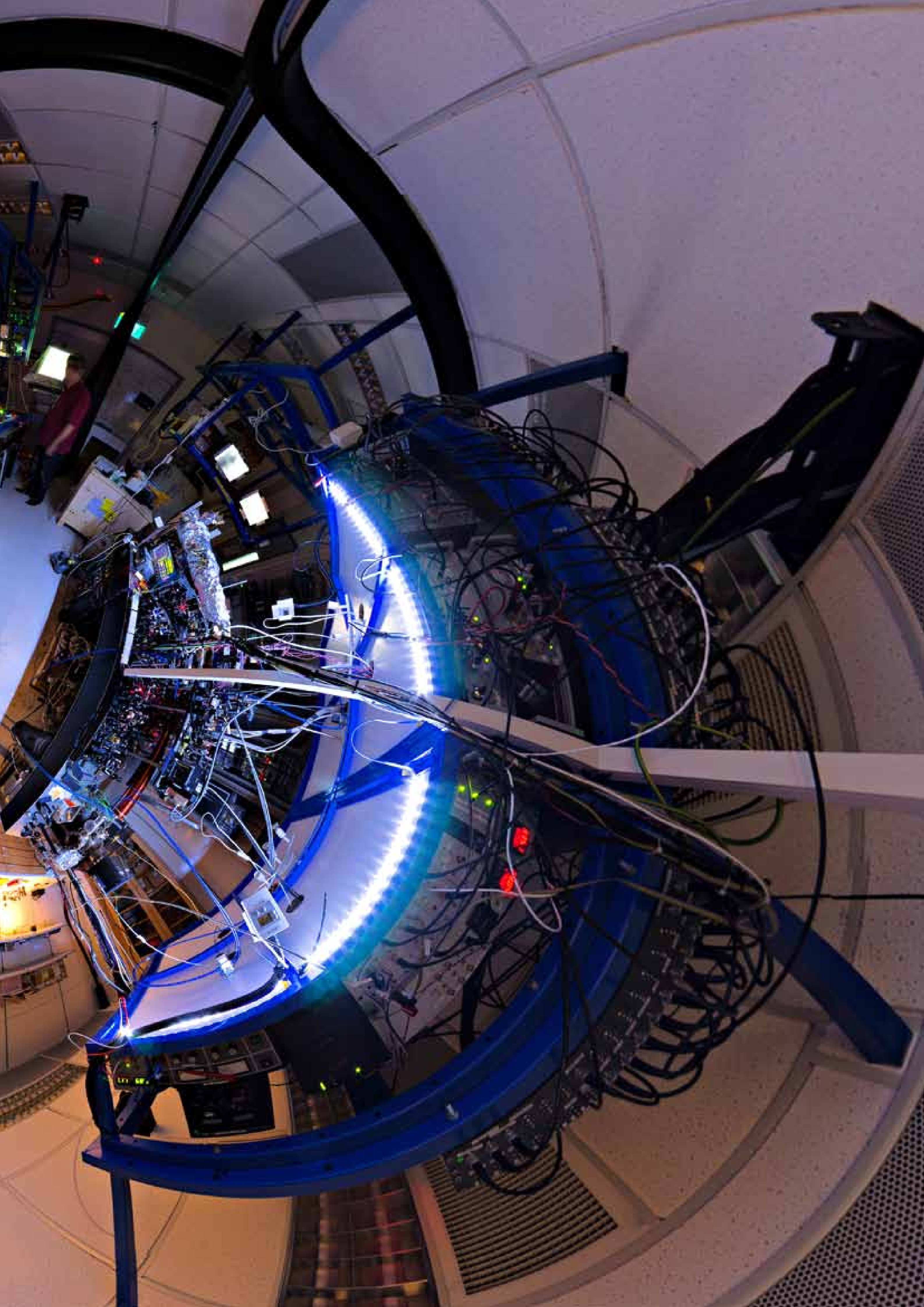
A fat snake of optical fibres feeds laser signals from around CQT to interact with the optical comb. Next door to the shared facility, for example, is the CQT Microtraps lab headed by Principal Investigator Murray Barrett. The availability of a frequency reference and lock will "free up time and drastically simplify our setup," Murray says. The group had been using a mechanical system – optical cavities – to stabilize its lasers, which needed checking and adjusting throughout the day. The group also plans to implement a new scheme to detect a trapped ion's quantum state using two coherent frequencies from the comb.



▲ *CQT researchers (from left to right) Kai Dieckmann, Johannes Gambari, Nick Lewty, and Murray Barrett pictured with the new shared facility.*

In the second lab of the Quantum Matter group, headed by Principal Investigator Wenhui Li, the comb will be enlisted to help with the creation of Rydberg atoms — cold atoms in an excited state, where they interact strongly with each other. The requirements are similar to those for STIRAP-based cooling: two lasers with a very stable relative frequency. However, the lasers push the atoms up from a low-energy state to an excited state rather than vice-versa. This has to be done efficiently because Rydberg atoms have only a very short lifetime (some 10s of microseconds). Wenhui, who is currently setting up the apparatus for the Rydberg experiment, expects to be using the frequency comb before the end of 2012. ■

This photograph is a panorama shot inside one of CQT's quantum matter labs. The lab houses the frequency comb shared facility (see article on p. 24) and an experiment probing the properties of ultra-cold fermions. The panorama is shown in stereographic projection, which puts the ground at the centre. Ringed around this you can see apparatus bristling from the surface of the lab's two optical benches and the experiments' controlling electronics, which sits on blue shelving above the tables. Photo: Daniel K. L. Oi



CQT @ NTU

A quirk of the quantum world is that an object can be in two places at once. CQT has acquired this ability thanks to a new partnership with Singapore's Nanyang Technological University. CQT Principal Investigator **Rainer Dumke** *explains.*

In 2011, CQT officially extended its research facilities to laboratories on the campus of the Nanyang Technological University (NTU). The campus is a short drive away from the National University of Singapore, where CQT's HQ is hosted.

My group at NTU investigates novel ideas in the field of coupled quantum systems. Projects underway in the CQT@NTU research laboratories currently include:

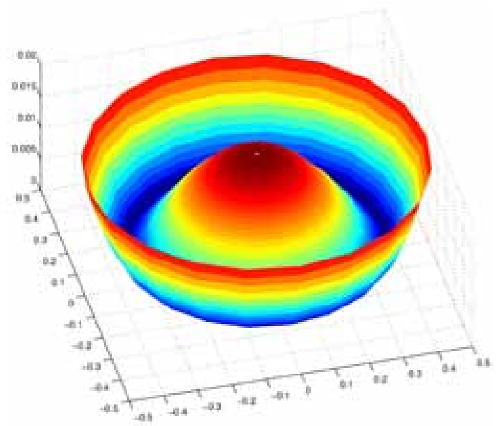
- Interaction of superconducting microstructures with atomic quantum states
- Gravity measurement based on matter-wave interferometry
- Quantum registers for neutral atoms

Here I present an update on these three main projects. There will be more to come from NTU in the years ahead. We have room for expansion, and new labs are currently under construction to host some of the planned precision experiments. Laboratory space for a new experimental group in ultracold gases being established by CQT Visiting Associate Research Professor David Wilkowski is expected to be ready in early 2012.

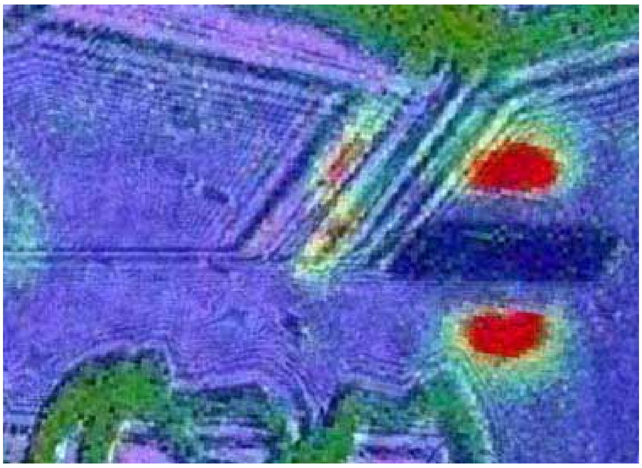
Superconducting atom chips

Experiments that trap quantum matter on 'atom chips' have over the past few years revealed the potential of this approach for fundamental research and for quantum information processing. In my group, we investigate the innovative use of high-temperature superconductors in such chips, exploring the controlled interaction of the trapped atomic matter with superconducting quantum states.

One variable is the design of the chip, how the superconducting material is patterned. However, it's not only the superconducting micro structures that can be shaped. By applying sequences of magnetic field pulses, we are able to write a variety of vortex patterns in the YBCO-based superconducting chip structure. Each vortex carries a magnetic flux quantum, and the total magnetic field produced by the vortices can serve as traps for neutral atoms.



▲ *Figure 1: Calculated ring shaped magnetic field distribution of a superconducting disk after preparing the vortex pattern by two magnetic field pulses and a DC magnetic field.*



▲ *Figure 2: False-colour image of an atom cloud (shown red) floating below a superconducting square. The image of the atom cloud has been superimposed on the image of the superconducting chip.*

Employing these ideas we have realised a variety of trap geometries including mergeable multiple traps, self-sustaining traps, and ring structures. The experiments were carried out by PhD student Chang Kin Sung and postdoctoral fellow Mirco Siercke. Postdoc Zhang Bo has been working on the theoretical side of the project. Her theoretical models simulating the two-dimensional vortex patterns forming inside the superconductor (see Fig. 1) are in agreement with our experimental findings. After initially investigating simple one dimensional superconducting stripes we have turned our attention to two dimensional structures including rings, disks, and squares (see Fig. 2).

In the future our project will focus on exploiting coupling between the atomic magnetic dipole moment and the magnetic field induced by vortices inside type-II superconductors. This will allow us to make the most of the advantages of each physical system. We hope to play on the different strengths of solid state and atomic matter to work towards a controllable coupled quantum system.

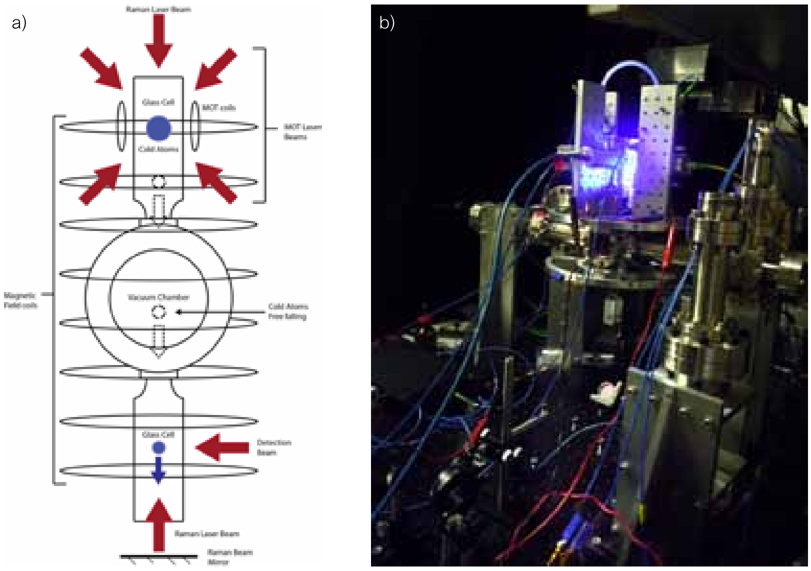
Building a gravimeter

It is possible to make highly precise measurements of quantities such as local gravity with devices that exploit the quantum properties of ultra-cold atoms. Atom interferometers measure the gravitational field, or more precisely the absolute local g, following the same ideas known from light interferometers. The light beam is replaced by ultra-cold atoms and the optical elements like mirrors and beam splitters by laser pulses. At the exit of the atom interferometer we can infer local g by analysing the interference pattern.

Typically such measurements are performed in controlled, laboratory environments to meet the stringent demands that precision places on the stability of the instruments. However, laboratories are not necessarily sited in the most geologically interesting places for observing changes in local g. Compact and portable atom interferometers that could operate in tough conditions would therefore fill a need: for example, they could be used for navigation or measurement of local g in geothermally active areas.

In the CQT@NTU laboratories, in collaboration with Singapore's national defence R&D organisation, DSO National Laboratories, we are developing a compact and portable atom interferometer (see Fig. 3).

The project is still in the setup phase, but we have recently realised the first samples of ultra-cold atoms in our setup, thanks to the hard work of Zhang Chaobo and Tang Cheng. After a long fight with the lasers which are the heart of the interferometer, Andrew Chew, who is attached to DSO, succeeded to phase lock them. This was an important step in the progress of the project. Maral Sahelgozin, the PhD student on this project, is investigating how we can eliminate in our final design noise contributed by vibrations. Uncontrolled vibrations will be one of the major limitations on the accuracy of this device. We hope to make decent progress in the near future, especially since a new Post Doctoral Fellow, Raaj Vellore Winfred, has joined our team recently.



▲ *Figure 3: a) Schematic of an atom interferometry setup. An atomic cloud is cooled with laser beams. After reaching a temperature in the micro-Kelvin range, the atomic cloud is released and freely falls under gravity. A sequence of laser pulses split and reflect the atom cloud so that it interferes. By detecting the phase evolution of the atomic cloud, we will infer local gravity. b) Our experiment. Atoms are collected into a magneto optical trap via light-induced atom desorption when the UV LEDs are switched on.*

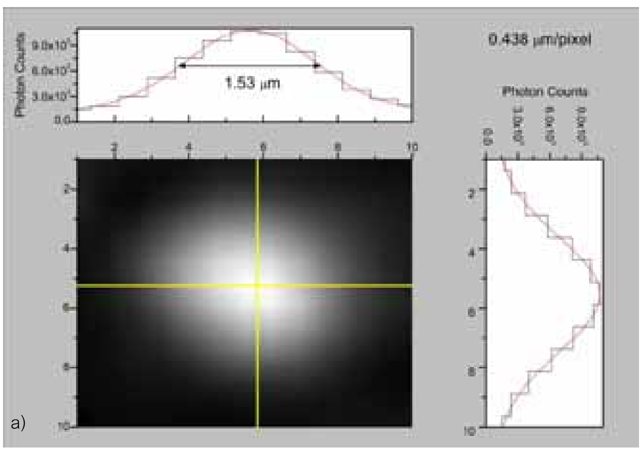
A quantum register

Ultra-cold neutral atoms are good candidates for qubits, the 'quantum bits' needed to hold information for quantum information processing, thanks to their simple quantum-level structure and good isolation from the environment. Techniques to control neutral atoms draw on years of expertise in coherent spectroscopy, an optical approach to atom manipulation developed for application in precision measurements. Current techniques allow us to trap and manipulate a very large ensemble of identical atoms.

