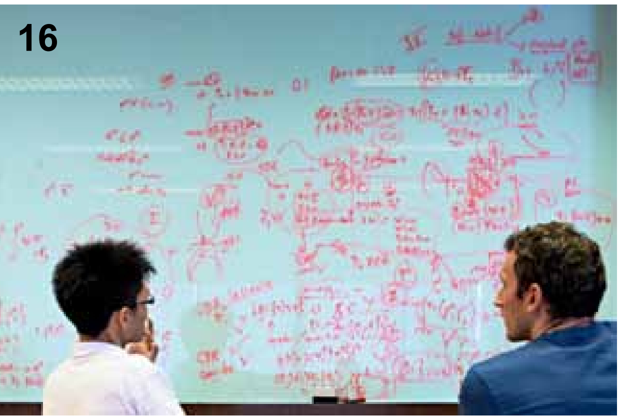
Centre for Quantum Technologies

ANNUAL REPORT

2010

Contents



"Piled Higher and Deeper" by Jorge Cham

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Photos D.K.L. Oi © 2010 p.3, 4, 8-10,15, 16-20, 24, 25, 27, 30, 31, 32 (#s 4, 6, 7), 37-39, 41, 43.
The Editor would like to thank J. Hogan, E. Tan, C.T. Chan, D. Kaszlikowski, and everyone else who helped in the production of this report.
Centre for Quantum Technologies website: www.quantumlah.org

Letter from the Director

Welcome. It is again that time of year when Daniel, who puts this annual report together, fills my inbox with gentle reminders and Evon, who coordinates it all, threatens to lock me up in my office until I deliver these few words from the Director. I like to argue that our science stands on its own merits, so let me keep this brief.

It turned out to be a busy year. Research at CQT did not cool down after we cooled local atoms to the Bose-Einstein condensate level in 2009. Murray and his colleagues went on to trap ions and started playing with cavity quantum electrodynamics (see Murray's article, p.27). Bjorn worked on his atom-chip experiment, and Christian kept tinkering with focusing light on individual atoms, with a great deal of success. Also on the experimental side, our newly appointed Principal Investigators were busy setting up their labs (see Kai's article, p.33). Lorries arrived and, accompanied by the sound of drilling and hammering, more and more equipment was brought in. Throughout, theorists performed their usual pantomime in front of our whiteboards, arguing vehemently about the meaning of quantum theory, the nature of information and the like. They have produced some amazing results, to mention only the information causality paper (see Dagomir's article, p.24). Adding to the activity was a stream of visitors, friends, colleagues, students and journalists flying in to spend time at CQT, uninterrupted even by the volcanic eruption in Iceland. Our coffee machine was pressurised to its limit, delivering endless espressos.

Taking time out from pushing optical benches, tuning lasers and writing academic papers, some of our scientists have honed their pedagogical skills by explaining quantum physics to the public at large. Vlatko's popular book titled "Decoding Reality" (see extract, p.36) has been very well received, Valerio and Kwek lectured at the local schools, and crowds were attracted to our demonstration of quantum entanglement in a shopping mall. Yes, in a shopping mall, for where else would you find crowds in Singapore? To be sure, much of what we do at CQT is far from simple. For us, secret communication is not about whispering messages into baked bean cans painted in pretty colours and connected with string, as we learnt to do as children. But even the most sophisticated quantum technology can be described in simple terms, and to this end our outreach team did an excellent job. Altogether, I believe, by a combination of good research and making quantum theory more accesible, we have demonstrated to the local taxpayers that their money is well spent.

It is difficult to summarise in a few pages all the excitement of our research this year, but we have tried. As in years past, this annual report is intended to be both informative and readable. I hope you will like it.

Artur K. Ekert

People

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Exec. Director, Institute of High Performance Computing
Director, Planning and Policy Department, A*STAR

Scientific Advisory Board together with CQT Director. (left-right) Jun Ye, Atac Imamoglu, Artur Ekert, Umesh Vazirani, Ignacio Cirac, Michele Mosca. Dave Wineland not present.

Scientific Advisory Board

Ignacio CIRAC
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Max-Planck Institute of Quantum Optics

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Institute of Quantum Electronics
ETH Zurich

Michele MOSCA
Deputy Director & Co-founder
Institute of Quantum Computing
University of Waterloo

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

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

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

Principal Investigators

Quantum Optics

Christian KURTSIEFER

In 1997, after completing his doctorate in experimental physics in Konstanz, Germany, Christian joined IBM Almaden Research Center in San Jose, California, where he worked on an ion trap experiment. Between 1999 and 2003, while a research staff member at the Ludwigs-Maximilians-Universität München in Germany, he focused mostly on quantum optical experiments, constructing one of the best sources of entangled photons. He joined NUS in 2003, as an Associate Professor, and CQT in 2007. He was promoted to Professor at NUS in July 2010. He is chiefly responsible for the development of experimental quantum optics in Singapore. (National Science Award 2008).

Antia LAMAS-LINARES

Originally from Galicia, in northern Spain, Antia studied optics at Imperial College London and the University of Oxford in the UK, with a clear temptation to control photons at the quantum level. She demonstrated that entangled photons can be generated in the process of stimulated emission. In 2003, after she was awarded her doctoral degree from Oxford, and after spending some time at the University of California in Santa Barbara, she joined NUS as an Assistant Professor. She is now a Visiting Research Associate Professor at CQT. Her current research interests involve quantum communication, cryptography and the foundations of quantum physics. (National Science Award 2008).

Valerio SCARANI

Valerio, our European polyglot, received his PhD in 2000 from Ecole Polytechnique Federale de Lausanne in Switzerland, with experimental work in nanoscience. He then moved to the Group of Applied Physics of the University of Geneva, working as a theorist in the group of Nicolas Gisin. In 2007 he moved to NUS where he is an Associate Professor. His main research topics are quantum cryptography and quantum correlations. He is also an author of a popular book on quantum physics and is leading CQT outreach activities. (National Science Award 2008)

Dzmitry MATSUKEVICH

Originally from Minsk, Belarus, Dzmitry received his PhD in 2006 from the Georgia Institute of Technology in Atlanta, Georgia. His graduate research in the group of Prof. Kuzmich involved quantum networks with atomic ensembles. He then moved to the University of Michigan in Ann Arbor and later to the University of Maryland in College Park and its Joint Quantum Institute, a partnership with the National Institute of Standards and Technology, to work as a postdoctoral researcher in the group of Prof. Monroe. He joined NUS and CQT as an Assistant Professor in 2010. His research interests include quantum optics and trapped ions.

Quantum Matter

Kai DIECKMANN

After completing his German Physics Diploma at the University of Konstanz, Kai obtained his doctoral degree in 2001 from the University of Amsterdam and worked in the group of Prof. J.T.M. Walraven at the Institute for Atomic and Molecular Physics (AMOLF) in Amsterdam as an individual Marie Curie fellow. He went on as a postdoctoral fellow in the group of W. Ketterle at the Massachusetts Institute of Technology in Boston. In 2003 he joined the group of Prof. T.W. Hänsch at the University of Munich and the Max-Planck Institute for Quantum Optics, Garching, Germany, where he began his own research project in cold quantum gases. He has worked on laser cooling, ultracold bosonic and fermionic quantum gases, precision atom optics, and atomic and molecular physics. In January 2009 he started engaging in a new experimental project to realise fermionic quantum gases in optical lattices. In March 2010 he fully settled in Singapore as an Associate Professor at NUS and CQT after moving his Munich experimental setup on mixed ultracold Fermi gases.

Wenhui LI

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

Interdisciplinary Theory

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 (University of Otago, 1972). He returned to serve at the University of Science of Malaysia (1972-1983), and joined NUS in 1983. He started his career as a theoretical physicist, specializing in the Yang-Mills gauge fields, particle phenomenology, and integrable models. As the Head of the Physics Department (2000-2006) at NUS, he recruited a number of researchers in the field of quantum information, all of whom subsequently contributed to forming CQT. (National Science Award 2006).

Berthold-Georg ENGLERT

Born and educated in Germany, Berge was a postdoc at the University of California, Los Angeles, after receiving his doctorate in 1981. He taught at the University in Munich, Germany from 1985-1995, and then became a "physicist at large" until arriving at NUS in late 2002, becoming professor six months later. He 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 ongoing research on ultra-cold atomic fermion gases. Other current interests concern quantum computation as well as the question of what can be known about quantum systems. (National Science Award 2006, Provost Chair in Science 2009-2012)

Dagomir KASZLIKOWSKI

In 2001, soon after he received his doctoral degree from the University of Gdansk (2000) in Poland, Dagomir joined NUS as a Research Fellow. In 2004 he was appointed an Assistant Professor in the Department of Physics and in 2009 to Associate Professor. With CQT since 2007, his research interests are in the foundations of quantum theory, and the properties of entanglement, in particular in many-body systems. (National Science Award 2006)

Andreas WINTER

Andreas received his PhD in mathematics from the University of Bielefeld in Germany in1999. Since then he has been at the University of Bristol in the UK, first as a postdoctoral researcher in the Department of Computer Science, then as a lecturer in Mathematics and currently as a Professor in Mathematics. Since 2007, he has also held a joint appointment at CQT as a Visiting Research Professor. His research interests cover quantum information theory, discrete mathematics, and statistical physics.

Vlatko VEDRAL

Vlatko is a Professor of Quantum Information Science, University of Oxford, Professor of Physics, NUS and Principal Investigator at the Centre for Quantum Technologies, NUS. He obtained his BSc (Physics; 1995) and his PhD (Physics; 1998) from Imperial College London. He has won many awards, most recently, the World Scientific (Physics Research) Medal and Prize, Singapore IOP (2009), and the Royal Society Wolfson Research Merit Award (2007). His main contribution to the field is in the understanding of quantum correlations and their use in information processing. He has also been active in outreach events, participating in radio and tv shows/interviews, and writing for many newspapers. Most notable among his outreach activities were his weekly two-hour BBC radio shows on science (2006-2008). He has recently published a popular book: "Decoding Reality: The Universe as Quantum Information" (OUP 2010).

KWEK Leong Chuan

Born and bred in Singapore, Kwek completed his undergraduate degrees in New Zealand under a Colombo Plan scholarship. Returning to Singapore, he served his government bond as a teacher for eight years before pursuing his doctoral degree at the National University of Singapore, completing his PhD on condensed matter and integrable models in 1999. One year later, he joined the National Institute of Education at the Nanyang Technological University. He is primarily responsible for initiating research in quantum information science in Singapore leading to the formation of CQT. His current research interests include the foundations of quantum theory and distributed quantum computing. (National Science Award 2006)

Dimitris ANGELAKIS

Born and educated in Crete, Greece, Dimitris moved to Imperial College London in 1998 where he received a PhD in theoretical quantum optics. In 2001 he was elected a Junior Research Fellow at St Catharine's College, University of Cambridge, UK a position he held jointly in the Department of Applied Mathematics and Theoretical Physics and the Centre for Quantum Computation. In 2007 he was appointed a lecturer in the Department of Sciences at the Technical University of Crete. Since 2009, he has held a joint appointment in CQT. His research interests lie at the interface of quantum optics, quantum computation and condensed matter physics with emphasis in photonic quantum simulators, an emerging field which he co-founded in 2006.

Microtraps

Murray BARRETT

Murray received his PhD from the Georgia Institute of Technology in Atlanta, Georgia 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 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. After a brief stay back in his home country of New Zealand, he joined NUS in October 2006 and is an Assistant Professor. He is currently working on integrating micro-traps and cavity QED for quantum information applications.

Björn HESSMO

Björn obtained his undergraduate degree from Uppsala University in Sweden and Ecole Polytechnique in Paris, France, and after that he obtained his doctorate in quantum chemistry at Uppsala University (2000). In 2001 he was appointed Assistant Professor (forskarassistent) at the Royal Institute of Technology in Stockholm. In Stockholm he worked with experimental photonics and quantum optics. In 2005 he moved to the University of Heidelberg in Germany as a Marie Curie fellow, where he worked on experimental cold atom physics. In 2007 he was appointed Universitätsassistent at the Technical University of Vienna in Austria. In Vienna he continued his work on atom chips and photonics. In 2009 he joined the CQT team and NUS as an Assistant Professor to lead the experimental activity on microtraps for neutral atoms.

Computer Science

Miklos SANTHA

Born and educated in Budapest, Hungary, Miklos moved to France in 1980 and received his PhD in Mathematics from the Université Paris 7 in 1983. To satisfy his growing interest in computer science, he spent two years at the University of California in Berkeley, and then obtained a Doctorat d'Etat in this field from the Université Paris-Sud, Orsay in 1988. In 1988 he also joined France's Centre National de la Recherche Scientifique where he is a senior researcher in computer science. He works in the Laboratoire de Recherche en Informatique at Orsay where he is the head of the Algorithms and Complexity Division. He was a Humboldt Fellow in the Max Planck Institute in Saarbrücken, Germany, from 1990 to 1991. Since 2008 he is also a Visiting Research Professor, in charge of building up the computer science component at CQT. His research interests include quantum computing, randomized algorithms and complexity theory.

Rahul JAIN

Rahul obtained his PhD in computer science from the Tata Institute of Fundamental Research, Mumbai, India in 2003. He was a postdoctoral fellow for two years at the University of California in Berkeley (2004-2006) and for two years at the Institute for Quantum Computing (IQC), University of Waterloo, Canada (2006-2008). In 2008, he joined NUS as an Assistant Professor in the Computer Science Department with cross appointment with CQT. His research interests are in the areas of information theory, quantum computation, cryptography, communication complexity, and computational complexity theory.

Stephanie WEHNER

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. Since then she was a postdoctoral scholar at the California Institute of Technology in Pasadena and joined NUS in July 2010 as an Assistant Professor. 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.

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 (CWI) in Amsterdam, the Institute for Advanced Study in Princeton, New Jersey, and the University of Calgary in Canada before joining the University of Frankfurt as a Junior Research Group Leader. In 2010 he joined Nanyang Technological University as Assistant Professor in the Division of Mathematical Sciences and CQT as a Principal Investigator. His research interests include quantum Information, communication complexity, and computational complexity.

Research Staff*

Senior Research Fellows

Janus Hallelov Wesenberg
Ling Euk Jin, Alexander
Markus Grassl
Yu Sixia
Gleb Maslennikov

Research Fellows

Ng Hui Khoon
Tobias Muller
Rachele Fermani
Stephen Clark
Uwe Dorner
Alastair Kay
Wonmin Son
Kavan Kishore Modi
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Lana Susan Sheridan
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Paul Constantine Condylis
Jimmy Sebastian
Thomas Decker
William Henry Rosgen
Matthew Mckague
John Goold
Dario Poletti
Zhang Xiaolong

Research Assistants

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Chng Mei Yuen Brenda
Dao Hoang Lan
Chia Chen Ming
Arpan Roy
Aarthi Lavanya Dhanapaul
Chen Li
Chuah Boon Leng
Sivakumar s/o Maniam
Tarun Johri
Lim Chin Chean
Syed Muhamad Assad
Tan Ting Rei
Deng Dongling
Lim Ci Wen

Visitors and CQT researchers attending a research seminar

PhD Students

Eilidh Gudgeon
Arun
Marta Wolak
Han Rui
Wang Guangquan
Shang Jiangwei
Ritayan Roy
Ng Tien Tjuen
Syed Abdullah Aljunid
Siddarth Joshi
Bharath Srivathsan
Gurpreet Kaur Gulati
Poh Hou Shun
Tan Kok Chuan Bobby
Huo Mingxia
Li Ying
Kyle Arnold
Nicholas Charles Lewty
Markus Baden
Jiabin You
Penghui Yao
Attila Pereszlenyi
Wang Yimin
Rafael Rabelo
Teo Zhi Wei Colin
Yang Tzyh Haur
Elisabeth Rieper
Giovanni Vacanti
Ved Prakash

Visiting Research Profs

Dieter Hans Jaksch
Giulio Casati
Erik Sjöqvist
John Baez
Rosario Fazio
Ghassan Georges Batrouni
Christian Miniatura

Visiting Research Assoc Profs

Simon Charles Benjamin
Masahito Hayashi
Benoit Gremaud
Cord Axel Muller
David Wilkowski