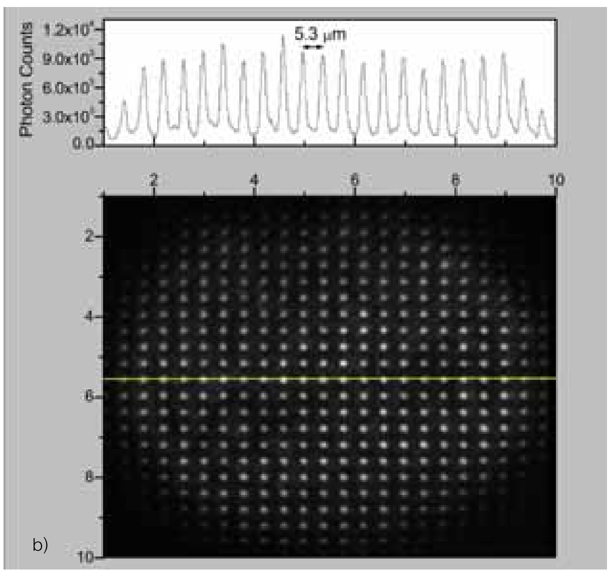
In our laboratories, with support from Singapore's Agency for Science, Technology and Research (A*STAR), we are working towards the realization of an addressable atomic register for storing quantum information. Our register will allow for interaction between atoms at neighbouring sites.

We have designed and realised an optical system which generates an array-type pattern of light (see Fig. 4). The light field will be used to create dipole traps for neutral atoms with a separation of approximately 5 micrometres. The width of these light foci is 1.5 micrometres, which makes light-assisted single atom preparation possible, if needed. The trap separation of 5 micrometres should be large enough to comfortably address single array sites but at the same time with this separation atoms in highly-excited Rydberg states can interact with each other via dipole-dipole interaction.

In a supporting experiment, postdoctoral fellow Wang Zhi Wei recently realized a Bose-Einstein condensate — in which ultracold atoms adopt a shared quantum state, behaving as a matter wave — in this setup. He is now investigating with PhD student Anushyam Mohan the coupling between proximate Rydberg atoms in a quantum degenerate atomic ensemble. ■



▲ ▶ *Figure 4: Images of the dipole trap array generated by our optical system. The spacing between adjacent traps is approximately 5 micrometres, which is large enough that we can optically address individual sites.*



Quantum conference comes to Singapore

*CQT Principal Investigator **Andreas Winter** tells the story of the 14th QIP.*

The Quantum Information Processing workshop, started in 1998 as a small event (then called AQIP), is now the leading conference in quantum information and computation. I was very happy when Singapore got to organise the 14th edition — even if that meant that I had to take on unprecedented responsibility at the helm. Aided by the Steering Committee, the Programme Committee, and a Local Organising Committee, I set about to make this a truly special and memorable QIP. The conference took place 8-14 January 2011.

How was our QIP memorable? We secured locations at the Capella Resort on Sentosa island and at the two universities NUS and SMU, which let our some 300 participants sample different sides of Singapore. We were proud to offer tutorials by Patrick Hayden, Maciej Lewenstein, and Ben Reichardt, and a public lecture delivered by Charles Bennett, to frame the core scientific programme of 40 talks selected by the Steering and the Programme Committees. Talks covered the crop of production during the past year, ranging from quantum algorithms to computational and communication complexity, to quantum Shannon theory, cryptography, nonlocality, all the way to foundations of quantum mechanics.

Despite the appearance of a packed programme, which also included two massive poster sessions (with a total of 156 posters) and a "rump session" on a beach, it somehow was possible to maintain a light touch, allowing the participants to enjoy themselves and interact widely. Only a single thing went patently wrong with the scientific programme, when John Martinis couldn't make it to Singapore (also another speaker couldn't come but was duly replaced by a colleague familiar with his work) to give his plenary lecture on superconducting qubits: still, within 24 hours we managed to secure CQT's own Christian Kurtsiefer who delivered a blistering account of his work on "quantum hacking". I recommend a look at the conference website qip2011.quantumlah.org and the booklet we produced for an overview over the range of activities we offered and the detailed scientific content of all talks and posters. We have made videos of the talks available on the website.

▲ *QIP talks took place in the splendour of The Capella hotel's grand ballroom. Photo: Dagomir Kaszlikowski*

▲ *Members of CQT's admin team (from left to right) Jessie Ho, Irene Tan, Mashitah Bte Mohammad Moasi, Chan Chui Theng and Ow Yam Hou.*

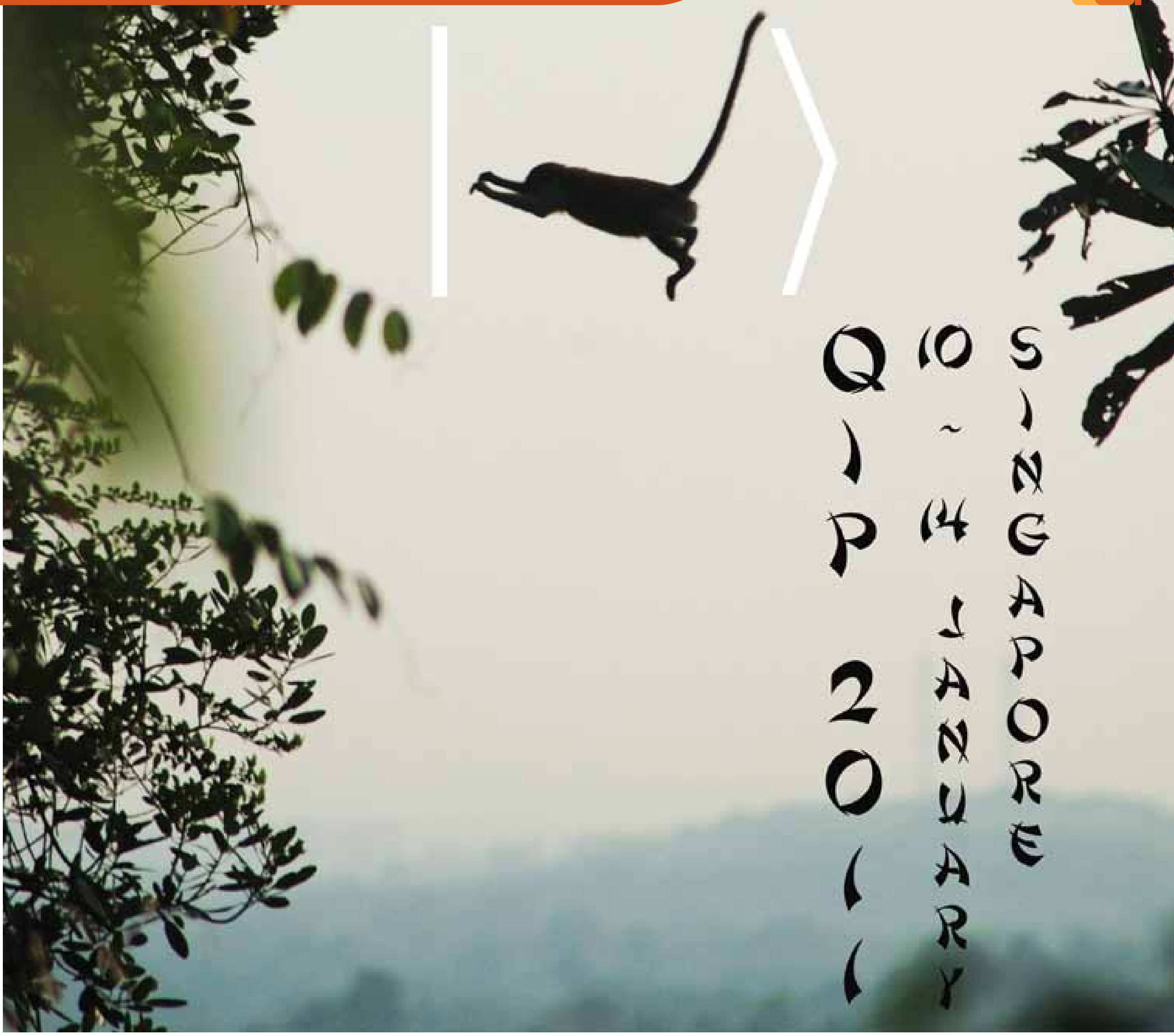
Ensuring a smooth delivery

*CQT Admin Executive **Evon Tan** describes the hard work behind the scenes that made QIP happen.*

Getting to know CQT was organising QIP 2011 was a moment of happiness, excitement and nervousness. It was the first big international conference CQT was to arrange and host. From that day, organising QIP 2011 was like going through a pregnancy — lots of planning and anticipation leading to a dramatic end.

The gestation was long. An entire year before the event, the administration team and the organising committee scouted for event venues. We also had to build up the QIP 2011 website and registration system months

Schrödinger's Monkey (Bukit Timah) courtesy of Ben Ravilious



Aside from the work done by the various committees and other professional and volunteer workers, the conference was made possible due to a host of sponsors, both Singaporean and international, and generous support from CQT. We also raised a modest conference fee.

Personally, in spite of all the stress involved, I had the time of my life during the conference. My personal highlight was the award of the poster prizes in five categories during the conference dinner. This was an innovation to the conference, intended to make the rather large poster session lighter and more interactive. During the dinner I also took the occasion, which I wish to repeat now, to thank everyone involved with the planning and running of the conference, especially the Local Organising Committee. ■

ahead of time, meanwhile working out many little but important details that would keep the event running smoothly. We aimed to make the conference a nice and memorable experience for QIP 2011 delegates.

The actual conference days were our delivery time. There were some challenges we expected and some hiccups we didn't expect, but with the CQTian-spirit we worked as a team and brought solutions to situation(s).

It was a team effort where everyone contributed to make the event successful. QIP 2011 not only brought everyone in the administration team together but also involved CQT's researchers and students. They gave extra help with jobs such as packing delegate kits and putting up posters and managing the many, many other tasks (too many to list!).

Some of my colleagues are pictured. Ow Yam Hou (far right), a temporary administrative assistant during 2010–11, remembers it taking a long time to remove the posters because so many participants were still in intense discussions at the poster booths when the time to remove the posters came. But we didn't mind because it showed that the event was going well and had a good atmosphere. As Yam says, "the passion of this burgeoning community was undeniable and it was an honour to experience this wonderful conference."

At the end of QIP 2011 (baby delivered), we felt relieved, happy and satisfied. We are glad that many delegates enjoyed the conference and that we created good memories for them. Many thanks to all who contributed to QIP 2011 in one way or another. :)

Quantum immersions

CQT Outreach and Media Relations Manager **Jenny Hogan** *introduces the Centre's new residency programme.*

One of the highlights for researchers at CQT is the number of visitors that come through the place: conversations spark ideas and collaborations take shape as the mix of people changes. In the past year we have started to invite a new type of person into this mix. Whereas the more than 700 visits hosted by the Centre in its first three years were mostly academic, since December 2010 the Centre has also welcomed writers and artists under a new residency programme.

▲ *Stills taken from the short film, "The Mechanics", by Karol Jałochowski.* ▼

Through the new 'Quantum Immersion' programme, CQT will host writers or other creative types with a track-record of sharing scientific ideas with the public. Over short or long stays, the writers- and artists-in-residence will have the opportunity to interact with CQT scientists and engage with the Singapore public. We anticipate these residencies will continue to inspire the individuals in their work after their visit, helping to bring concepts in quantum science to wider attention. At the same time, the residencies will enrich the working culture at CQT and can contribute in a small way to Singapore's cultural scene.

As this report goes to press, CQT has hosted two writers-in-residence and two artists-in-residence, with a third writer due to arrive in October 2011. The first writer, UK-based Zeeya Merali, visited for a week in December. Zeeya is a freelance journalist whose articles have appeared in *Nature*, *Discover* and *Scientific American*, among other publications. The second writer, Karol Jałochowski from the Polish newsweekly *Polityka*, spent 10 days at CQT in February and has written a number of articles inspired by this and his previous visit. Karol is also working on a short film called "The Mechanics" about quantum physicists.

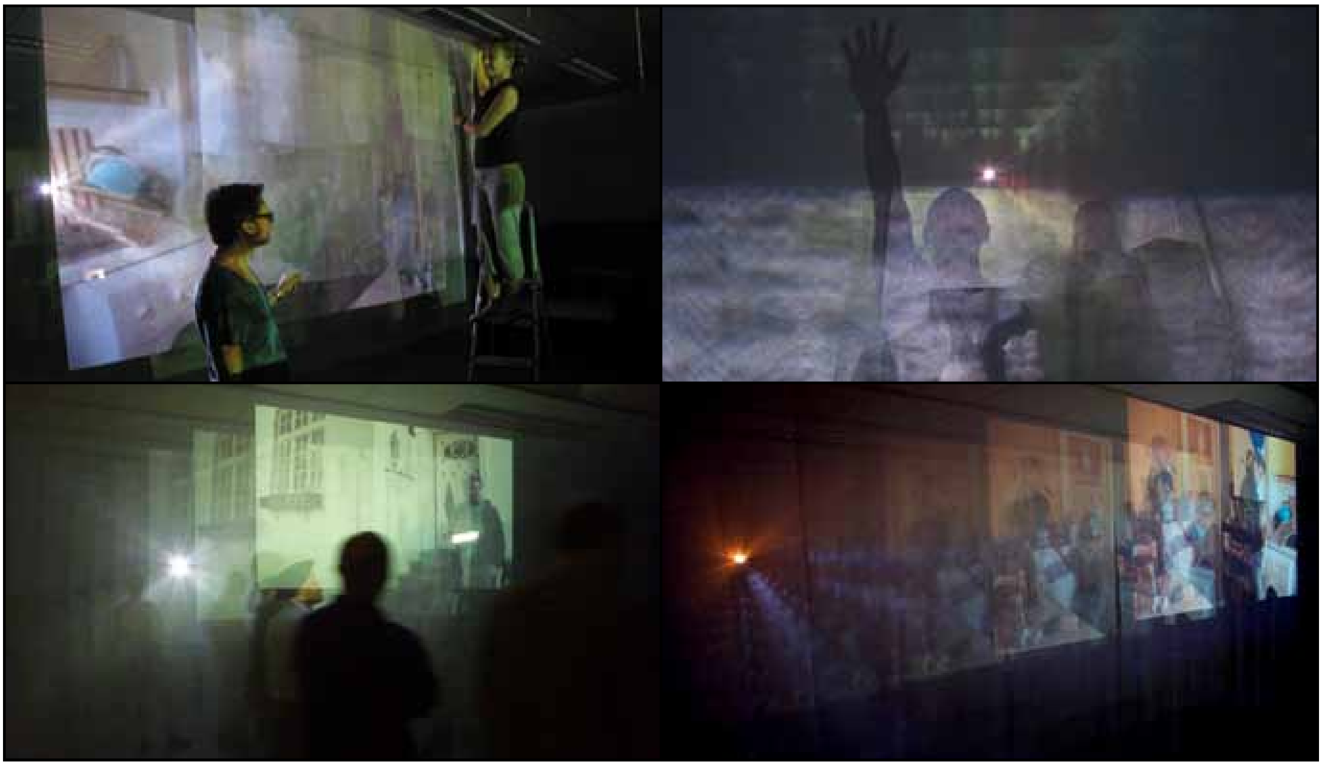
Karol and Zeeya both found the residency rewarding: see the box "The writer's perspectives". Likewise, researchers at the Centre welcome the writers' visits. "Ultimately, I see our aim to understand nature not as a mere personal intellectual curiosity. Rather we hope that our research will provide new insights and technological ideas to the general public, maybe even contributing to the basic human need to understand the world around us. To this end, it seems essential for someone to 'translate' and make CQT's work more accessible to non-scientists, and hence I greatly welcome interested journalists to visit us here," says CQT Principal Investigator Stephanie Wehner, who was interviewed and filmed by Karol.