Visiting Senior Research Fellows

Marcelo Franca Santos
Yi Xuexi
Tong Dianmin

Visiting Research Fellows

Libby Heaney

Staff Relaxing in the Quantum Cafe

* As of the 15th August 2010

Students taking notes during a presentantion

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Artur Ekert
Director

Lai Choy Heng
Deputy Director

Kuldip Singh
Admin Director

Chan Chui Theng
Admin Manager

Tan Hui Min Evon
Admin Executive

Building & Infrastructure

Jessie Ho
Buildings and Infrastructure Manager

Swee Yee Wee
Operations Associate

Finance & Procurement

Chan Hean Boon Thomas
Finance Manager

Chin Pei Pei
Procurement Manager

Tan Lay Hua
Finance Executive

Mashitah Bte Mohammad Moasi
Procurement Executive

Human Resources

Valerie Hoon
HR Manager

Tan Ai Leng, Irene
HR Executive

IT Support

Darwin Gosal
IT Manager

Lim Jeanbean, Ethan
System Engineer

Outreach and Media

Jenny Hogan
Outreach and Media Relations Manager

Research Support Group

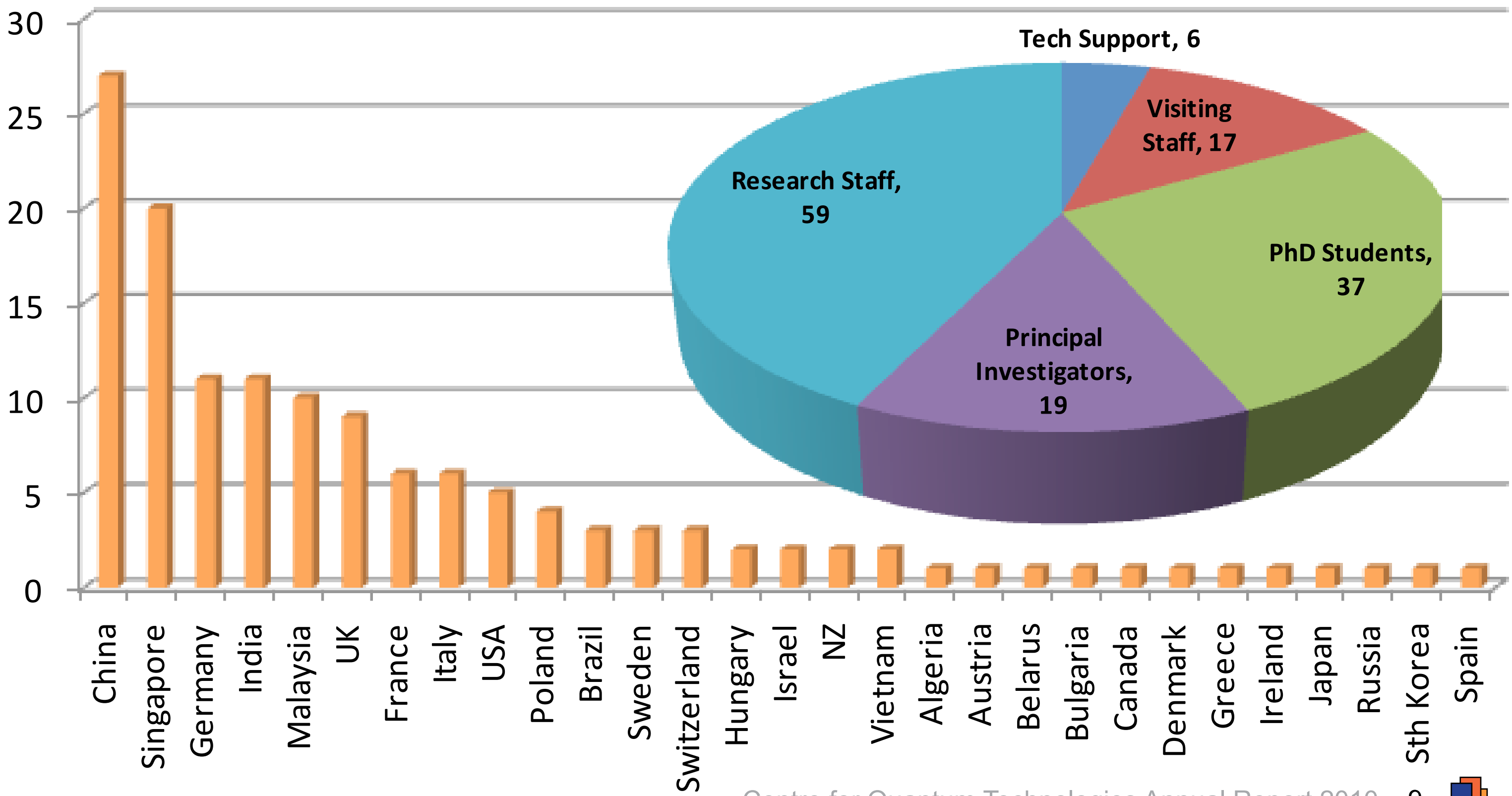
Gan Eng Swee
Laboratory Executive

Kwek Boon Leng Joven
Laboratory Technologist

Chia Zhi Neng Bob
Laboratory Technologist

Mohammad Imran Bin Abdol Raman
Laboratory Technologist

CQT Member Profile



Calendar of Events

Colloquia

Date	Speaker	Title
24-Feb-10	Klaus Mølmer, University of Aarhus	Ensemble encoding of quantum registers for quantum computing and communication
18-Mar-10	Adrian Kent, University of Cambridge	One World Versus Many
27-May-10	Sankar Das Sarma, University of Maryland	Computing with Quantum Knots: Majorana Fermions, Non-Abelian Anyons, and Topological Quantum Computation
10-Aug-10	Christophe Salomon, Laboratoire Kastler Brossel, France	Space Clocks and Fundamental Tests
12-Aug-10	Carlton M. Caves, University of New Mexico	Quantum-limited measurements: One physicist's crooked path from quantum optics to quantum information

Atac Imamoglu briefing CQT on the latest experimental developments on the Kondo Effect

Workshops

Event	Date
Complex Quantum Systems CQS 2010	1-28 Mar-10
Joint CQT—CCRG Workshop on Quantum Error Correction	23-24 Feb-10
Workshop on Quantum Correlations	30-Nov-4-Dec-09

(L-R) Valerio, Dagomir & Daniel discussing quantum reference frames

Congratulations

Dagomir Kaszlikowski, NUS Young Researcher Award 2010.
Rahul Jain, Best Paper STOC (Symposium on Theory of Computing) 2010.
Giulio Casati, International Prize for Physics for 2010 of the Accademia Nazionale dei Lincei.
Dario Poletti, Materials Research Society of Singapore Medal, Most outstanding PhD thesis in the Department of Physics, NUS.
Thiang Guo Chuan, Lijen Industrial Development Medal, IPS Medal, Outstanding Undergraduate Researcher Prize, Sugar Industry of Singapore Book Prize and Jurong Shipyard Prize 2010.
Yang Tzyh Haur, Jurong Shipyard Prize 2010

Talks

Date	Speaker	Title
15-Sep-09	Peter Janotta, Julius-Maximilians-Universität Würzburg	Foundations of Quantum Mechanics – Can Steering Provide a New Physical Principle?
29-Sep-09	Stephanie Manz, Technical University of Vienna	Second—order correlations of (one-dimensional) Bose gases in expansion
6-Oct-09	Leandro Aolita, ICFO	Almost all quantum states have non-classical correlations
13-Oct-09	Ciara Morgan, Dublin Inst. for Advanced Studies	The classical capacity of quantum channels with memory
15-Oct-09	Andrew Scott, Griffith University Brisbane	SIC-POVMs and other designs
20-Oct-09	Ashley Montanaro, University of Bristol	On the communication complexity of XOR functions
27-Oct-09	Cesar Rodriguez-Rosario, Harvard University	Quantum stochastic walks
28-Oct-09	Masahito Hayashi, Tohoku University	Capacity with energy constraint in coherent state channel
17-Nov-09	Masahito Hayashi, Tohoku University	Universal approximation of multi-copy states and universal quantum lossless data compression
24-Nov-09	Borivoje Dakic, University of Vienna	Quantum Theory and Beyond: Is Entanglement Special?
26-Nov-09	Thomas Durt, Free University of Brussels	Quantum Coherence in Biology: Myth or Reality?
1-Dec-09	Agnieszka Gorecka, Institute of Physics, Polish Academy of Sciences	Distillation of the BEC
3-Dec-09	Giulio Casati, Universita' degli studi dell'Insubria, Como	Can we build efficient thermoelectric cooling nano-devices?
10-Dec-09	Carlos Sa de Melo, Georgia Institute of Technology	The Evolution from BCS to Bose-Einstein Condensation: Superfluidity in Metals, Neutrons Stars, Nuclei, and Ultra-Cold Atoms.
16-Dec-09	Matthias Steiner, Universität Stuttgart	Towards quantum information processing in diamond

17-Dec-09	Huanqian Loh, JILA Boulder, Colorado	Search for the electric dipole moment (EDM) of an electron
2-Feb-10	Déborah Alvarenga, UFMG- Federal University of Minas Gerais, Brazil	The (experimental) aspects of quantum dots
3-Feb-10	Kristian Baumann, ETH Zürich	The Dicke Quantum Phase Transition in a Superfluid Gas Coupled to an Optical Cavity
9-Feb-10	Daniel Oblak, Niels Bohr Institute	Entanglement assisted metrology beyond the standard quantum limit
25-Feb-10	Bill Munro, National Institute of Informatics	From quantum fusiliers to high-performance networks: a road to ultimate success or failure
1-Mar-10	Nicolas Treps, Laboratoire Kastler Brossel, UPMC	Multimode quantum optics in the continuous variable regime: from quantum information to quantum metrology
2-Mar-10	Andrew Briggs, University of Oxford	Molecular spin states for quantum technologies
11-Mar-10	Tobias Fritz, Max Planck Institute for Mathematics, Germany	Curious properties of iterated measurements
16-Mar-10	Ognyan Oreshkov, University of Vienna, Austria	Adiabatic Markovian Dynamics
17-Mar-10	Jonathan Home, NIST	Experimental quantum information science by coherent and dissipative control
23-Mar-10	Cyril Branciard, University of Queensland	Testing Bell's locality assumption with independent sources
25-Mar-10	John Weiner, NIST/CNST, Gaithersburg, MD USA	Extraordinary optical transmission revisited: how light gets through isolated or periodic arrays of subwavelength slits and holes (or not)
7-Apr-10	Crispin H. W. Barnes, University of Cambridge	Observation of single-electron coherent states in a quantum dot
7-Apr-10	Carsten Schuck, ICFO	Interfacing single-ions and single-photons for quantum networks
8-Apr-10	Mile Gu, Centre for Quantum Technologies, NUS	Sharpening Occam's Razor with Quantum Mechanics
15-Apr-10	Myoung-Sun Heo, Seoul National University	Ideal Mean-Field Transition in a Modulated Cold Atom System
16-Apr-10	Elsi-Mari Laine, University of Turku, Finland	Measure for the Non-Markovianity of Quantum Processes
27-Apr-10	Kanhaiya Pandey, Indian Institute of Science Bangalore	Towards precision spectroscopy using laser cooled Yb atoms
27-Apr-10	Kanhaiya Pandey, Indian Institute of Science Bangalore	Towards precision spectroscopy using laser cooled Yb atoms
6-May-10	Pier A. Mello, Instituto de F´ısica, U.N.A.M., Mexico	The Problem of Successive Measurements in Quantum Mechanics
11-May-10	Pier A. Mello, Instituto de F´ısica, U.N.A.M., Mexico	Statistical Scattering of Waves in Disordered Waveguides. An Overview of old and new results
13-May-10	Manas Mukherjee, Indian Association for the Cultivation of Science	Single photons & A search for a quantum hybrid system
14-May-10	Falk Unger, UC Berkeley	Fault-tolerant interactive quantum communication or An interactive version of the quantum Shannon Theorem
20-May-10	Elisabeth Rieper, CQT	The relevance of continuous variable entanglement in DNA
25-May-10	Pawel Lachowicz, Centre for Wavelets, Approximation and Information Processing, Temasek Lab, NUS	X-ray whispers of black-holes: from standard deviation to adaptive wavelet analysis
1-Jun-10	Jimmy Sebastian, Tata Institute of Fundamental Research, Mumbai (TIFR)	Differential ac Stark shift measurement in a hybrid magneto - optical dipole trap and loading chromium atoms in a magnetic guide
19-Jul-10	Bilal Shaw, University of Southern California	Quantum Steganography
22-Jul-10	Andreas Wallraff , ETH	Measuring the correlations of a microwave frequency single photon source
22-Jul-10	Kazimierz Rzazewski, Center for Theoretical Physics, Polish Academy of Sciences	Bose statistic and classical fields
23-Jul-10	Juergen Volz, Laboratoire Kastler Brossel	Cavity-based atomic state readout: Detection 'without' spontaneous emission
23-Jul-10	Saverio Pascazio, Universita di Bari, Italy	Maximally multipartite entangled states
28-Jul-10	Alexander Ling, CQT	Towards improved end-to-end system efficiency of photon pair systems
29-Jul-10	Y. M. Cho, Ulsan National Institute of Science and Technology, Korea	Non-Abelian Structure in Atomic and Condensed Matter Physics
3-Aug-10	Jakub Zakrzewski, Jagellonian University, Cracow	Cold atoms in optical lattices with disorder
4-Aug-10	Artur Widera, der Universität Bonn	Exploring Quantum Physics with Single Neutral Atoms
5-Aug-10	Nir Navon, LKB, ENS, Paris	Exploring the thermodynamics of a Fermi gas
5-Aug-10	Blas Manuel Rodriguez Lara, National Tsing-Hua University, Taiwan.	Quantum Phase Transition and Entanglement in Finite Size Extended Dicke Models: The BEC-in-the-box case.
6-Aug-10	Frederic Brossard, Hitachi Cambridge Laboratory	Photonic bandgap materials for cavity quantum electrodynamics
10-Aug-10	Ho-Tsang Ng, Rikken Japan	Quantum phase measurement in a superconducting circuit
24-Aug-10	Abolfazl Bayat, University College London	Entanglement in Kondo Spin Chain Model
25-Aug-10	Alessandro Restelli, NIST and University of Maryland	Speeding-up Quantum Key Distribution

Outreach Activities

Date	Activity	Who	Audience	Additional Information
27-Oct-09	Talk on quantum physics	V. Scarani	Secondary school students	Students of Zhonghua Secondary school
29-Oct-09	Visit to CQT	B. Hessmo	VIP@NUS	Visit of Par Olming, Swedish Research Council
19-Jan-10	Visit to CQT	K. Singh	Visiting scientist	Visit of Alexandre Refregier, CEA Saclay, France
12-Feb-10	Visit to CQT	V. Scarani	Visiting scientists	Visit of Aharony and Ora-Entin, Ben-Gurion University, Israel
09-Mar-10	Visit to CQT	L.C. Kwek	Students	Selected students from Tokyo University
17-Mar-10	Visit to CQT	V. Scarani	VIP@NUS	Oliver Graydon, editor-in-chief of Nature Photonics
21-Mar-10	Theatre play	V. Vedral	Large audience	Play "The Ethics of Progress"
14-Apr-10	Guest-of-Honor in scientific competition	V. Scarani	Secondary school students	VJC Science Quest 2010
13-May-10	Cafe scientifique	V. Vedral	Large audience	Singapore Science Centre
15-May-10	FoS Open House	C. Kurtsiefer, Le Phuc Thinh, Melvyn Ho, Chia Chen Ming	Prospective NUS students	Participation in the Physics booth and Bell-o-Meter
10-Jun-10	Visit to CQT	V. Scarani, Y. Cai	Visiting scientist	Visit of Gary Oas, EPGY Stanford
30-Jun-10	Consulting for a newspaper	C. Kurtsiefer	Large audience	Article in Neue Zuercher Zeitung
16-Jul-10	Visit to CQT	V. Vedral, V. Scarani, H. Klauck, D. Angelakis	VIP@NUS	David Gevaux, editor of Nature Physics
28-Jul-10	Visit to CQT	C.H. Oh, V. Scarani and [others]	Students	Selected students of Ulsan National Institute of Science and Technology (Korea)
29-Jul-1-Aug-10	Exhibit	C. Kurtsiefer and [students]	Large public	Bell-o-meter in Xperiment exhibition, Marina Square shopping mall

Social Events

Date	Event
24-Sept-09	Paintball @ Sembawang
1-Oct-09	Mid-Autumn Festival BBQ Celebration
9-Dec-09	CQT Family Day & Christmas Dinner @ Rasa Sentosa
20-Jan-10	Welcome 2010 Lunch @ Quantum Cafe
6-Feb-10	One Day Trip to Malacca
23-Feb-10	Chinese New Year Reunion
19-Mar-10	Movie Marathon Outing @ The Cathay
29-Apr-10	Southern Ridge Walk
13-Jul-10	CQT Soccer Tournament 2010

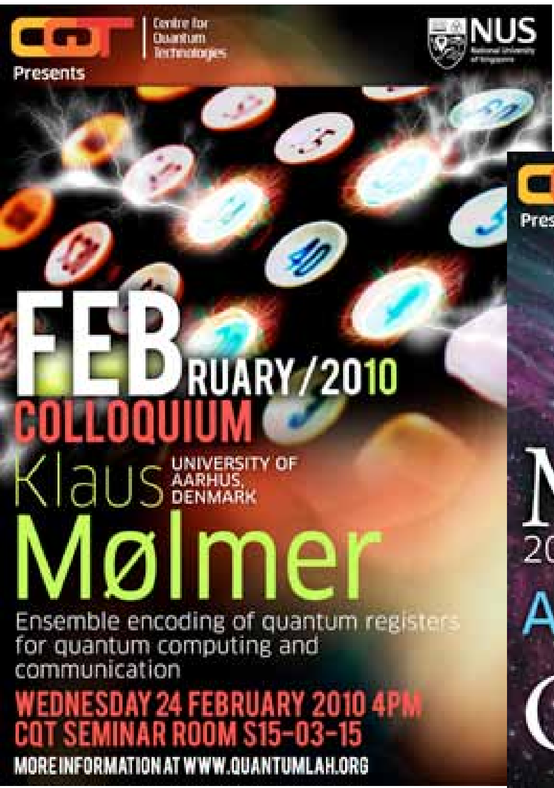
Group photo of the Southern Ridge Walk in April

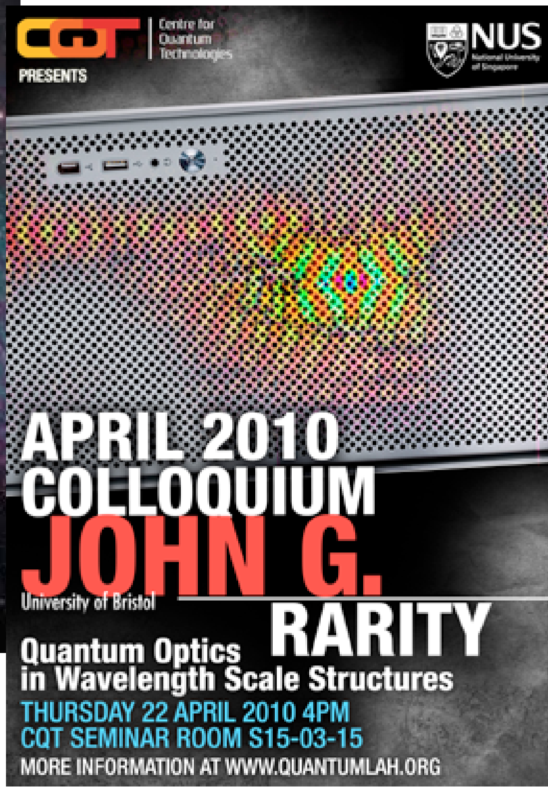
Christian Kurtsiefer (left) explaining the operation of a portable quantum cryptography system to visitors to the Xperiment event

Other Events

Date	Event
8 Jul-10	Governing Board Meeting and interaction with CQT members
22-23 Apr-10	CQT Retreat 2010
16-20 Aug-10	Scientific Advisory Board Meeting

CQT Colloquia





Colloquium postponed till 2011

Poster designs by Dixon Chan

Centre for Quantum Technologies

GRADUATE PROGRAMME

NUS National University of Singapore




Research Areas

Experimental and theoretical quantum physics

Information theory

Quantum cryptography and quantum computation

Single-photon, single-atom physics

Ultracold gases and ions

Scholarship

Monthly stipend of S$2,600 which will be revised to S$3,200 upon passing the qualifying exam for a total duration of up to 4 years

Payment of full tuition fees

Other allowances include
Allowance towards the purchase of a computer
Airfare to Singapore reimbursed
Book and software allowance
Conference allowance

Eligibility

Open worldwide

Graduates with a passion for research in quantum information

Graduates with at least good 2nd Upper Honours, or equivalent qualifications

Conditions include

Student must commit to PhD from the outset
Award is renewable, subject to satisfactory academic performance
No bond is attached
GRE and TOEFL may be requested

Application

1. Contact a Principal Investigator (PI) of your choice at CQT to agree on a preliminary project and solicit the PI's endorsement

2. Submit online application

Application is open throughout the year

Contact Us

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Singapore 117543

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Fax: +65 6516 6897
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CQTPhD.QUANTUMLAH.ORG

Graduate Programme

The Centre for Quantum Technologies is committed to producing high-caliber graduates. It seeks and attracts highly talented students from around the world to undertake PhD studies, offering top-class education in a vibrant environment. CQT also accepts short internships, undergraduates and students pursuing Masters-level degrees at their home university.

The aim of the PhD@CQT Programme is to train approximately 80 PhD students over 10 years. The programme had its first intake in August 2008 and there are presently 29 students in the programme, with more candidates under consideration. An intake of 8 students per year is planned. Research and training are multidisciplinary, with each student having a focus in science, computing or engineering. Students under the programme receive competitive scholarships.

In addition to students under the PhD@CQT programme, 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. Currently, there are 11 PhD students and 5 MSc students conducting their research projects at CQT with funding from external sources.