A longer visit is planned for George Musser, a staff editor and writer for *Scientific American*. He will spend two months at CQT as writer-in-residence from mid-October 2011, using the time in part to write a popular science book dealing with ideas related to quantum nonlocality. George will also offer talks in CQT and NUS.

The writers' perspectives

Zeeya Merali: As a freelance journalist — and one-time physicist — I often have the privilege of writing about topics close to my heart: the nature of reality and quantum mechanics. Visiting CQT as a writing fellow gave me the unusual luxury of being able to take part in seminars and to snoop around labs to see the sort of tests I often write about from my desk in London, England, being carried out first hand. The atmosphere at CQT is extremely relaxed and I spent much of my day in the centre's social hub, the Quantum Café. Many thanks to each of the physicists who devoted huge chunks of time to talk to me over coffee about their own research and share their thoughts on cutting-edge experiments being carried out by independent groups around the world. Had it not been for those chats, for instance, I would not have realized that the international race to close "loopholes" in quantum experiments (Bell tests) has applications in quantum cryptography — a topic that I later wrote about (*Science* 331, 1380 (2011)). I thoroughly enjoyed my time at CQT, and I hope that I was also able to impart a few tips to my hosts on how to deal with the media.

Karol Jalochowski: I simply couldn't overestimate the value of my visits to CQT. They are a source of constant inspiration – both in professional and personal terms. The direct results are the easiest to list down — several articles on quantum aspects of reality that I published in my mother weekly, the Polish-language magazine *Polityka*, a videocast about the brave CQTians, and a larger documentary project about quantum information on the way. The indirect intellectual impact is at least as valuable — meetings and conversations with the fiercely intelligent, daring folks of CQT always suggest new paths worth investigating and, ultimately, reporting. The intellectual vibrations that CQT is the local epicentre of give me a positive energy boost that shifts me into a higher mental gear. Yes, I know, it sounds a bit bombastic. But that's how it is. *See p. 34 for translated extracts from one of Karol's articles.*



▲ *"Timensions" at CQT. The installation's central element is a series of large semi-transparent curtains, onto and through which a looping video is projected. The visitor can wander between and through slits in the curtains, which reference the idea of parallel universes. The video shows everyday scenes that have been filmed multiple times, the characters behaving differently in each take. The layering of these scenes calls to mind the many-worlds interpretation of quantum mechanics, which supposes that every event acting on an object's quantum wavefunction triggers a branching of the universe, with every possible outcome allowed by the wavefunction occurring in separate splinter universes.*

More experimental, perhaps, was the invitation to artists Linda Sim and her collaborator Dario Lombardi to spend time at CQT as artists-in-residence. Linda, who lives in Singapore, had initiated informal discussions with a few CQT researchers about a large-scale, physics-inspired installation artwork called "Timensions" she was developing with Dario (see box "Timensions: the concept" for the artists' description of their project). Based on this contact, we were pleased to offer them a residency starting in May 2011. Linda was resident for eight weeks. Dario, who lives in Vienna, Austria, came for two weeks.

Linda and Dario turned a large empty room in CQT into a temporary studio, nick-named the "Timensions lab". There they built a prototype of the installation artwork (see pictures), testing materials and setups. As well as giving a talk about their project, they hosted an open house in their studio for CQT and NUS researchers. The artists are in discussion with venues in Singapore to exhibit the work. They also hope to show the installation in Vienna.

"Perhaps this exhibition can open a new window to the quantum world through art," says Christian Kurtsiefer, one of the CQT Principal Investigators who spent time with the two artists. Concepts from quantum physics are difficult to convey without mathematics and sometimes impossible to visualise. Encouraging artists to develop interpretations may offer new routes to inspire interest in and communicate ideas about quantum science, and to reach a more diverse audience than traditional outreach activities.

We look forward in 2012 to continuing and developing the residency program. Expressions of interest are welcome by email to jenny.hogan@quantumlah.org ■

Timensions: the concept

Timensions investigates the possibility of multiple existences, inspired primarily by many-worlds theory in quantum physics as well as string theory's concept of parallel universes and multiple dimensions.

By modifying the perceived spatial distribution of the exhibition visitor with semi-translucent curtains and projections, we aim to create an immersive and personal experience of artistic interpretative analogies for current quantum theories proposing explanations for mankind's cosmological and sub-atomic origin.

We are investigating moments of choice & chance in our lives by creating an experiential space of suggestion, possibilities and feelings about the multilayered nature of all existence (and our variable perception thereof), referencing the behavioural nature of elementary particles.

The objective of the proposed installation is to create the sensation of immersion and personal investigation into elemental theories of existence by the exhibition visitor; surpassing the commonly perceived complexities of the subject matter. We are encouraging introspection beyond a plain theoretical assessment and so aim to initiate questioning of our ever-present reality continuum.

Linda Sim and Dario Lombardi

Extracts from

Physics of the impossible:

The bold ones in the land of strange

By **Karol Jałochowski**. Translation by **Kamila Slawinska**. Originally published in Polityka magazine in October 2010. Visit Polityka at www.polityka.pl

This summer night is as hot as any other night in equatorial Singapore (December ones included). Five men, seated at a table in one of the city's countless bars, are about to finish another pitcher of local beer. They are Artur Ekert, a Polish-born cryptologist and a Research Fellow at Merton College at the University of Oxford; Leong Chuan Kwek, a Singapore native; Briton Hugo Cable; Brazilian Marcelo Franca Santos; and Björn Hessmo of Sweden. While enjoying their drinks, they are also trying to find a trace of comprehensive tactics in the chaotic mess of ball-kicking they are watching on a plasma screen above: a soccer game played somewhere halfway across the world.

"My father always wanted me to become a soccer player. And I have failed him so miserably," says Hessmo. His words are met with a nod of understanding. So far, the game has provided the men with no excitement. Their faces finally light up with joy only when the score table is displayed with the results of Round One of the ongoing tournament. Zeros and ones – that's exciting! All of them are quantum information physicists: zeroes and ones is what they do.

Nauka

SCIENCE DRIVE 2

W Singapurze przy Science Drive 2 powstał ośrodek badań najskrytszych tajemnic przyrody. Przyciąga ekscentrycznych i zdolnych młodych fizyków – również Polaków.

Karol Jałochowski
Z SINGAPURU

Dziwność dla zuchwałych

Letnia noc, upalna jak wszystkie, również te grudniowe, noce w leżącym tuż nad równikiem Singapurze. W jednej z niezliczonych knajp kryptolog polskiego pochodzenia, kawaler Merton College w Oksfordzie, Artur Ekert (pisaliśmy o nim w POLITYCE 27), krajowiec Kwek Leong Chuan, Brytyjczyk Hugo Cable, Brazylijczyk Marcelo Franca Santos i Szwed Björn Hessmo opróżniają kolejny dzban lokalnego piwa. Usiłują dostrzec na telebimie elementy taktyki w nieskładnej kopaninie uprawianej gdzieś na drugim końcu świata. Hessmo mówi: – *Mój ojciec chciał zawsze, żebym został piłkarzem. A ja tak się stoczyłem.* Jego słowa zostają przyjęte ze zrozumieniem. Na ekranie nuda. Dopiero kiedy wyświetlona zostaje tabela punktacji po serii pierwszych meczów turnieju, panowie, sami fizycy, nagle radośnie się ożywiają: zera i jedynki! Jedynki i zera – to ich chleb powszedni.

Jak widać, zamiłowanie do fizyki to przypadłość, której nie zdoła zapobiec najlepsza nawet rodzina. Szczęśliwie jest na świecie kilka ośrodków, które korzystają z objawów tej przypadłości – ku chwale nauki. Wśród nich jest nowo powstałe Centre for Quantum Technologies (CQT), skupiające się na badaniach podstawowych. To prawdziwa osobliwość w technokratycznym, zorientowanym na szybki przekład wiedzy na zastosowania Singapurze – i symbol ▶

© KAROL JAŁOCHOWSKI

REKLAMA

▲ *Originally published in Polish, POLITYKA 41, 85 (2010). Read the translated article in full at: www.quantumlah.org/highlight/071010_polityka.php*

As Hessmo's story illustrates, one's passion for physics is a condition not easily uprooted, not even by the strictest of upbringings. Thankfully, there are a few places in the world where those affected by this peculiar condition are welcomed with open arms, and where their strange fixations are put to good use for the benefit of science. One such place is the newly opened Centre for Quantum Technologies (CQT), where the focus is on basic research. The centre is truly a singularity by Singapore's standards: its philosophy challenges the local principle of taking a technology-driven, practical approach. CQT is also a symbol of the new vision of development that is gaining ground in this vast city of 4.6 million people...

Audacity sets the tone

…Asked why he agreed to accept the challenge of leading the new centre, [Artur] Ekert explains: "Doing science in established places like Oxford, the Massachusetts Institute of Technology, or the California Institute of Technology is easy; here, on the other hand, where everything has to be built from scratch, one gets a chance to really make a difference."

In his search for the right people to run the centre, Ekert faced a dilemma: Should he bank on established scientists – or pursue the young, the bold, the ambitious ones? "I got the best doctoral candidates in the business, the people who still think of proving things rather than just patenting them," he explains. Today, the staff of the Singapore centre consists of 90 scientists from 24 different countries; it also retains dozens of research fellows and a wide network of consultants and advisers. Ekert was able to assemble one of the most unique scientific teams in this field: "I don't shy away from hiring people who are deemed eccentric or difficult. A scientist does not have to be nice and cuddly; it's the creativity that counts," he says…

One has to be brave

How to inspire originality in people, which seems to be the key to understanding the bizarre world of quantum mechanics? How to provoke them so they question the opinions of their teachers? In Asia, where the common mentality bears a strong imprint of Confucianism, this challenge is particularly daunting (they say the younger generation tends to be more independent-minded), but it is almost as difficult in the hedonistic and statist West. "I often ask people what would they want to do if they only had five years to live," Ekert tells me, "And you know what? They get scared." In Singapore, the team seems less frightened. Perhaps the reason for this is CQT's unwritten rules; they are: No micromanagement. No job titles. "Here there is no reason to feel embarrassed when nine out of ten of your ideas turn out to be crap – it's sort of a given things will turn out this way," says Elisabeth Rieper, a PhD student from Germany. "And then there is this one that may turn out to be dynamite."…■

The Singapore-Oxford connection

Dieter Jaksch explains how shared postdocs are building strong ties between two centres of quantum research. Dieter is a Visiting Research Professor at CQT and a Professor of Physics at the University of Oxford.

Research collaborations between CQT and the University of Oxford in the UK, have been in place since CQT started under the directorship of Artur Ekert, who holds professorships in both places. Over the past year, the collaborations have gained particular momentum, with an increasing number of researchers from both institutions working on joint projects. The scientists' complementary skills and expertise, and the bigger pool of brains, push projects forward faster than would otherwise be possible.

To a large degree, CQT and Oxford's strong ties are thanks to a joint postdoc scheme. CQT invites some of the young, aspiring scientists it hires as Research Fellows to share their time between CQT and the University of Oxford. These CQT–Oxford postdocs are associated with one research group at each institution, and they are encouraged to initiate new research directions and collaborative projects. They thus form an important backbone of the CQT–Oxford connection. In 2010–11, five new postdocs joined the scheme.

Only high-calibre scientists with potential to become leaders in their fields are selected for the shared posts. The posts are intended to be one of the final career steps before a faculty position at an internationally leading research institution. Being attached to two research centres gives the Fellows the opportunity to build a more diverse professional network and gain expertise in a wider range of research areas than could be achieved at either centre alone. Fellows can also gain teaching and teaching-management experience through involvement in the small-group tutoring provided to undergraduates in Oxford colleges.

Brian Smith was one of the first postdocs in the scheme. A Research Fellow in 2009-10, his experimental work focused on the generation and characterization of quantum states of light, geared towards applications in quantum communication and quantum-enhanced precision measurements. Based on this research, Brian secured a post at the University of Oxford — a University Lectureship in Atomic and Laser Physics in conjunction with a Tutor- and Fellowship at Keble College — starting in 2010.

Stephen Clark joined the scheme after completing his theoretical DPhil

▲ *Dieter Jaksch and Xian-Min Jin are involved in a project creating quantum entanglement between macroscopic diamonds.*

▲ *Stephen Clark (left) and Uwe Dorner (right) at Keble College, University of Oxford.*

on tensor networks for describing the ground states and dynamics of strongly correlated quantum systems. His research focuses on connections between the complexity of classical descriptions of quantum systems and the amount and character of entanglement contained in them. The insights gained from this research have led to application of novel numerical methods for simulating strongly correlated matter in a range of systems including ultra-cold atoms, organic Mott insulating salts at room temperature, and even classical 'real world' systems such as vehicular traffic flow.