Student	Supervisor
Eilidh GUDGEON	Andreas Winter
ARUN	Berge Englert
Marta WOLAK	Berge Englert
Han RUI	Berge Englert
WANG Guangquan	Berge Englert
SHANG Jiangwei	Berge Englert
Ritayan ROY	Bjorn Hessmo
Ved PRAKASH	Hartmut Klauck
NG Tien Tjuen	Christian Kurtsiefer
SYED Abdullah Aljunid	Christian Kurtsiefer
Siddarth JOSHI	Christian Kurtsiefer
Bharath SRIVATHSAN	Christian Kurtsiefer
Gurpreet Kaur GULATI	Christian Kurtsiefer
POH Hou Shun	Christian Kurtsiefer
TAN Kok Chuan Bobby	Dagomir Kaszlikowski
HUO Mingxia	Kwek Leong Chuan
LI Ying	Kwek Leong Chuan
Kyle ARNOLD	Murray Barrett
Nicholas Charles LEWTY	Murray Barrett
Markus BADEN	Murray Barrett
Jiabin YOU	Oh Choo Hiap
Penghui YAO	Rahul Jain
Attila PERESZLENYI	Rahul Jain
WANG Yimin	Valerio Scarani
Rafael RABELO	Valerio Scarani
TEO Zhi Wei Colin	Valerio Scarani
YANG Tzyh Haur	Valerio Scarani
Elisabeth RIEPER	Vlatko Vedral
Giovanni VACANTI	Vlatko Vedral

The CQT is home to an international group of graduate students from 13 different countries from around the world.

Internships

For students contemplating a career in research, CQT offers an internship programme. Internships 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 2011 (dates flexible). Interns will receive a stipend. Follow-up applications of successful interns to the PhD@CQT programme will be given high priority.

For more information on the graduate programme, please see the CQT website:

www.quantumlah.org

Meet some PhD students

Colin Teo is one of the Centre's newest PhD students, joining after graduating from NUS in May 2010. Having completed his final year research project in theoretical quantum physics at CQT, he knew he liked the environment. Another factor in him choosing to stay at CQT rather than head overseas, he says, was CQT's current security of funding.

Both Bharath Srivathsan and Siddarth Koduru Joshi came to CQT after studies in India. They now work on experiments in the quantum optics group. Independently, they read about the group's research on one of its researcher's website, sent an email expressing interest in a PhD and were invited to visit. They praise the fact that the application process was straightforward.

Research Report

Adapted from the Scientific Advisory Board Report 20th August 2010

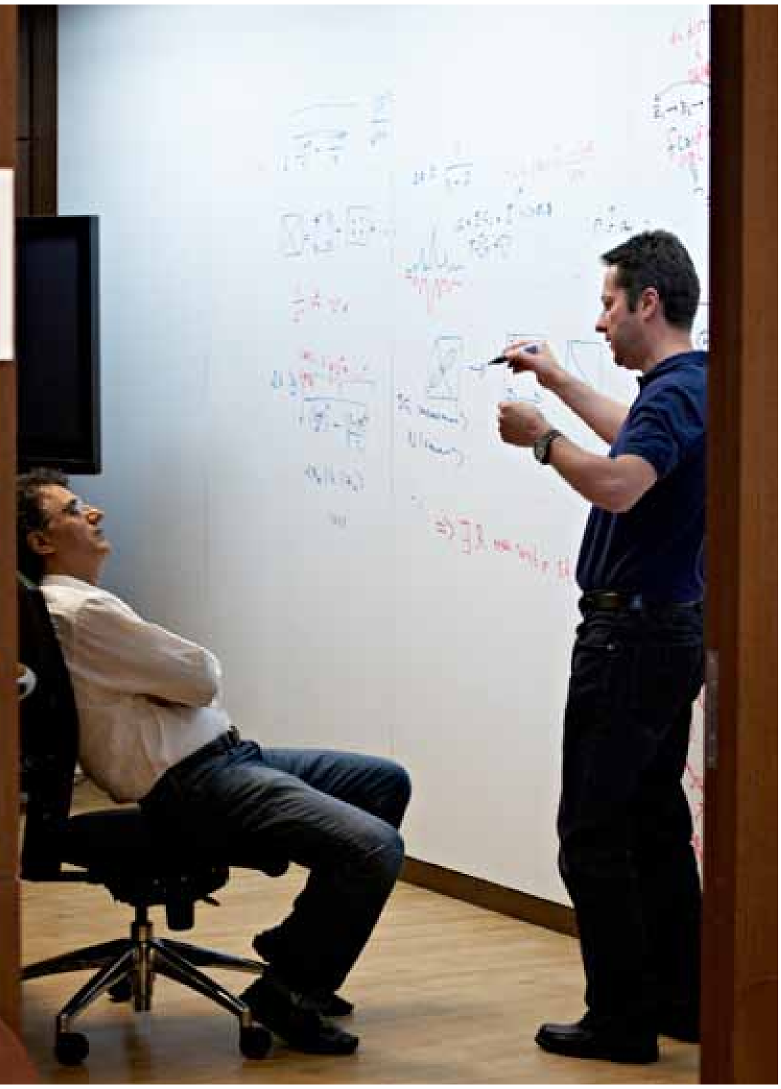
Scientific Advisory Board: J. Ignacio Cirac, Atac Imamoglu, Michele Mosca, Umesh Vazirani, Jun Ye, Dave Wineland

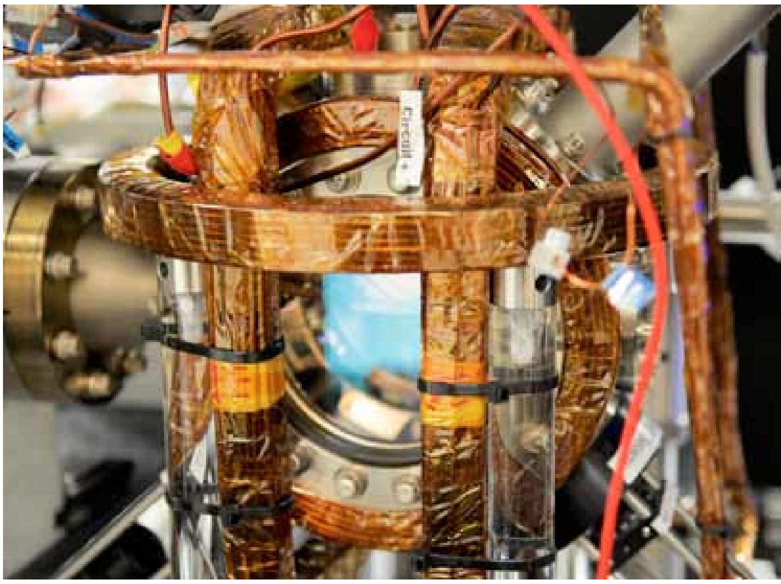
Introduction

Peer review is an important part of how science is done, and it's not just for papers on their way to publication. The Centre for Quantum Technologies has a Scientific Advisory Board (SAB) comprising six leading scientists who undertake a type of peer review of the Centre and its research annually. The expertise of the SAB members spans the remit of research carried out at CQT.

Each year, SAB members are invited to spend a week at CQT attending and giving talks, taking part in meetings and mingling with research staff over buffet lunches of local foods and afternoon tea. CQT's Principal Investigators (PIs) prepare summaries of their work for discussion and the building's corridors are filled with research posters. At the end of this intense week, the SAB compiles a report that reflects on the Centre's achievements and provides suggestions for its future direction. What follows is an edited summary of the SAB report for 2010.

Umesh Vazirani and Ignacio Cirac in conference during the SAB visit in August





Neutral atom experiment in the Microtraps group

Overview

Last year, the SAB noted that the Centre was already enjoying a gain in recognition and visibility and commented on its potential to reach the highest international level. Since then, new theoretical and experimental results have confirmed and even surpassed the Board's expectations. The amount and quality of the research produced since CQT was founded in December 2007 has established CQT as one of the reference research centres in quantum science around the world. The Centre is in extraordinary shape to achieve all its original goals and objectives.

In terms of the research atmosphere and conditions at CQT, the SAB observed some changes since its last visit and have some recommendations:

- Integration: Several important steps have been taken to improve connections between the three different areas of research, namely experimental and theoretical quantum physics and computer science. Firstly, joint seminars presented by students and postdocs have taken place. Secondly, a new PI has been hired whose field of expertise expands over the fields of computer science and quantum information theory. The SAB suggests that the Centre takes further action to encourage integration, such as organizing events aimed at creating links between the research areas. Additionally, it advises hiring PIs who, apart from being extraordinary scientists, could serve as a bridge between the different research areas.

- Training: The number of special lectures has increased, giving students new opportunities to improve their preparation. The SAB still encourages the PIs to offer more new courses to create more chances for students to learn about quantum information, quantum optics and experimental techniques.

• Experimental groups: New PIs of excellent quality have been hired, such that a self-sustained core of experimental groups has been established. The SAB recommends a new hiring in this field as soon as an outstanding candidate is identified.

• Computer science: Two new PIs have been hired, consistent with the excellent standards established in previous hires. As in the experimental effort, the SAB recommends an additional hire once an extraordinary opportunity, both in caliber and fit, presents itself.

The report also identified some further opportunities for the Centre to strengthen and extend its work:

• It emphasizes that the experimental component of CQT is crucial for the success of the Centre. Experiments typically have a long build-up phase, and the experimental

Umesh Vazirani discussing business with Miklos Santha during the SAB visit

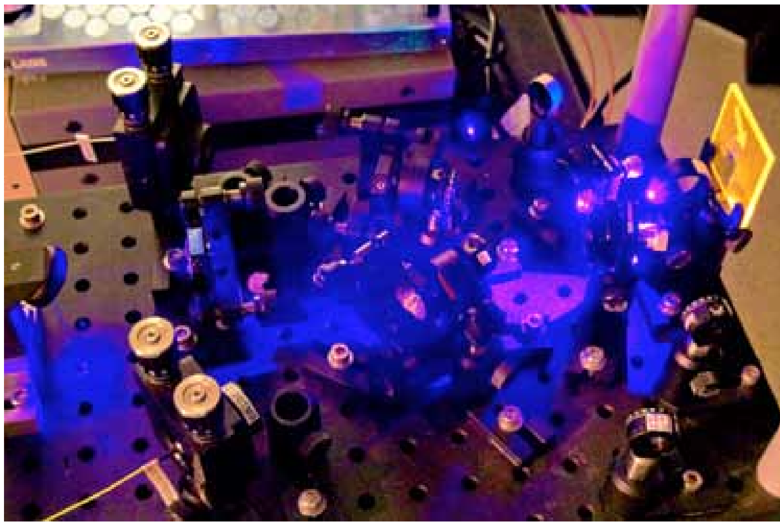
groups may benefit from extra support during this phase to maintain their visibility. More experimental students and postdocs should also be hired.