New recruits to the CQT–Oxford postdoc scheme are Xian-Min Jin, an experimental physicist working on the realization of memory-enabled photonic quantum networks; Uwe Dorner, a theoretical physicist exploring methods for quantum-enhanced metrology and quantum networks; Erik Gauger, a material scientist researching spin-based quantum computation; Alastair Kay, a mathematical physicist studying theoretical aspects of quantum information processing, with a particular focus on quantum networks and quantum memories; and Jamie Vicary, a computer scientist working on categorical models of nonlocality and entanglement.

Erik's work is carried out within an interdisciplinary research project partly funded by the John Templeton Foundation, a philanthropic organisation. The Templeton-funded project, which started this year, goes beyond traditional research in quantum technology to include questions on quantum logic and the philosophical study of the implications of quantum physics for our understanding of the Universe.

It is not only postdocs that link the centres, and the exchanges aren't only academic, with staff visits helping to share best practices. In research, additional collaborations are led by the handful of academics that split their time between CQT and Oxford. For instance the theoretical description of coupled cavity arrays, systems that could enable coherent transfer of quantum information between light and matter, has recently been enhanced through a joint effort of Oxford and CQT researchers Tom Grujic, Stephen Clark, Dimitris Angelakis and myself. This is expected to lead to novel insights in quantum optics with strongly correlated atoms, an emerging field of quantum technologies where both light and matter need to be described fully quantum mechanically. ■

Graduate programmes

The Centre for Quantum Technologies is committed to training the next generation of scientists. It attracts talented students from around the world 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 and will soon see its first graduates. The inaugural intake was in August 2008 after the Centre was founded at the end of 2007. There are currently 40 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 stipendiary 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 during the period of April to July 2012 (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. ■

▶ *CQT Principal Investigator Berge Englert (left), seen here meeting with students in his office, coordinates the CQT student programmes.*

▼ *In 2011, CQT had around 40 students pursuing PhD degrees. This year has also seen the very first batch of PhD@CQT students getting ready to graduate. CQT congratulates them on their research achievements so far, and we look forward to following their careers in the future.*

The student life

True enough, there are free cookies in CQT's Quantum Café, but the life of a grad student at CQT is not much like kindergarten otherwise. Students at CQT, whether enrolled in the PhD programme or doing a stint as an intern, participate fully in the Centre's projects and are encouraged in their research interests. Here three students explain how they came to study at CQT and what they have thought of the experience.

Elisabeth Rieper

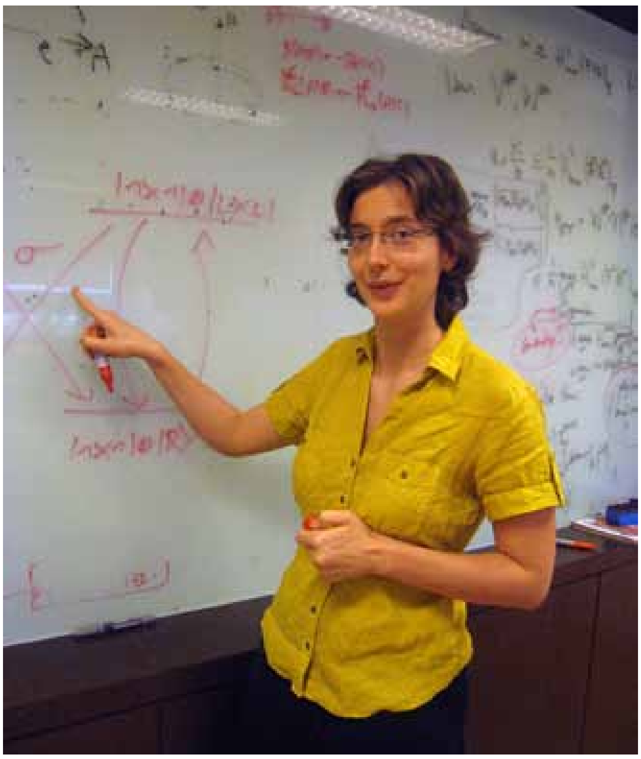
CQT PhD student from January 2008
Thesis submitted
Supervised by Vlatko Vedral

Joining CQT as a PhD student was an important step in my life.

After I finished my physics 'Diplom' in Germany I started research on 'Quantum coherence in biological systems' under the supervision of Vlatko Vedral at CQT. Nobody can anticipate what it is going to be like to move to the other end of the world and enrol at a brand new institute where half the staff have not yet been hired. This move had a great influence not only on my academic path but also on my private life. I am now finishing my PhD and I can say that choosing CQT was a great decision.

From the academic point of view, there have been many positives. One is having so many experts in the field of quantum information together. Students can freely choose with whom to work. A downside is that neighbouring institutions are far away (8 hours flight to Sydney, 12 to Europe, 6 to Beijing, 8 to Japan), but that is balanced by generous travel support for students. I enjoyed the chance to present my research at several conferences and participate in physics schools.

"Piled Higher and Deeper" by Jorge Cham



My work focused on quantum biology, i.e. the search for nontrivial quantum effects in biological systems. One success came from studying 'flying qubits' – but not the conventional kind. We investigated how spin-spin entanglement may allow living birds to navigate by Earth's magnetic field, leading to a paper in *Physical Review Letters*. When I started this research the field was brand-new. This was a huge advantage for me. Even as a student I could contribute significantly and was invited to present my research.

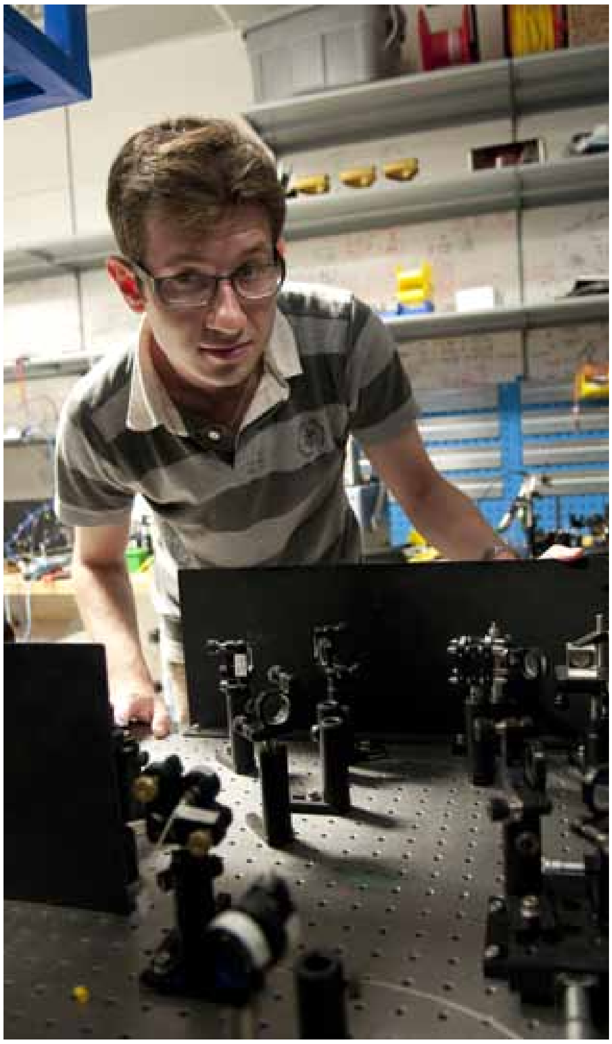
CQT has a never-ending flow of visitors, which is great for making new contacts and staying in touch with the world. Some visitors also give guest lectures on their field of expertise, which is a great opportunity to learn. Another upside at CQT is the flat hierarchy. If you want to change something, even if you have just started as a student, your ideas will be taken seriously and supported. This allowed me to develop more confidence in important skills beyond mathematics and physics.

While I believe that other institutes could offer a similar academic profile, I am certain that no place in the world offers the feeling of being in Singapore, which is a true cultural hot-pot. My years in Singapore have shaped my character and helped me become a citizen of the world. The researchers at CQT speak at least 22 different languages and every nationality brings its own special character. After suffering a few OMG moments – for example, not everyone shared my punctual German attitude to appointment times – I came to understand and better appreciate other cultures. I have also learnt to speak a little Mandarin.

I haven't yet finalised my plans for the future, but I know that my academic and personal achievements at CQT have given me the best preparation for my coming work life.

Michael Kalenikin

CQT Intern May–October 2011
Masters student at ETH Zürich, Switzerland
Supervised by Christian Kurtsiefer



I first heard about the opportunity to do an internship at CQT from my professor at ETH Zurich in Switzerland, where I am a Masters student in my final year. He warmly recommended CQT as a good place for research in quantum optics.

Quantum optics lies at the heart of my scientific interest. I am intrigued by the counter-intuitive phenomena that can be studied in quantum optics labs, making my decision to apply for a four-month internship in such a lab very straightforward. The application process was straightforward, too. Only a few months after contacting Christian Kurtsiefer, I was starting my first day at work here. CQT's staff was very helpful in making the internship happen so quickly and in an uncomplicated way.

My internship focuses on efficient sources of entangled photon pairs and their applications. I was thrilled by the opportunity to work with one of the best groups in this field. Indeed, my internship at CQT is proving a great learning experience.

Singapore as a place captivates the newly-arrived visitor. But as you get used to your exotic surroundings, you come to fully appreciate the merits of CQT — its facilities, its spirit and its talented and friendly people.

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, which to me is one of the defining characteristics of CQT. I have also been struck by the physical proximity and top-level collaboration between theoretical and experimental physicists, which I witness at CQT on a daily basis.

The internship at CQT has effectively shaped my understanding of work as a scientist and is an experience I would not have wanted to miss.

Le Phuc Thinh

CQT PhD student from July 2011
NUS Outstanding Undergraduate Researcher Prize
Supervised by Valerio Scarani

My connection to CQT started in my second year as a physics undergraduate at NUS when a friend of mine, Charles Lim, who was working in CQT's experimental labs, introduced me to Valerio Scarani. Valerio offered me a place as an intern to study nonlocality and quantum cryptography.

After the internship, I stayed in Valerio's group to work on my final year project. My project extending the reference frame independent protocol for quantum key distribution to d-level systems earned me the Outstanding Undergraduate Researcher Prize from NUS.

I finally decided to do a PhD at CQT because it offers a friendly atmosphere yet stimulating research environment. The Centre also offers me the opportunity to work with many competent researchers, both those based here and visitors in the field. It has been a good experience to be a CQT PhD student so far. ■

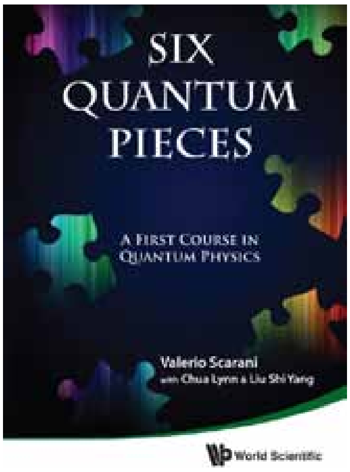
No degree needed

When CQT Principal Investigator ***Valerio Scarani*** *decided to write a textbook introducing quantum physics to pre-University students, he asked for help… from two such students. Valerio and his coauthors* ***Chua Lynn*** *and* ***ShiYang Liu****, then students at NUS High School in Singapore, describe how* Six Quantum Pieces – A First Course in Quantum Physics *came about.*

The beginning

ShiYang: Quantum Physics? If you had quizzed me on quantum physics when I was still a Secondary 4 student, you would have got only a puzzled look. At the time, my ideas about quantum physics were fuzzy but I found it unexplainably interesting. After I accidentally stumbled into a lecture theatre in school where Professor Valerio happened to be giving a talk, I was more determined than ever to learn quantum physics.

Valerio: Nanyang Technological University, Singapore, 6 March 2009. I am walking around a poster session by students of NUS High school. Several of them had visited CQT two weeks earlier. Here is Darryl, who had smiled when I had told them that quantum physics was too much at their age. There is Nicholas, one year older, with an impressive poster on quantum NOON states. And there, a two-girl team who would be quite keen to take on some quantum project. A sudden thought: maybe, something can be done…



Six Quantum Pieces:
A First Course in Quantum Physics
Valerio Scarani with Chua Lynn and Liu Shi Yang
Cover and illustrations by Haw Jing Yan
Published by World Scientific
ISBN: 978-981-4327-53-4, 981-4327-53-0
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Available September 2010
160 pages

Lynn: When ShiYang and I were in our fifth year of NUS High, we met Prof. Valerio on several occasions: during a school visit to CQT, and at a science fair and presentation. We were interested in learning about quantum physics, thus when Prof Valerio kindly proposed that we write with him a booklet introducing quantum physics to high school students, we were grateful for the opportunity. Our task was to write the concepts at a level targeted at high school students.

ShiYang: The idea of writing a booklet on quantum physics for interested students of our age was born. That was it, a small booklet, nothing fantastically difficult about it ... or so it seemed.

The toughest moments

Lynn: Like all collaborations, there were tough moments in this project. Being high school students, we had to balance several commitments, from school work to competitions, and there were times when we had difficulty finding time to work on the book.

Valerio: Why should training for Physics Olympiads have priority over writing a book? Which is the most lasting and original endeavour of the two, for those two students? Will I ever understand the priorities of Key Performance Indicators?

ShiYang: For me, the toughest moments were going through the tedium of proof-reading. The initial excitement of absorbing new concepts gave way to the more boring and mechanical process of double, triple and multiple- checking mathematics and grammar. After editing the same section for the umpteenth time, the mind is so conditioned that mistakes slip through like fish through a tattered net.

Lynn: Fortunately we were able to work everything out and finish the book as scheduled.

The outcome

Lynn: When the book was finally published, I felt glad that our hard work over the past year had paid off, especially when many of my friends and schoolmates took an interest. We hope that the book will allow many people to understand more about quantum physics, and even inspire them to study it in greater depth. I am also grateful to everyone who helped in publishing this book.

ShiYang: When I first received the hardcopy of the book, it felt like a dream. I traced the puzzle pieces on the cover with my fingertips, savouring the feel of the paper. We had only ‘seen’ our book on the computer as we edited it, so I felt surprise, relief and joy as the real, physical book weighed on my hands. I’m grateful for all the help we received to make this book possible. Hopefully as I learn more about quantum physics, we can produce further, better editions.

Valerio: I am certainly pleased at the reception the book has received, especially that some colleagues at universities in Bristol, Brisbane and Calgary are using it to form undergraduate and even graduate students. But a published book has to live its own life, which means – yes, I am hopeless in promotion: but there are so many interesting things to do in one’s lifetime! ■

▲ *From left to right, Haw Jing Yan, who drew cartoons for the book, CQT Principal Investigator Valerio Scarani and his co-authors Lynn and ShiYang, then students at NUS High School. ShiYang and Lynn are now undergraduates at the Massachusetts Institute of Technology in Cambridge.*

Interview with Lam Chuan Leong

Among the distinguished members of CQT's Governing Board is civil servant ***Lam Chuan Leong****, who chairs the board. We asked him a few questions.*

How did you come to be involved with CQT?
I was approached by the Permanent Secretary of the Ministry of Education.