• A highly-visible group focusing on graphene physics and its applications has been formed at the NUS Physics Department. The report notes that CQT could benefit from involving both theoretical and experimental scientists from the graphene group in quantum technology research.

Graduate Programme

There are roughly 40 graduate students studying at CQT (including graduate students from faculty supervised by CQT PIs). The quality of its PhD students will be critical to CQT achieving the highest level of excellence it pursues.

Very importantly, CQT has a thorough screening process for the students it recruits, and this seems to be reflected in the relatively high grades of the CQT students. The faculty appears to be happy with the quality of their students, and a handful of students who have completed



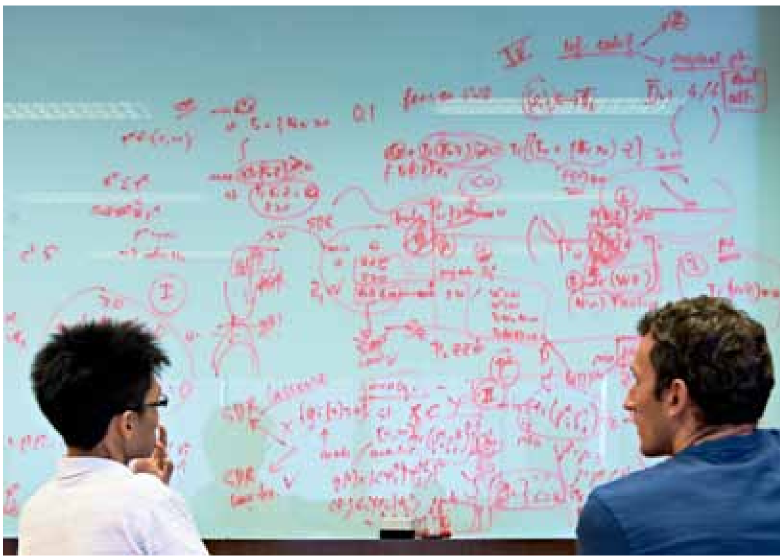
Source of highly entangled pairs of photons

degrees at CQT under the supervision of PIs have gone on to industry jobs and good postdoc and PhD positions in academia in Singapore and abroad. A more definitive view on the quality of the students and their training can be formed when most of the present students graduate and one follows their careers.

The more well-established groups have a good steady state number of students, and are even turning down strong candidates because there aren't enough positions. The newer groups have a smaller number of students, which is to be expected since these groups have not had as much time to recruit high quality students. It will also become easier to attract students once these groups become more established and well-known.

CQT is being proactive and strategic in recruiting students, and this effort should be augmented, especially for experimental and computer science students. The SAB discussed a number of initiatives in place or being deployed soon. For example, the upcoming AQuA (Alliance for Quantum Academia) graduate student conference to be held in December 2010 at CQT, planned in collaboration with MIT, Imperial College, and IQC Waterloo, should further raise awareness of CQT among students.

A student and postdoctoral researcher discussing a thorny theoretical problem



Stephanie Wehner

Interview with a Principal Investigator

How have you been settling into Singapore?
After one month, pretty well so far, although I wouldn't say that I have settled yet.

What has struck you the most in moving to Singapore compared to other places you have lived?
It was relatively easy to move here, although this may have less to do with Singapore than with the fact that CQT made my move very easy.

You have not followed the traditional academic path. Could you tell us about your experiences as a [White Hat] "hacker for hire"? Sounds like fun.
It was incredibly fun at times, and evidently there is a certain thrill associated with a successful hack. In retrospect it also leaves you with a permanent reminder that no matter how beautifully secure systems might look on paper, all theoretical proofs and adversary models are just very crude and limited approximations of real implementations. For example, in all my time as a hacker for hire, I never really felt the need to factor a large integer. Of course this does not mean that we should not try to prove security, quite the contrary, it just means we need to realize its limitations.

What brought you to university after a life in the "real world", then to do a PhD, especially in an "esoteric" subject like quantum information theory which seems to be diametrically opposite to running penetration tests on corporate clients?
I don't think that quantum information is diametrically opposite to hacking; although it certainly is to running penetration tests for clients, which is ultimately just a job. Hacking is essentially about exploring systems and using them in ways which was not their intended purpose. It is as much an attitude as it is a skill. The essence of hacking is to let go of any preconceived notions about what the purpose of some computer system should be, to let go of any ideas what may be allowed or not, indeed maybe even to let go of consequences, and all other things which may constrain your thoughts. It's the idea that it's quite ok to first think freely, and then censor your ideas at some later point in time should the need really arise.

Are you still active in (classical) computer/network security? Have you tested CQT security?
No, I'm not active in practical security anymore. I still have a lot to do with the crowd, and was again involved in organizing the program for a hacking festival last summer (HAR 2009), but I'm more excited about other things these days.

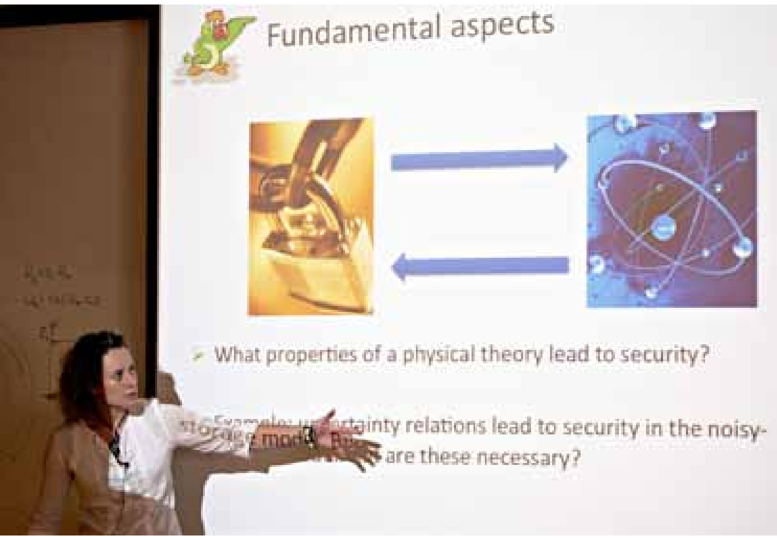
What drew you to CQT?
One of the things I like about CQT is that compared to other places it is still relatively small, retaining some shred of community which is important to me. I also like the fact that we have no official division into subgroups like computer science, maths or physics which often

strikes me as rather artificial in quantum information, and I hope to expand my research horizon as a result of this. In particular, I don't feel constrained by the confines of my original discipline compared to other places which focus on computer science. So far, I feel completely free in my research, which is very important to me.

Of course, there are also some practical matters, like the relative lack of bureaucracy of the operation. I realize this may seem an odd thing to say in the SAB (Scientific Advisory Board visit) week, but it seems a rather minor thing to do compared to the efforts other people have to go through elsewhere.

What is your favourite research result and why?
This is a very difficult question, since I haven't really thought of ranking my results. Maybe my personal favorite is actually something that I worked on a few years ago with Andreas Winter, where we discovered a class of two outcome measurements for which there are maximally strong uncertainty relations. I think it's a very interesting fundamental question how strong such relations can be in nature, but even for three measurements and three outcomes we are still in the dark.

What are you currently working on?
My research interests are rather broad, but let me give you a few examples of the questions that I'm most excited about right now. The first one relates to the question



of how well we can send quantum information over a quantum channel, which remains surprisingly ill understood. The capacity of a channel should tell us how much information we can send over the channel without an error: when sending information at a rate below the capacity we can recover it perfectly, but when sending at a rate above the capacity we necessarily make an error. But just how dramatic are those errors? Do we merely make a relatively small error, or does information transmission become virtually impossible? In more theoretical terms, does the capacity indeed constitute a sharp threshold for information transmission? Finding conditions when transmission becomes impossible also relates to understanding just how non-additive certain capacity quantities can be and I think it's interesting to investigate this question from the other end. You might be surprised, but even for the simplest examples of quantum channels we do not know the answer.

A second question that is on my mind is to understand the quantum properties that enable us to perform quantum cryptography, both quantum key distribution and two-party computation. On the one hand there are questions like whether we can gain any quantum advantage in cryptography without the existence of uncertainty relations? On the other hand, if the only thing I promise you about a physical theory describing our world is that there do exist uncertainty relations for measurements, does this already enable you to solve cryptographic problems? Another small question that I became curious about very recently is whether there exist conditions on how uncertain or how non-local quantum measurements can actually be given the limited resources in an experiment. For example, what are the Bell inequality violations that can be achieved within a certain time frame?

Is there any other research at CQT that you want know more about, find interesting, or in which you see potential for collaboration with experimentalists?
I would like to gain a deeper physical understanding of quantum information, beyond my original background in computer science. Since our centre is so interdiscplinary, I'm hoping that by merging different backgrounds we may be able to make progress in answering some of the unsolved problems in quantum information, and indeed probably discover many new problems. I have a strong interest in working on more physical problems, so this is an invitation to everyone at CQT! For example, some people at CQT have recently posted a paper on the preprint arXiv concerning the thermodynamic meaning of negative entropy, and I'm extremely curious to learn more about it.