Could you please explain your role as chair of the Governing Board?
I was told that the chair is to ensure that the Centre is well run and to ensure that it has good governance.

You are officially an Ambassador-at-Large for Singapore's Ministry of Foreign Affairs (MFA). What does this entail?
My duties are to help in giving an economic input into the MFA's activities particularly in relation to new countries and region.

▲ *Mr Lam Chuan Leong (right) breaks for coffee with CQT Director Artur Ekert at the 14th Workshop on Quantum Information Processing in Singapore in January, at which he gave the opening address.*

You dedicated your career to the Administrative Service, holding many and various senior positions, including serving as Principal Private Secretary to Singapore's Prime Minister. What have been some highlights of your career? Do you have any reflections on the changes you have seen in Singapore over this period?
I have been privileged to help set up two key statutory boards, the Infocomm Development Authority and the Competition Commission. These activities have helped me in promoting sound economic practices in both the public and business sectors. It is gratifying to see both of them and eventually the CQT blossom from the initial buds.

You graduated with a BSc in physics from NUS in 1970. Was it a shock to go from science to politics? Do you think you benefited in your later jobs from having studied a "hard numbers" science, and if so, how?
This transition was unexpected. Physics and mathematics both helped in clarifying new concepts from economics. It was therefore easy for me to come to teach myself economics. Conversely, I believe that it would be more difficult for a soft scientist to teach himself or herself physics. Basically, physics and maths are both very useful in that they train the mind to be critical and logical. This is most useful in Singapore where someone has described public management as a high form of rationality tempered by pragmatism.

On a light note, is it true that you were behind the ban on chewing gum in Singapore? This is a rule the city is famous for. How did this come about, and what do you think of it now?
I am merely an implementer, not an initiator of this ban. The rationale is that the residue of gum was responsible for jamming HDB lifts and MRT train doors. They pose a social nuisance and entails considerable cost to remove. Interestingly enough, the UK eventually imposed a fine on anyone who left behind the gum residue for the same reasons. I think the ban is still relevant; most do not miss chewing gum.

Somehow, you also seem to have found time for other activities. You contributed to an exhibition of travel photos at CQT. Could you tell us more about your interest in and enthusiasm for photography?
I wish I had more time for photography. I do it on and off. I have been much inspired by Ansel Adams in nature photography (witness his work on Yosemite) and Henri Cartier-Bresson for his work on people and street photography. There is a lot to learn in this art still.

Have you enjoyed returning to science in your role at CQT? Are there any aspects of the Centre's research or operations that have particularly interested you?
Not quite right to say I have returned. The science in CQT is only for the young. I believe it is Eric Temple Bell who said that if you are not a PhD in math by 19, you can forget about a career in that subject; there simply is too much to learn. I have long passed the stage where I can return to science. At most I can appreciate its beauty and general outlines and share in its excitement, its holy grail and its value in the pursuit of truth (speaking loosely) and beauty (Bertrand Russell says pure maths shares the austere beauty of sculpture).

What influence do you think CQT has had on Singapore's research scene and how Singapore science is perceived internationally?
Artur is better at answering this. However, I think CQT set an excellent model for research that is not immediately to be applied. It is a significant milestone in that it demonstrates Singapore's greater appreciation of fundamental knowledge and not just the immediate practical returns. The results are good for humanity and not just for short run business benefits. This sort of value resonates in the hearts of all true scientists. ■

Publications

CQT researchers and their collaborators published 60 papers peer-reviewed places in the year to 20 August. Here is a list. Papers are ordered chronologically with descriptions of selected results adapted from news highlights published on CQT's website.

Surprise link between quantum phenomena

CQT's Stephanie Wehner and Jonathan Oppenheim from the University of Cambridge, UK, uncovered a fundamental link between 'nonlocality' and 'uncertainty', the two defining properties of quantum mechanics. Their finding, published in *Science*, adds to our basic understanding of quantum mechanics. It addresses the question of why quantum behaviour is as weird as it is — but no weirder.

Nonlocality determines how well two distant parties can coordinate their actions without sending each other information. Quantum mechanics allows better coordination than would be possible under the laws of classical physics. Einstein famously referred to this phenomenon as "spooky action at a distance".

However, quantum nonlocality could be even spookier than it actually is. It's possible to imagine theories that allow distant parties to coordinate their actions better than nature allows, while still respecting the rule that no information should travel faster than light. Nature could be weirder, and yet it isn't. Quantum theory appears to impose an additional limit on nature's weirdness. Where does this limit come from?

▲ *Attaining nonlocality stronger than allowed in quantum theory would require us to break the uncertainty principle -- there is no telling what may be unleashed! Cartoon Illustration by Frans Bartels, concept by Haw Jing Yan.*

The surprising result by Stephanie and Jonathan is that the uncertainty principle provides an answer. The Heisenberg Uncertainty Principle says that it is impossible to know certain things, such as a particle's momentum and position, simultaneously: knowledge of one property affects the accuracy with which you can learn the other. It turns out this principle imposes a strict bound on how strong nonlocality can be.

"It would be great if we could better coordinate our actions over long distances, as it would enable us to solve many information processing tasks very efficiently," Stephanie says. "However, physics would be fundamentally different. If we break the uncertainty principle, there is really no telling what our world would look like."

Science news outlets *Cosmos*, *Wired*, and *New Scientist*, among others, ran stories about the work.

The Uncertainty Principle Determines the Nonlocality of Quantum Mechanics
Jonathan Oppenheim and Stephanie Wehner
Science 330, 1072 (2010); arXiv:1004.2507

Query complexity

CQT Research Fellow Troy Lee and Visiting Professor Mario Szegedy have contributed to a new result in quantum query complexity. A paper describing the work was accepted for the 52nd Annual IEEE Symposium on Foundations of Computer Science (FOCS 2011), a prestigious conference in computer science.

Quantum query complexity is a simplified model of quantum computation in which algorithms are formulated as a sequence of queries to the input. For example an algorithm to solve the problem "does this graph have a triangle?" would proceed via queries such as "is there an edge between vertex i and j?".

As the algorithm is quantum, these queries can be made in superposition. The total number of queries required is a measure of the hardness of the problem the algorithm tackles and, as long as appropriate queries can be identified quickly, the query complexity is also a measure of how long the algorithm will take to run. Well-known quantum programs such as Grover's search algorithm and Shor's factorization algorithm can be formulated in the query model.

Troy, Mario and their collaborators show that the query complexity of a problem is approximately equivalent to a new quantity that measures the distance between a successful algorithm's initial and final states. "Hopefully, this characterization will aid in finding new algorithms and resolving the query complexity of some open problems," says Troy. The information-theoretic measure is related to a previously studied quantity known as the 'Schur product operator norm'.

Quantum query complexity of state conversion
Troy Lee, Rajat Mittal, Ben Reichardt, Robert Spalek, Mario Szegedy
Proceedings of IEEE FOCS, 2011; arXiv:1011.3020

A time-dependent Tsirelson's bound from limits on the rate of information gain in quantum systems
Andrew C. Doherty, Stephanie Wehner
New J. Phys. 13 073033, 2011; arXiv:1105.2268

A Parallel Approximation Algorithm for Positive Semidefinite Programming
Rahul Jain, Penghui Yao
Proceedings of IEEE FOCS, 2011; arXiv:1104.2502

The influence lower bound via query elimination
Rahul Jain, Zhang Shengyu
Theory of Computing 7 147, 2011; arXiv:1102.4699

Optimal bounds for quantum bit commitment
Andre Chailloux, Iordanis Kerenidis
Proceedings of IEEE FOCS, 2011; arXiv:1102.1678

Fully Distrustful Quantum Cryptography
J. Silman, A. Chailloux, N. Aharon, Iordanis Kerenidis, S. Pironio, S. Massar
Phys. Rev. Lett. 106 220501, 2011; arXiv:1101.5086

Magnet field sensing beyond the standard quantum limit under the effect of decoherence
Yuichiro Matsuzaki, Simon C. Benjamin, Joseph Fitzsimons
Phys. Rev. A 84 012103, 2011; arXiv:1101.2561

On Arthur Merlin Games in Communication Complexity
Hartmut Klauck
Proceedings of IEEE CCC 189, 2011; arXiv:1101.0523

Does ignorance of the whole imply ignorance of the parts? Large violations of non-contextuality in quantum theory
Thomas Vidick, Stephanie Wehner
Phys. Rev. Lett. 107 030402, 2011; arXiv:1011.6448

More non-locality with less entanglement
Thomas Vidick, Stephanie Wehner
Phys. Rev. A 83 052310, 2011; arXiv:1011.5206

Quantum query complexity of state conversion
Troy Lee, Rajat Mittal, Ben Reichardt, Robert Spalek, Mario Szegedy
Proceedings of IEEE FOCS, 2011; arXiv:1011.3020

Rapid and robust spin state amplification
Tom Close, Femi Fadugba, Simon C. Benjamin, Joseph Fitzsimons, Brendon W. Lovett
Phys. Rev. Lett. 106 167204, 2011; arXiv:1011.1217

Quantum Commitments from Complexity Assumptions
Andre Chailloux, Iordanis Kerenidis, Bill Rosgen
Proceedings of ICALP, 2011; arXiv:1010.2793

Self-testing graph states
Matthew Edmund McKague
Proceedings of TQC, 2011; arXiv:1010.1989

Tight bounds for classical and quantum coin flipping
Esther Hänggi, Jürg Wullschleger
Proceedings of TCC, 2011; arXiv:1009.4741

Entangling unstable optically active matter qubits
Yuichiro Matsuzaki, Simon C. Benjamin, Joseph Fitzsimons
Phys. Rev. A 83 060303, 2011; arXiv:1009.4171

On the hitting times of quantum versus random walks
Frederic Magniez, Ashwin Nayak, Peter C. Richter, Miklos Santha
Algorithmica DOI: 10.1007/s00453-011-9521-6, 2011; arXiv:0808.0084

Super-quantum non-local correlations in quaternionic quantum theory
Matthew Edmund McKague
Int. J. Quant. Info. DOI No: 10.1142/S0219749911008052, 2011

On the Power of Lower Bound Methods for One-Way Quantum Communication Complexity
Zhang Shengyu
Proceedings of ICALP, 2011

Search via Quantum Walk
Frederic Magniez, Ashwin Nayak, Jeremie Roland, Miklos Santha
SIAM Journal of Computing 40 142, 2011; arXiv:0608026

Improved Bounds for the Randomized Decision Tree Complexity of Recursive Majority
Frederic Magniez, Ashwin Nayak, Miklos Santha, David Xiao
Proceedings of ICALP, 2011

Atomic trios promise robust quantum data storage

Physicists working on designs for quantum computers are dealing with an urgent problem: how to preserve data for long enough to complete operations and read out the result. In a paper published in *Physical Review A*, CQT researchers and their collaborators assess a design for quantum data storage that could offer a million-fold improvement in lifetime over the current experimental best.

Quantum states are readily affected by properties of the environment such as stray magnetic fields. As a result, the quantum state decoheres, which equates to erasure of any stored data. With current technology, decoherence times may reach a few seconds. CQT's Berthold-Georg (Berge) Englert and Han Rui, and their collaborators, show that data stored in a novel 'reference-frame-free' quantum bit (see figure) could survive with 99.99% fidelity for two hours. The decoherence time would be many times longer.

Building on previous proposals for reference-frame-free qubits, the paper presents detailed calculations of the scheme's experimental performance. Specifically, realistic assumptions are made for qubits stored in sets of three Lithium-6 atoms trapped in an optical lattice created by carbon-dioxide lasers.

▲ *The reference-frame-free qubit is stored in the combined state of three spin-1/2 atoms which is resistant to perturbations from the environment, such as stray magnetic fields. This is an artist's impression of three-atom state.*

Before pursuing this qubit design for quantum computers, however, one important piece of the puzzle remains. As Han Rui explains, "We proved the qubit is robust. Now the next step is to work out smart schemes for encoding, decoding and manipulating information."

Long-lived qubit from three spin-1/2 atoms
Han Rui, Niels Lörch, Jun Suzuki, Berge Englert
Phys. Rev. A 84 012322, 2011; arXiv:1008.1523

The bird's-eye view

European robins delivered researchers at CQT a paper in *Physical Review Letters*. With collaborators at the University of Oxford, UK, CQT's Vlatko Vedral, Simon Benjamin and Elisabeth Rieper analysed the results of a recent experiment on the robins' ability to perceive magnetic fields.

Photo: Walter Corno CC-BY-NC-SA

The CQT and Oxford scientists are interested by the idea that quantum effects can be important in the 'warm and wet' environment of life, when quantum experiments in the lab often require very cold temperatures and vacuum conditions.

One theory for how birds' magnetic compass operates, known as the radical pair (RP) mechanism, relies on the evolution of a quantum state of two electron spins under the influence of Earth's magnetic field. The RP mechanism supposes that light excites the electron-spin pair in special molecules at the back of the bird's eye.

Experiments by other researchers had shown that exposing robins to a small oscillating magnetic field disrupts their ability to orientate. Considering the oscillating magnetic field as 'noise' that disturbs the quantum state of the electron-spin pair, the CQT and Oxford scientists estimated the state's robustness. Their calculations suggest that the electron spins remain in a coherent and entangled state for at least tens of microseconds. The best artificial molecular systems for preserving coherence in the lab (such as atoms trapped in carbon buckyballs) only manage 80 microseconds at room temperature.

Protecting the coherence and entanglement of quantum states is important in designs for practical quantum technologies such as computing systems. Do birds do something that quantum information scientists can learn from?

Sustained Quantum Coherence and Entanglement in the Avian Compass
Erik Gauger, Elisabeth Rieper, John J. L. Morton, Simon Benjamin, Vlatko Vedral
Phys. Rev. Lett. 106 040503, 2011; arXiv:0906.3725

State detection using coherent Raman repumping and two-color Raman transfers
Chuah Boon Leng, Nicholas Charles Lewty, Murray Barrett
Phys. Rev. A 1 84 013411, 2011, arXiv:1105.0763

Detection of Single Molecules Illuminated by a Light-Emitting Diode
Ilja Gerhardt, Mai Lijian, Antia Lamas-Linares, Christian Kurtsiefer
Sensors 11 905, 2011, arXiv:1101.2773

All-Optical BEC in a 1.06 μm dipole trap
Kyle Arnold, Murray Barrett
Optics Comm. 284 3288, 2011, arXiv:1101.1140

Full-field implementation of a perfect eavesdropper on a quantum cryptography system
Ilja Gerhardt, Qin Liu, Antia Lamas-Linares, Johannes Skaar, Christian Kurtsiefer, Vadim Makarov
Nature Communications 2 349, 2011, arXiv:1011.0105

Sagnac-loop phase shifter with polarization-independent operation
Ng Tien Tjuen, Darwin Gosal, Antia Lamas-Linares, Christian Kurtsiefer
Rev. Sci. Instrum. 82 013106, 2011, arXiv:0804.2135

Impurity transport through a strongly interacting bosonic quantum gas
T.H. Johnson, Stephen Clark, M. Bruderer, Dieter Hans Jaksch
Phys. Rev. A 84 023617, 2011, arXiv:1106.3650

The Basics of Perfect Communication through Quantum Networks
Alastair Kay
Phys. Rev. A 84, 022337 2011, arXiv:1102.2338

Correlation induced non-Abelian quantum holonomies
Markus Johansson, Marie Ericsson, Kuldip Singh, Erik Sjoqvist, Mark Simon Williamson
J. Phys. A: Math. Theor. 44 145301, 2011, arXiv:1011.5182

Making quantum cryptography truly secure

CQT physicists-turned-hackers and their collaborators published in *Nature Communications* details of work that led to tightened security for quantum key distribution (QKD) systems.

QKD enables secure communication by providing each party with a 'key' to scramble and unscramble their messages. An attraction of QKD is that, in principle, the security of the key exchange is guaranteed by physics.

Researchers from Christian Kurtsiefer's group at CQT collaborated with scientists from the Norwegian University of Science and Technology in Trondheim, Norway and the University Graduate Center in Kjeller, Norway to perform the first full field-implemented hack of a QKD system, in which an eavesdropper acquired a full secret key without being noticed.

"Quantum key distribution has matured into a true competitor to classical key distribution. This attack highlights where we need to pay attention to ensure the security of this technology," says Christian.

The attack did not target the QKD protocol but a practical behaviour of detectors typically used to implement it. Detectors meant to receive the key sent one photon at a time were blinded, essentially overriding the system's ability to detect a breach of security. The open publication of how the 'perfect eavesdropper' was built had already enabled this particular weak spot in QKD to be fixed.

▲ *Researchers at work: Principal Investigator Christian Kurtsiefer (right) pictured with former CQTians Ilja Gerhardt and Antía Lamas-Linares setting up a quantum cryptography system. Image © 2009 Vadim Makarov www.vad1.com*

Full-field implementation of a perfect eavesdropper on a quantum cryptography system
Ilja Gerhardt, Qin Liu, Antia Lamas-Linares, Johannes Skaar, Christian Kurtsiefer, Vadim Makarov
Nature Communications 2 349, 2011, arXiv:1011.0105

Committed to quantum bits

An open question concerning the security of a type of quantum information protocol known as bit commitment has been answered by CQT Visiting Scholar Iordanis Kerenidis and his collaborator. They presented their work at one of the most important conferences in theoretical computer science, the 52nd Annual IEEE Symposium on Foundations of Computer Science (FOCS 2011).

Bit commitment refers to a scheme where one party, Alice, 'commits' a bit, 0 or 1, to another party, Bob. After committing the bit, Alice should not be able to change it, and the bit should remain secret from Bob. Later Alice reveals the bit to Bob. Neither party trusts the other, and the question is, with what probability can either party cheat?

The cheating probability of Alice is the probability with which she is able to change her committed bit while revealing it. The cheating probability of Bob is the probability with which he is able to guess the bit committed by Alice, before the reveal phase starts. The cheating probability of the protocol is the maximum of these two cheating probabilities. Using quantum protocols a better level of trust can be enforced than can be achieved in classical protocols.

Previously the best known quantum protocol had cheating probability of no more than 3/4 (0.750). It had also been shown that no quantum protocol could have cheating probability less than $1/\sqrt{2}$ (0.707). In the new paper, Iordanis and his coauthor close the gap, showing that the smallest possible cheating probability is 0.739 and identifying a quantum protocol that achieves this.

Optimal bounds for quantum bit commitment
Andre Chailloux, Iordanis Kerenidis
Proceedings of IEEE FOCS, 2011;
arXiv:1102.1678

Perfect Quantum Routing in Regular Spin Networks
Peter J. Pemberton-Ross, Alastair Kay
Phys. Rev. Lett. 106 020503, 2011;
arXiv:1007.2786

Optimal Detection of Entanglement in GHZ States
Alastair Kay
Phys. Rev. A 83 020303, 2011;
arXiv:1006.5197

Quantum interference between charge excitation paths in a solid-state Mott insulator
S. Wall, D. Brida, Stephen Clark, H.P. Ehrke, Dieter Hans Jaksch, A. Ardavan, S. Bonora, H. Uemura, Y. Takahashi, T. Hasegawa, H. Okamoto, G. Cerullo, A. Cavalleri
Nature Physics 7 114, 2011;
arXiv:0910.3808

Parallel approximation algorithm

CQT researchers had three papers accepted for one of the most important conferences in theoretical computer science, the Annual IEEE Symposium on Foundations of Computer Science (FOCS). Selection for such a major conference counts in computer science as publication in a peer-reviewed journal does in physics.

Principal Investigator Rahul Jain and PhD student Penghui Yao presented an algorithm that provides an efficient way to solve 'positive semi-definite programs'. Fast parallel algorithms for solving semi-definite programs have had several applications in the past, including the derivation by Rahul and others of QIP=PSPACE, an important result in theoretical quantum computing.

◀ *CQT researchers (from left to right) Iordanis Kerenidis, Troy Lee, Penghui Yao and Rahul Jain had papers accepted at the prestigious computer science conference FOCS 2011.*

The time the new parallel approximation algorithm takes scales polylogarithmically with the size of the problem, i.e., as (log n)k for problem size n where k is a constant. It gets rid of a polynomial dependence that the previous algorithms of this type had on certain 'width parameters'.

The three CQT papers were among a total of 85 selected for FOCS 2011. "It is encouraging to see the work conducted in our group get recognition," says Rahul. The two other CQT papers are described in the highlights "Committed to quantum bits" and "Query complexity".

A Parallel Approximation Algorithm for Positive Semidefinite Programming
Rahul Jain, Penghui Yao
Proceedings of IEEE FOCS, 2011; arXiv:1104.2502

Quantum ignorance is hard to expose

No-one likes a know-it-all but we expect to be able to catch them out: someone who acts like they know everything but doesn't can always be tripped up with a well-chosen question. Can't they? Not so. Stephanie Wehner at CQT and Thomas Vidick at the University of California, Berkeley, have found that a quantum know-it-all could lack information about a subject as a whole, yet answer almost perfectly any question about the subject's parts.

"This is something conceptually very weird," says Stephanie (pictured). It's a new phenomenon to add to the list of philosophical conundrums in quantum physics. But the work also has practical motivation: understanding how information behaves in the quantum context is important in emerging technologies such as quantum cryptography and quantum computation.

To frame the problem, consider a book. If someone has incomplete knowledge about a book as a whole, one expects to be able to identify the pages or words of which they are ignorant. Stephanie and Thomas simplify the situation to a book with two pages. They invite the usual quantum players, Alice and Bob, to collaborate. Alice reads the book and is allowed to give Bob only one page of notes.

If Bob only gets classical information, it is always possible to work out what he doesn't know. Say Bob is a student trying to cheat in an exam. An examiner, having secretly inspected the notes from Alice, could set questions that Bob couldn't answer. The craziness comes if Bob gets one page's worth of quantum information from Alice. In this case, the researchers show, the examiner cannot pinpoint Bob's ignorance. Challenge Bob and he can guess either page (though only one page) of the book almost perfectly.

Researchers had been trying to prove that quantum ignorance would follow classical intuition and be traceable to ignorance of details, and finding that it isn't raises new questions.

Stephanie and Thomas have begun to design experimental tests and other explorations of this strange new frontier.

Does ignorance of the whole imply ignorance of the parts? Large violations of non-contextuality in quantum theory
Thomas Vidick and Stephanie Wehner
Phys. Rev. Lett. 107 030402, 2011; arXiv:1011.6448

Probing half-odd topological number with cold atoms in a non-Abelian optical lattice
Feng Mei, S L Zhu, Feng Xun-Li, Z M Zhang, Oh Choo Hiap
Phys. Rev. A 84 023622, 2011; arXiv:1107.1755

Converting zitterbewegung oscillation to directed motion
Zhang Qi, J B Gong, Oh Choo Hiap
Europhys. Lett. 96 10004, 2011; arXiv:1105.2884

Testing tripartite Mermin inequalities by spectral joint measurements of qubits
Huang Jinsong, Oh Choo Hiap, L F Wei
Phys. Rev. A 83 062108, 2011; arXiv:1103.5107

Alternative non-Markovianity measure by divisibility of dynamical maps
S C Hou, Yi Xuexi, Yu Sixia, Oh Choo Hiap
Phys. Rev. A 83 062115, 2011; arXiv:1102.4659

Quantum discord of two-qubit X-states
Chen Qing, Zhang Chengjie, Yu Sixia, Yi Xuexi, Oh Choo Hiap
Phys. Rev. A, 84, 042313 2011; arXiv:1102.0181

Detecting full N-particle entanglement in arbitrarily-high-dimensional systems with Bell-type inequalities
J L Chen, Deng Dongling, H Y Su, Wu Chunfeng, Oh Choo Hiap
Phys. Rev. A 83 022316, 2011; arXiv:1010.3762

High effciency tomographic reconstruction of quantum states by quantum nondemolition measurements
Huang Jinsong, L F Wei, Oh Choo Hiap
Phys. Rev. A 83 032110, 2011; arXiv:1009.4252

Device-independent certification of entangled measurements
Rafael Rabelo, Melvyn Ho, Daniel Cavalcanti Santos, Nicolas Brunner, Valerio Scarani
Phys. Rev. Lett. 107 050502, 2011; arXiv:1105.3138

NOON-state formation from Fock-state Bose-Einstein condensates
Hugo Cable, F. Laloë, W. J. Mullin
Phys. Rev. A 5 83 053626, 2011; arXiv:1103.2304

Thermal States as Universal Resources for Quantum Computation with Always-On Interactions
Li Ying, D.E. Browne, Kwek Leong Chuan, R. Raussendorf, Tzu-Chieh Wei
Phys. Rev. Lett. 107 060501, 2011; arXiv:1102.5153

Experimentally realizable control fields in quantum Lyapunov control
Yi Xuexi, S L Wu, Wu Chunfeng, Feng Xun-Li, Oh Choo Hiap
J. Phys. B: At. Mol. Opt. Phys. 44 195503, 2011; arXiv:1102.4895

Extremal correlations of the tripartite no-signaling polytope
Stefano Pironio, Jean-Daniel Bancal, Valerio Scarani
J. Phys. A: Math. Theor. 44 065303, 2011; arXiv:1101.2477

Quantum knowledge cools computers

From a laptop warming a knee to a supercomputer heating a room, the idea that computers generate heat is familiar. But CQT and ETH Zurich scientists discovered something astonishing: not only do computational processes sometimes generate no heat, under certain conditions they can even have a cooling effect. The findings were published in *Nature* and received widespread media coverage.

Not all heat production by computers is an engineering issue. Since the 1960s it has been thought that deleting data in a computer is fundamentally associated with the release of energy. This is known as Landauer's principle.

CQT's Vlatko Vedral (pictured) and Oscar Dahlsten, with collaborators led by Renato Renner at ETH Zurich, Switzerland, showed that the deletion of data can have a cooling effect rather than generating heat when the quantum phenomenon known as entanglement is invoked.

Could the cooling effect be harnessed? So far the work has all been theoretical. "Achieving the control at the quantum level that would be required to implement this in supercomputers is a huge technological challenge, but it may not be impossible. We have seen enormous progress is quantum technologies over the past 20 years," said Vlatko. With the technology in quantum physics labs today, a proof-of-principle experiment on a few bits of data should be possible.

The scientists combined ideas from two different fields – information theory and thermodynamics – about a concept called entropy. Entropy is usually a positive quantity, but in information theory an entangled object can be thought of as having negative entropy. The scientists' work explains the thermodynamic meaning of negative entropy.

The thermodynamic meaning of negative entropy
Lídia del Rio, Johan Åberg, Renato Renner, Oscar Dahlsten, Vlatko Vedral
Nature 474 61, 2011; arXiv:1009.1630

Light could show electrons' personality split

CQT researchers have proposed a new way to study the quantum effect of spin-charge separation, sought since its prediction three decades ago. The approach depends on the simulation of a Luttinger liquid with light.

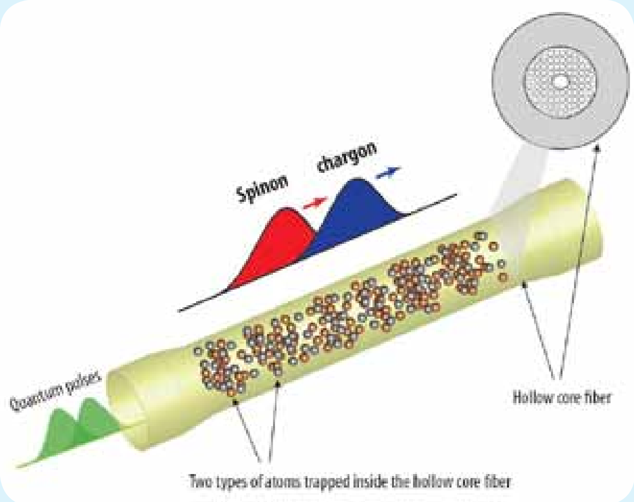
The work by CQT's Dimitris G. Angelakis, Mingxia Huo, Elica Kyoseva, and Leong Chuan Kwek, published in *Physical Review Letters*, was highlighted by the journal as an "Editors' Suggestion", featured in a *Physics* "Viewpoint" article, and selected for the "Research Highlights" section of the weekly journal *Nature*.

Electrons (or other fermions) in one-dimensional conductors are thought to form a 'Luttinger liquid'. Theory suggests that electrons in such a liquid split into a magnetic and an electric part, known as a spinon and a chargon, that move at different speeds.