As for collaborations with experimentalists, I would greatly welcome them. Amongst other things, I think it would be great if there was a way to actually experimentally verify some properties of quantum information theory in the lab. For example, we recently obtained a rather surprising property of the minimum entropy conditioned on quantum vs. classical information and I would be curious if one could test this effect.

Where do you think the field of quantum information will be in 5-10 years time?
The CQT oracle has pondered your question deeply. For sure, we will have the iphone 7Qs, capable of performing quantum communication. More seriously, I think quantum information will further expand into related areas in physics that are much more general than quantum information processing itself. For example, some of our techniques might enable us to gain further insight in other areas.

There is a distinct underrepresentation of women in technical fields, especially mathematics, physics and computer science. Do you think this is a particular problem? If so, what could be done to rectify the situation?
I do think that women are underrepresented, but I am not sure whether I would call this a problem, which seems quite a serious term. I do think however that it is highly desirable that there would be more women in technical fields. There are many things that could be done about this at an official level, but I think the more important question is what we as individuals can do about it. For example, we could encourage more female students to do quantum information. As a woman in quantum information, we could talk to female students already in our field. To be honest, it is occasionally a bit lonely as a woman.

You have expressed a deep interest in parrots. What is it about them that fascinates you?
I'm interested in parrots since they are known to exhibit rather intelligent behaviour in nature. It seems to me that intelligence is more of sliding scale, rather than a step function, and seems to be especially prominent in social animals living in groups. Possibly, intelligence arises in animals that gain a significant advantage by communicating and coordinating their actions. One thing I'm particularly interested in is the communication abilities of parrots in the wild. If you have spend a long time listening to groups of them outside, you may have noticed that their "vocabulary" is extremely rich. It would be great if one could decode some of their "language", and maybe determine whether they can, for example, convey simple concepts like the the presence of food.

Stephanie Wehner joined CQT as a new Principal Investigator in 2010. Before CQT, she worked in the group of John Preskill at Caltech, and prior to that she completed her PhD under the supervision of Harry Buhrman at the University of Amsterdam/CWI.

Visitor Notes: Jacob Biamonte

Categorical Models of Quantum Information in the Simulation of Many-Body Systems

CQT attracts both long and short term visitors from all over the world. Jacob Biamonte, a Research Fellow at the University of Oxford and Lecturer in Physics at St Peter's College, explains the results of his two collaborative visits with several members of CQT staff, including Stephen Clark. Their work involved using higher mathematics to create a new theory of tensor network states and has numerous practical applications in the simulation of physical systems.

It was quite the honour to be asked to contribute to CQT's annual report by outlining my experience as a visitor. I agreed instantly and after a bit of thought, I came to realise that my CQT visits and a lot of what's happened since are traced back to a single instant.

That instant occurred when I was signing up for coffee in the common room of Wolfson College at the University of Oxford. A large part of the Oxford accounting system requires no electricity, and many of those spending time here sign for small expenditures often enough to see their signature evolve slowly into, say, a line with some bumps, or another slur of the pen. On this occasion, however, I noticed something elegant scribed on the page – the name of "V. Vedral". I still recall the flavescent paper, and the excitement when I realised that Vlatko Vedral, the long-awaited Wolfson Physics Fellow, had finally arrived. I recognized Vlatko's name as one of the founders of entanglement theory, and later that year ended up paying him with a Cuban cigar in exchange for a guest lecture in the course I organize. He spent several years in Oxford early in his research career and is now a Principal Investigator at CQT.

From Candle-Light Accounting to Collaboration

I've become accustomed to the shock people get when they realise that I, as a physicist, dabble in a strange branch of higher mathematics known as category theory. Vlatko, on the other hand, he seemed to like the idea of figuring out if category theory can tell us something we didn't already know about quantum information science (or at the very least, he was not openly opposed to it). It was around the time we met when I realised that category theory could precisely describe one of the deepest and most powerful theories being used in quantum physics: the theory of tensor network states. This was some time ago, and we have now been able to produce several notable results new to both tensor network theory and category theory, and in the process we've made pioneering steps towards connecting these two fields.

Computer simulations of physical processes form the backbone of many technological developments. For example, quantum chemistry simulations enable scientists to better understand large molecules used in pharmaceuticals. An aspect of the theory of tensor network states is an approach to efficiently describe complex states of physical systems by a connected network of components called tensors. This approach has proven useful in attempts to simulate quantum systems for many reasons: the most elementary perhaps being that many tensor networks require little memory storage. It struck me that the range of expressiveness of the existing mathematical theory of tensor network states and the associated graphical language would be broadened by elevating the theory to a rigorous tool. At the same time, this ended up allowing us to expose hosts of internal algebraic structure. Category theory with its long history in mathematics provided a way to achieve this.

Through Vlatko, I met Stephen Clark and Dieter Jaksch, both leading experts on the (then current) theory of tensor network states. Stephen is employed by CQT and Dieter is a Visiting Professor at the Centre. Although they both spend time in Oxford, we were all too busy locally, so we had to take a plane to Singapore, meet at CQT and then collaborate around the clock. I made two month-long visits in 2010. I won't have the space to give CQT's visitor program the respect it deserves for enabling us to work daily to develop our new framework. I also won't have room to go into details of how exciting it was for the three of us to meet the well known mathematician John Baez on his visit to Oxford – especially when we realised he was on his way to CQT for two years and that we all had many common interests. Instead, I'll skip to our results.

Out of the necessity for improvements to the current tensor network theory and the opportunity presented by noticing its similarity to category theory, we have developed a categorical approach to tensor network simulations that binds techniques across disciplines and creates a more expressive and powerful tensor network theory. The existing tensor network approach revolves around ways to approximate quantum states. What we have done boils down to creating a much better way to control the way states are expressed, making it possible to "zoom in" and expose new found internal structure.

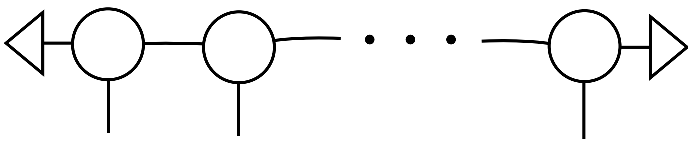


Figure 1: Tensor network states in the current formalism have this generic form. The legs on the bottom index spin degrees of freedom.

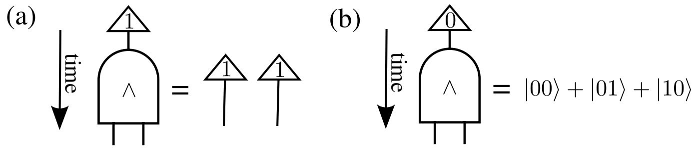


Figure 2: The quantum AND-state. This corresponds to a valid quantum operation, realisable in a quantum optics experiment.

Our results have opened a new door, leading to several novel results in both category theory and tensor networks. In particular, we have used the new framework to give a new solution to the quantum decomposition problem. Specifically, given a quantum state S, we are now able to directly construct a tensor network that describes the state S in terms of clearly defined building blocks. This solution became possible by synthesizing and tailoring several powerful modern techniques from higher mathematics: category theory, algebra and coalgebra and applicable results from classical network theory and graphical calculus.

Tensor Network States

A key idea behind using a tensor network based computer algorithm to describe a large class of quantum states efficiently is finding a way to approximate the state. Typically, this is done by a form of matrix factorisation known to experts as Vidal's iterative use of the SVD (skipping details, you simply throw away small singular values and truncate the Hilbert space). In many cases this provides highly accurate approximations of quantum states. The resulting matrix product states take essentially the form shown in Fig. 1.

Readers familiar with category theory might say, "this looks a lot like a string diagram, right?!" After digging through the details in a few collaborative meetings, John pinpointed the relation between these diagrams and his theory of spin networks (which he developed for use in quantum gravity).

Snap Shot: Categorical Tensor Network States

Our recent work concerns the development of a new tool set and corresponding framework to address problems in network descriptions of many-body physics and related disciplines. These tools and this framework is significantly different to and outside the range of methods used to date.

In the categorical network model of quantum states we present, each of the internal components that form our network building blocks are completely defined in terms of their mathematical properties, and these properties are given in terms of equations which have a purely graphical interpretation: category theory replaces *ad hoc* graphical methods in network descriptions of many-body physics and enables rigorous proofs to now be done graphically.

Say you have a quantum state, the quantum AND-state: |000>+|010>+|100>+|111>. If we draw this as a network (AND-tensor with two-inputs and one-output), and place a |1> on the output and run the network backwards, this leads to the product state |1>|1> (Fig. 2a). Now if we instead place a |0> on the output and run the network backwards, this leads to the entangled state |00>+|01>+|10> (Fig. 2b). The idea is we can now "wire" these quantum logic tensors together in a controllable way to create larger and larger tensor network states.

It turns out that our quantum logic-tensors enable us to translate a quantum state into a tensor network directly. For instance, the internal structure of a so-called W-state (|00…1>+|01…0>+|10…0>) as in Fig. 3.

Connecting the Dots

Categorical models of tensor network states enable us not only to "zoom out" and expose high-level structure, but also to "zoom in" and expose hidden algebraic structures that are not currently being considered in the tensor network simulation community. Enhancing the graphical language and mathematical component of these numerical methods should lead to the discovery of new theoretical models and numerical algorithms which challenge and shape our understanding of many-body physics.

Getting to the very bottom of why quantum systems are so difficult to simulate is one of those seemingly impossible research problems. It's bewildering but fascinating to explore. With each step towards better ways to handle complex quantum states, technological advancement follows. Adding quantum capability to simulations in physics and chemistry is of great commercial interest, meaning this research has the potential to attract R&D investment from Singapore and abroad.