Experiments to test the idea are challenging. In spite of seminal efforts since the effect was predicted in 1981, scientists have seen no clear proof of spin-charge separation yet.

Dimitris and his collaborators calculate that photons shone into hollow fibres packed with two types of atoms can mimic the predicted splitting behaviour of electrons. This experiment is within reach of current optical technology and, thanks to the wide tunability of the system parameters, it could provide an extremely clean result.

Seeing the equivalent of spin-charge separation in an optical system would not only confirm a major, puzzling prediction of many body quantum physics, but also support the emerging idea of using photonic systems as quantum simulators to understand complex condensed matter effects.



▲ *A schematic of the system under consideration. The way the photons propagate or bounce off the atoms trapped in the fibre is analogous to electrons' spin-charge separation.*

Luttinger Liquid of Photons and Spin-Charge Separation in Hollow-Core Fibres
Dimitris G. Angelakis, Huo Mingxia, Elica Kyoseva, Kwek Leong Chuan
Phys. Rev. Lett. 106 153601, 2011, arXiv:1006.1644

Nonlocality from nothing

Researchers at CQT and collaborators have shown how to conjure something from nothing in the quantum world. They found that quantum states with boringly classical behaviour by themselves can be 'activated' in a group to display quantum theory's bizarre nonlocality. The result, appearing in *Nature Communications*, may provide new clues to physicists struggling to understand where nonlocality comes from.

Nonlocality gives rise to the phenomenon Einstein called "spooky action at a distance"—the apparent ability of quantum particles to coordinate their actions without signals travelling between them. In modern research, nonlocality is viewed as a resource for quantum technologies including cryptographic systems and random number generators.

CQT's Daniel Cavalcanti, Mafalda Almeida, and Valerio Scarani, with Antonio Acin from the Institute of Photonic Sciences in Barcelona, Spain, started by considering a quantum state of some number of particles that does not show any nonlocality. The researchers then imagined creating multiple copies of the same quantum state, overlapping to form a network. Surprisingly, the network can display nonlocal correlations even though it was built from local states. "Each state has nothing of the property but together they have something," says Daniel.

Underlying the work is a fundamental question about the difference between nonlocality and another quantum phenomenon, entanglement. Particles that are linked inseparably in a single quantum state are described as entangled. Nonlocality cannot exist without entanglement, but entanglement does not neccessarily have to lead to nonlocality, a split that has physicists puzzled.

The states that Daniel and his colleagues consider are entangled but local. Finding that these states become nonlocal when multiple copies are made rekindles the sense of connection between entanglement and nonlocality. It may point the way towards a deeper understanding of how these phenomena are related.

Quantum networks reveal quantum nonlocality
Daniel Cavalcanti Santos, Mafalda Almeida, Valerio Scarani, Antonio Acín
Nature Communications 184 2, 2011; arXiv:1010.0900

Large violation of Bell inequalities using both particle and wave measurements
Daniel Cavalcanti Santos, Nicolas Brunner, Paul Skrzypczyk, Alejo Salles, Valerio Scarani
Phys. Rev. A 84 022105, 2011; arXiv:1012.1916

Lenses as an Atom-Photon Interface: A Semiclassical Model
Teo Zhi Wei Colin, Valerio Scarani
Optics Comm. 284 4485, 2011; arXiv:1012.0630

Quantum Bell Inequalities from Macroscopic Locality
Yang Tzyh Haur, Miguel Navascues, Lana Sheridan, Valerio Scarani
Phys. Rev. A 83 022105, 2011; arXiv:1011.0246

Comment on "Loophole-free Bell test for continuous variables via wave and particle correlations (Phys. Rev. Lett. 105, 170404 (2010))"
Daniel Cavalcanti Santos, Valerio Scarani
Phys. Rev. Lett. 106 208901, 2011; arXiv:1010.5358

Efficient excitation of a two level atom by a single photon in a propagating mode
Wang Yimin, Jiri Minar, Lana Sheridan, Valerio Scarani
Phys. Rev. A 83 063842, 2011; arXiv:1010.4661

Effects of uncertainties and errors on Lyapunov control
Yi Xuexi, B Cui, Wu Chunfeng, Oh Choo Hiap
J. Phys. B: At. Mol. Opt. Phys. 44 165503, 2011; arXiv:1010.2088

Local Realism of Macroscopic Correlations
Ravishankar Ramanathan, Tomasz Paterek, Alastair Kay, Pawel Kurzynski, Dagomir Kaszlikowski
Phys. Rev. Lett. 6 107 060405, 2011; arXiv:1010.2016

Correlation complementarity yields Bell monogamy relations
Pawel Kurzynski, Tomasz Paterek, Ravishankar Ramanathan, W. Laskowski, Dagomir Kaszlikowski
Phys. Rev. Lett. 18 106 180402, 2011; arXiv:1010.2012

Quantum networks reveal quantum nonlocality
Daniel Cavalcanti Santos, Mafalda Almeida, Valerio Scarani, Antonio Acín
Nature Communications 184 2, 2011; arXiv:1010.0900

Bound non-locality and activation
Nicolas Brunner, Daniel Cavalcanti Santos, Alejo Salles, Paul Skrzypczyk
Phys. Rev. Lett. 106 020402, 2011; arXiv:1009.4207

Entangling measurements for the cautious

Thinking ahead to an era of commercial quantum technologies, we want to safeguard against unscrupulous suppliers. How to ensure that quantum procedures can be carried out properly even if devices are purchased from a possibly untrustworthy source?

In a paper in *Physical Review Letters*, CQT's Valerio Scarani and his colleagues tackled this problem for quantum teleportation devices, proposing a design that could be certified to function prior to use. The paper was highlighted by the journal as an "Editors' Suggestion".

In order to teleport the state of Alice's system A to Bob's system B, B must be initially entangled with another of Alice's systems (A1). Teleportation occurs when Alice performs a measurement that entangles A and A1. Valerio and other CQT researchers Rafael Rabelo, Melvyn Ho and Daniel Cavalcanti, together with Nicolas Brunner of the University of Bristol, UK, showed how to test that an uncharacterised device creates such entanglement.

In their protocol, the device must be able to perform three measurements: two are used to check that two systems aren't initially entangled, and the third does the desired entangling. Entanglement is then confirmed by a violation of Bell's Inequality — exceeding 2 when quantum correlations are present, reaching a maximum of $2\sqrt{2}$ for maximally entangled states.

As long as the device passes the test, the cautious experimenter can use with confidence the 'entangling' setting in procedures such as teleportation. "It's the first time a device-independent proof has been made for a measurement box," says Valerio. Previous protocols were devised for sources.

Device-independent certification of entangled measurements
Rafael Rabelo, Melvyn Ho, Daniel Cavalcanti Santos, Nicolas Brunner, Valerio Scarani
Phys. Rev. Lett. 107 050502, 2011, arXiv:1105.3138

The thermodynamic meaning of negative entropy
Lídia del Rio, Johan Åberg, Renato Renner, Oscar Dahlsten, Vlatko Vedral
Nature 474 61, 2011; arXiv:1009.1630

Operational interpretations of quantum discord
Daniel Cavalcanti Santos, L. Aolita, S. Boixo, Kavan Modi, M. Piani, Andreas Winter
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Li Ying, Leandro Aolita, Kwek Leong Chuan
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G. Tabia, Berge Englert
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Salman Beigi, Isaac Chuang, Markus Grassl, Peter Shor, Bei Zeng
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The Weights in MDS Codes
Martianus Frederic Ezerman, Markus Grassl, Patrick Solé
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Sustained Quantum Coherence and Entanglement in the Avian Compass
Erik Gauger, Elisabeth Rieper, John J. L. Morton, Simon Benjamin, Vlatko Vedral
Phys. Rev. Lett. 106 040503, 2011; arXiv:0906.3725

Variations on Encoding Circuits for Stabilier Quantum Codes
Markus Grassl
Proceedings of IWCC, 2011

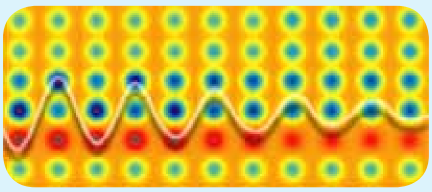
Transparency or spectral narrowing for two-mode squeezing and entanglement
X. Hu, Oh Choo Hiap
Phys. Rev. A 83 053842, 2011

Fully Ramified Characters and Clifford Codes
Alejandro P. Nicolás, Consuelo Martínez, Markus Grassl
Communications in Algebra 39 100, 2011 ■

Probing the quantum dynamics of electrons in a Mott insulator

In work published in *Nature Physics*, CQT researchers Stephen Clark and Dieter Jaksch helped uncover the ultra-fast quantum dynamics of electrons in a Mott insulator. Charges in a Mott insulator form a strongly-correlated system, which makes such materials interesting for the exploration of quantum many-body effects.

State-of-the-art experiments were performed and analysed with collaborators at the Max Planck Research group for structural dynamics at the University of Hamburg and the Clarendon Laboratory at the University of Oxford. The experiments revealed oscillations in the conductivity of a prototypical Mott insulator following excitation by a laser pulse, on a timescale of 10s of femtoseconds (one femtosecond is 10^{-15} seconds). Photo-excitation can be viewed as a



▲ *A theoretical model of charge behaviour in a Mott insulator shows that the probability of a photo-excited electron (blue) appearing away from the hole it left behind (red) oscillates and decreases over time (rightwards), in line with experimental conductivity measurements.*

'photo-doping' process in analogy to doping of conventional semiconductors, allowing the material to conduct by creating free charges and corresponding positive 'holes'.

Stephen and Dieter contributed to the successful theoretical interpretation of the measured conductivity, suggesting the conductivity oscillations arise from the excited electrons being repeatedly pulled back to their holes. In the model the electrons oscillate coherently, exhibiting quantum interference, between a freely propagating state and a state in which they are trapped by the hole.

Beyond revealing fundamental knowledge about charge transport, research of this sort also enhances our understanding of the interaction between lasers and solid matter. Light-induced charge delocalisation holds technological promise. For example, lasers might coherently drive new classes of materials between phases, say into a non-equilibrium superconducting phase.

Quantum interference between charge excitation paths in a solid-state Mott insulator
S. Wall, D. Brida, Stephen Clark, H.P. Ehrke, Dieter Hans Jaksch, A. Ardavan, S. Bonora, H. Uemura, Y. Takahashi, T. Hasegawa, H. Okamoto, G. Cerullo, A. Cavalleri
Nature Physics 7 114, 2011; arXiv:0910.3808

Visitors

CQT was pleased to welcome the following visitors between 18 August 2010 and 20 August 2011.

Antonio Acin
ICFO, Barcelona

Gerardo Adesso
University of Nottingham

Daiki Akimoto
Tohoku University

Boris Altshuler
Columbia University

Luigi Amico
Uni-Catania, Italy

Janet Anders
University College London

Alexia Auffeves
Institute Néel, Grenoble, CNRs

Martin Aulbach
University of Oxford

Joonwoo Bae
Korea Institute for Advanced Study (KIAS)

Pablo Barberis Blostein
IMAS, Universidad Nacional Autónoma de México

Abolfazl Bayat
University College London

Normand Beaudry
ETH Zurich

Almut Beige
University of Leeds

Ingemar Bengtsson
Fysikum, Stockholm

Charles Bennett
IBM Research USA

Ville Bergholm
Harvard University

Mario Berta
ETH Zürich

Jacob D. Biamonte
University of Oxford

Kate Blanchfield
Stockholm University

Isabelle Bouchoule
Institut d'Optique

Jan Bouda
Masaryk University

Fernando Brandao
Universidade Federal de Minas Gerais

Gilles Brassard
Université de Montréal

Aharon Brodutch
Macquarie University

Benjamin Brown
Imperial College

Dan Browne
University College London

Nicolas Brunner
University of Bristol

Iacopo Carusotto
INO-CNR BEC Center

André Carvalho
The Australian National University

Maryvonne Chalony
CNRS

Rakhitha Chandrasekara
University of Morutawa, Sri Lanka

Thierry Chanelière
Laboratoire Aimé Cotton

Darrick Chang
Caltech

Agata Checinska
University of Warsaw

Nicolas Cherroret
University of Freiburg

Frederic Chevy
LKB, ENS, Paris.

Chia Swee Ping
Malaysian Institute of Physics

Chen-Fu Chiang
University of Central Florida

Matthias Christandl
ETH Zurich

Charles Clark
National Institute of Standards and Technology, USA

Gerard Cohen
L'école Télécom ParisTech ENST

Monique Combescot
Institut des NanoSciences de Paris

Jian Cui
Institute of Physics, Chinese Academy of Sciences

Marcelo Cunha
Campus Pampulha - UFMG

Piotr Cwiklinski
Gdansk University of Technology

Ronald de Wolf
CWI, Amsterdam

Dominique Delande
National Center for Scientific Research, France

Xiaolong Deng
Leibniz Universität Hannover

Du Jiangfeng
University of Science and Technology of China

Runyao Duan
University of Technology Sydney

Martial Ducloy
Universite Paris-Nord

Omar Fawzi
McGill University

Matthias Fitzi
ETH Zurich

Joe Fitzsimons
Merton College, University of Oxford

Steve Flammia
Perimeter Institute

Michael Fleischhauer
Universität Kaiserslautern

Angela Florio
University of Bari

Daiji Fukuda
NMIJ/AIST

Tom Gallagher
University of Virginia

Jose Garcia Coello
University College London

Christopher Gaul
Universidad Complutense Madrid

Krzysztof Gawryluk
University of Bialystok

Ge MoLin
Chern Institute of Mathematics

Dario Gerace
Università degli Studi di Pavia

Christian Gogolin
Universität Potsdam

Philip Goyal
Perimeter Institute

Daniel M. Greenberger
City University of New York

Christian Gross
ETH Zurich

Peter Groszkowski
Insitute for Quantum Computing, Waterloo

Andrzej Grudka
Adam Mickiewicz University

Tom Grujic
University of Oxford

Italo Guarneri
University of Insubria at Como

Christopher Hadley
ICFO

Mohammad Hafezi
Harvard University

Heng Fan
Chinese Academy of Sciences

Gabriel Hetet
University of Innsbruck

Hu Bei Lok
University of Maryland

Marcus Huber
University of Vienna

Adrian Hutter
ETH Zurich

Tristan Irvine
University of Oxford

Gabor Ivanyos
Hungarian Academy of Sciences

Karol Jalochowski
Journalist, Polityka

Peter Janotta
Lehrstuhl für Theoretische Physik III der Universität Würzburg

Stacey Jeffery
Institute for Quantum Computing, Waterloo

Wei Jiang
Institute of Physics, Chinese Academy of Sciences

Tomi Johnson
University of Oxford

Robert Jordens
ETH Zurich

Jed Kaniewski
University of Cambridge

Tokishiro Karasawa
National Institute of Informatics, Japan

Siddharth Karumanchi
Birla Institute of Technology and Science, Pilani, India

Artem Kaznatcheev
McGill

Iordanis Kerendis
Universite Paris-Sud

David Kielpinski
Griffith University

Myungshik Kim
Queens University of Belfast

Robert Koenig
Caltech

Hans Kroha
Universitaet Bonn

Sergey Kulik
M.V.Lomonosov Moscow State University

Wataru Kumagai
Tohoku University

Younghun Kwon
Hanyang University

Lam Ping Koy
Australian National University

Antia Lamas Linares
NIST, University of Colorado at Boulder

Jeng Sang Lau
Ministry of Education, Singapore

Veronika Lechner
MPQ.Germany

Arthur Lee
University of Oxford

Su-Yong Lee
Texas A&M University

Frederic Leroux
Université Paris-Sud

Debbie Leung
University of Waterloo

Fu Libin
Institute of Applied Physics and Computational Mathematics

Michael Lim
Rowan University

Lin Hai Qing
Chinese University of Hong Kong

Zhao Liu
Chinese Academy of Sciences

Looi Shiang Yong
Carnegie Mellon University

Lu Zhenkai
ENS, France

Rossella Lupacchini
University of Bologna

Loïck Magnin
Université Libre de Bruxelles

▼ *CQT Research Fellow Akihito Soeda (left) explains his latest research to visiting student Carina Prunkl*

▲ *CQT staff and visitors interact over lunch in the Quantum Cafe*

Aabhaas Mallik
Indian Institute of Science Education and Research (IISER) - Kolkata

Prabha Mandayam
Caltech

Manukumara Manjappa
University of Mysore

Adriana Marais
University of KwaZulu-Natal, South Africa

Damian Markham
CNRS - Télécom ParisTech

Chiara Marletto
University of Oxford

Laura Mazzola
Queen's University Belfast

Mei Feng
South China Normal University

Zeeya Merali
Journalist, Freelance

Jiří Minář
University of Geneva

Anna Mo
NTU

Alex Monras
Universit`a degli Studi di Salerno

Jean-François Morizur
Laboratoire Kastler Brossel

Markus Mueller
Potsdam University

Manas Mukherjee
Raman Center for Atomic Molecular & Optical Science, IACS

Nachikethas A J
Indian Institute of Technology Madras

Takashi Nakajima
Kyoto University

Takafumi Nakano
University of Cambridge

Miguel Navascues Cobo
Department of Mathematical Analysis - UCM

Matteo Nespoli
Research Center for Applied Sciences, Academia Sinica, Taiwan

Gelo Noel Tabia
Institute for Quantum Computing, Waterloo

Changsuk Noh
University of Auckland

Franco Nori
University of Michigan

Paulo A. Nussenzveig
Instituto de Física, Universidade de São Paulo

Jeremy O'Brien
University of Bristol

Daniel Oi
University of Strathclyde

Jonathan Oppenheim
University of Cambridge

Jiannis Pachos
University of Leeds

Sambit Bikas Pal
Indian Institute of Science Education, Kolkata

Massimo Palma
Scuola Normale Superiore Pisa

Kanhaiya Pandey
Indian Institute of Science

Tobias Paprotta
THORLABS Inc.

Scott Parkins
University of Auckland

Julia Parreira
Universidade Federal de Minas Gerais

Saverio Pascazio
University of Bari

Mauro Paternostro
Queen's University Belfast

Marcin Pawlowski
University of Bristol

Francesco Petruccione
University of KwaZulu-Natal

Marco Piani
Institute of Quantum Computing

Susanne Pielawa
Massachusetts Institute of Technology

Olivier Pinel
Université Pierre et Marie Curie

Martin Plenio
Ulm University

Supartha Podder
École Normale Supérieure

Felix Pollock
University of Oxford

James Pope
University of Oxford

Vladislav Popkov
Università degli Studi di Salerno

Carina Prunkl
Free University of Berlin

Andre Ranchin
University of Bristol

Jarda Rehacek
University of Olomouc

Ben Reichardt
Institute for Quantum Computing, Waterloo

Blas Rodriguez
National Tsing-Hua University

Cesar Rodriguez-Rosario
Harvard University

Joachim Rosenthal
University of Zurich

Dorner Ross
Imperial College

Davide Rossini
La Scuola Internazionale Superiore di Studi Avanzati

Ressa Said
Macquarie University

Pablo Saldanha
Universidade Federal de Minas Gerais

Alejo Salles
Niels Bohr Institutet

Pradeep Sarvepalli
University of British Columbia, Vancouver

Fabio Scardigli
LeCosPA, National Taiwan Universi

Jean-François Schaff
Inln, Nice

Norbert Schuch
California Institute of Technology

Simone Severini
University College London

Zahra Shadman
Heinrich Heine University in Düsseldorf

Yutaka Shikano
Massachusetts Institute of Technology, Boston

Olivier Sigwarth
Photonique Lab

Ilya Sinayskiy
University of KwaZulu-Natal

Paul Skrzypczyk
University of Bristol

Wonmin Son
Sogang University

Michael Stay
The University of Auckland

Aephraim M. Steinberg
University of Toronto

Jun Suzuki
National Institute of Informatics, Japan

Mario Szegedy
Rutgers, the State University of New Jersey

Oleg Szehr
ETH Zurich

Nickos Sxetakis
Technical University of Crete

Daniel Terno
Macquarie University, Australia

Varun Theja Thammineni
Indian Institute of Technology Bombay

Marco Tomamichel
ETH Zurich

Abdul Hameed Toor
Quaid-i-Azam University

Jorge Tredicce
CNRS

Begzjav Tuguldur
National University of Mongolia

Luca Turin
BSRC Fleming Institute, Vari, Greece

Lev Vaidman
Tel Aviv University

Daniel Valente
Institute Néel, Grenoble, CNRS

Nisheeth Vishnoi
Microsoft Research

Matthieu Viteau
Università di Pisa

Eyuri Wakakuwa
University of Tokyo

Zhuo Wang
Chinese Academy of Sciences

XiaoHong Wang
Capital Normal University

Victoria Watson
Oxford University

Tzu-Chieh Wei
University of British Columbia

Colin Wilmott
University of Düsseldorf

Severin Winkler
ETH Zurich

Siye Wu
University of Hong Kong

Jürg Wullschleger
University of Bristol

Xu Ming
Sichuan Normal University

Yang Tao
Beijing Institute of Technology

Kazuya Yuasa
University of Bari

Man-Hong Yung
Harvard University

Robert Zeier
Technische Universitaet Muenchen (TUM)

Zhang Shengyu
The Chinese University of Hong Kong

Peng Zhang
Institute of Physics, Chinese Academy of Sciences ■

▼ *Visitor Norbert Schuch (left) in discussion with CQT Research Fellow Joe Fitzsimons*

Visitor notes: a year at CQT

CQT Visiting Research Professor ***John Baez*** *has found that conversations with CQT people sail straight into deep and interesting waters.*

I have just finished one year of a two-year visit to CQT. I came here with a mix of delight and trepidation.

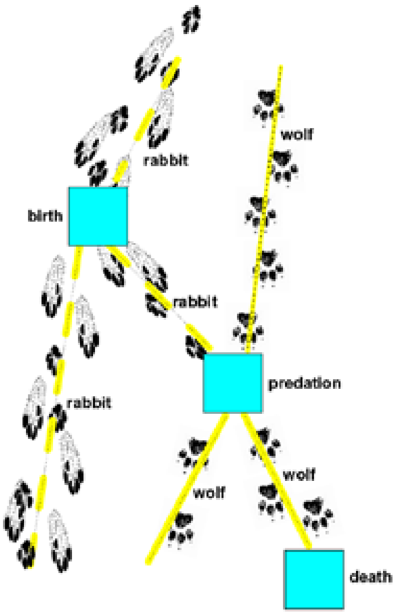
The chance to take a break from teaching and focus on research was delightful. So was the chance to work in an environment where everyone understands quantum mechanics at a deep level. It takes a lot of time to sift through the puzzles and `paradoxes' of this deeply coherent – though still somewhat mysterious – theory. Most people, even most physicists, haven't taken the time to do it. Here at CQT, people have. This means that instead of getting stuck in shallow waters, conversations sail straight into deep, interesting, new topics.

My trepidation came from the fact that 'quantum technology' is not how I'd describe my work. I'm a mathematical physicist who dabbles in a distressingly wide range of fields, from quantum gravity to particle physics to the foundations of quantum theory to environmental issues. However, this turned out to be okay. I have a lot to talk about with the people here, especially in the research groups of Dagomir Kaszlikowski and Vlatko Vedral. I get a lot of new ideas from them, and I think it helps them too sometimes.

Since I came here, I've been doing a lot of work on entropy. Entropy is a measure of disorder, or randomness. For example, when we melt an ice cube, the water molecules leave their well-ordered crystal state and start wiggling around, so their entropy increases. But ironically, entropy is also related to information. The more well-ordered and predictable the letters of a message are, the less information it can contain.

Recently Vlatko, Oscar Dahlsten and their collaborators have made new progress in understanding this connection. They came out with a paper in *Nature* showing that under some circumstances, a quantum computer could cool down by erasing information stored on it. This is a surprise because normally erasing information creates heat.

▲ *John Baez is spending two years at CQT. His permanent position is Professor of Mathematics at the University of California, Riverside.*



▲ *Predator-prey interactions can be modelled using Feynman diagrams, much like the interactions between elementary particles.*

I've been talking to Oscar, Mile Gu, and some other people here about information and entropy. In fact, we had a little 'entropy club' going for a while. I've written three papers on entropy since I've been here, and I'll probably write some more.

I've also been working to take math from quantum physics and stretch it so it applies to 'non-quantum' situations, ranging from chemistry to population biology and the spread of disease. In quantum physics, particles like protons and electrons can collide and interact, and Feynman showed us how to calculate what they do with the help of pictures called 'Feynman diagrams'. But it turns out that very similar techniques can be used to describe what happens when predators and prey interact as they roam around the landscape!

Some of these techniques were already being used in population biology, but since most biologists don't think about elementary particles, they didn't notice the connection. I think there's a lot to be gained by exploiting this connection. Things may get really interesting when we try to study systems that are teetering on the brink between the quantum and classical worlds.

I've been working on these ideas with Jacob Biamonte, a frequent visitor to CQT. I expect that as time passes, I'll develop even more collaborations at CQT. There's a lot going on here, and a lot of interesting people. ■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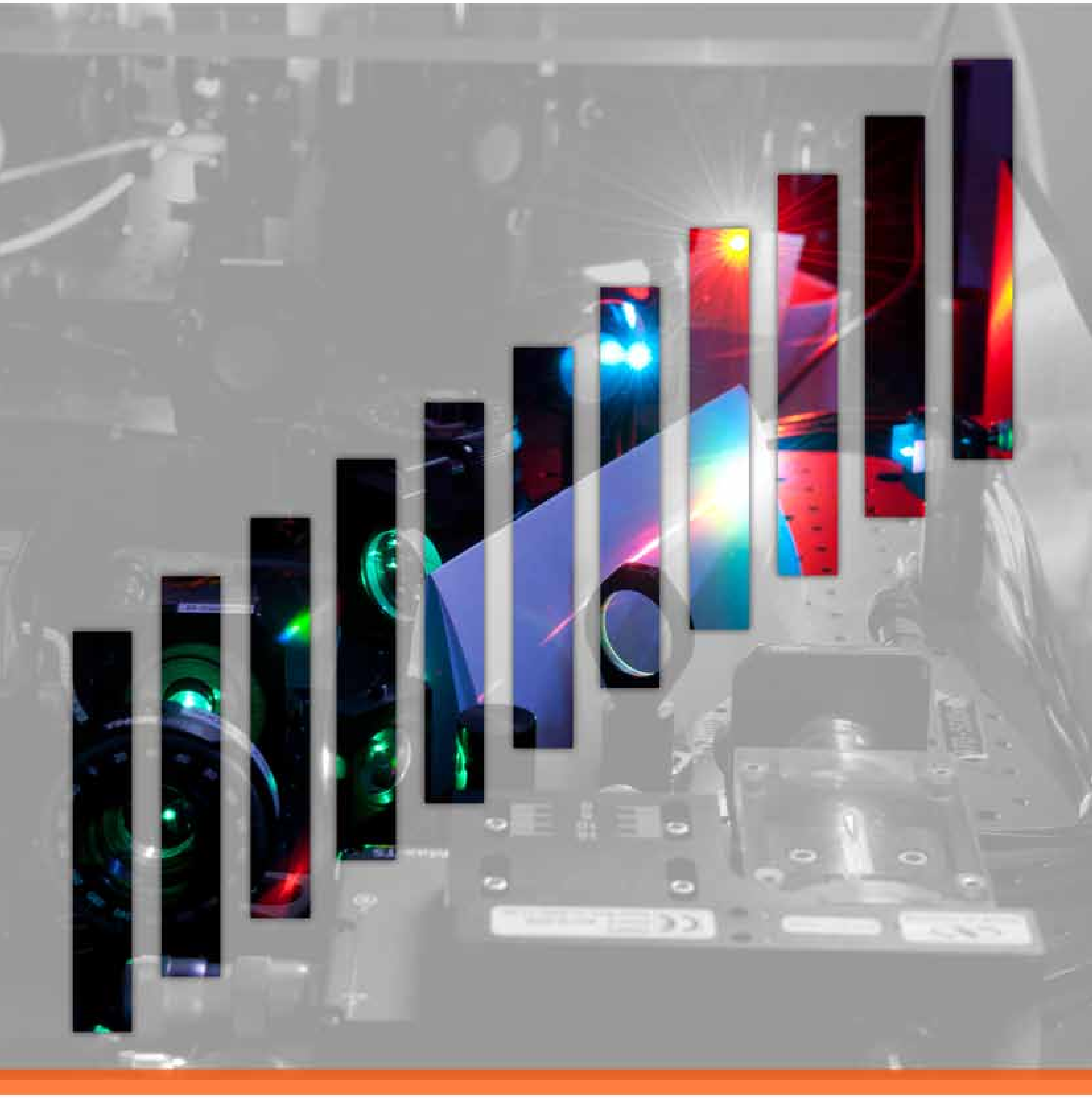

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