Further reading

Citations and background information on tensor network states can be found at http://www.comlab.ox.ac.uk/activities/quantum/course/. This webpage is for a graduate course given at the University of Oxford in 2010, "The Quantum Theory of Information and Computation", which I developed with Stephen Clark, Mark Williamson and Vlatko Vedral to foster the cross-communication needed to explore these multidisciplinary topics. This course will be given again at Oxford this year (with Dieter Jaksch) and we plan to give versions of this course at several leading research institutions and top universities, including Imperial College London, University College London and CQT (with several lectures by John Baez). For his trips to London, Vlatko doubled his fee: two Cuban cigars per lecture. What can we do?

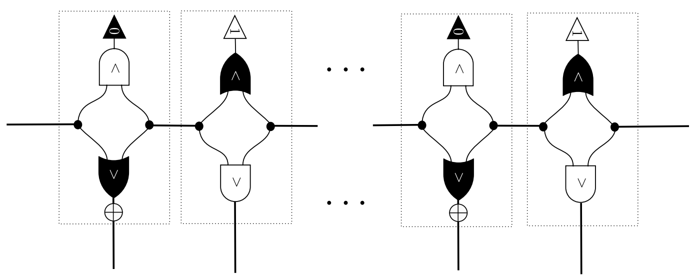
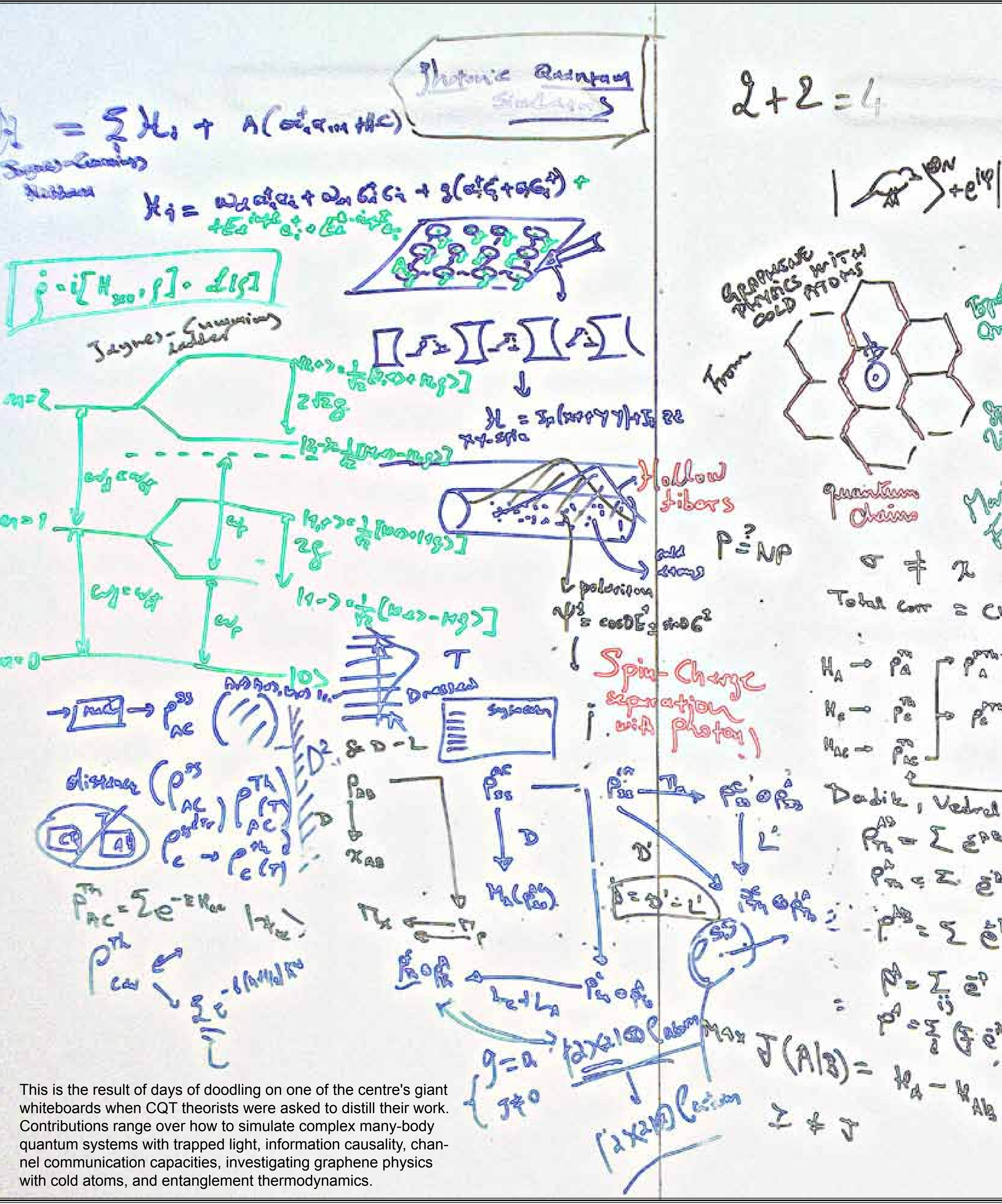


Figure 3: A tensor network state in our framework. Hosts of internal structure is exposed and the components that form the network are completely defined in terms of their mathematical properties by diagrammatic laws.



This is the result of days of doodling on one of the centre's giant whiteboards when CQT theorists were asked to distill their work. Contributions range over how to simulate complex many-body quantum systems with trapped light, information causality, channel communication capacities, investigating graphene physics with cold atoms, and entanglement thermodynamics.

What the Theorists

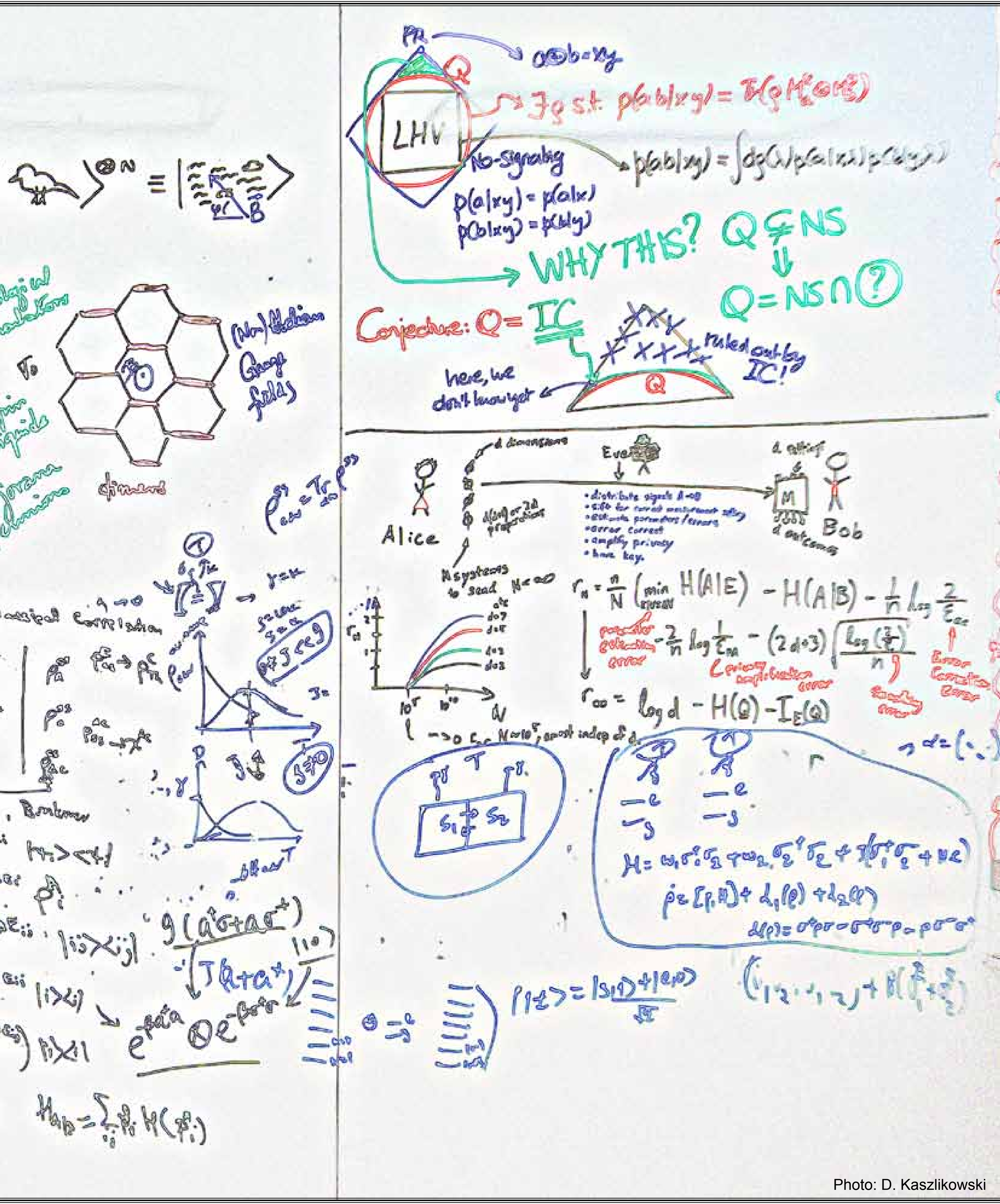


Photo: D. Kaszlikowski

Have Been Up To...

Understanding Quantum Mechanics *(and staying sane)*

Dagomir Kaszlikowski tells how six friends found evidence for what might be one of the foundational properties of nature

When I was a PhD student, I aspired to understand quantum mechanics, but I was met with skepticism by everyone around me. Professors whom I admired kept telling me that it was a futile and dangerous endeavour. One of their favourite phrases was “Nobody understands quantum mechanics”, which has the added gravity that Richard Feynman once said it. Finally, after an influential scientist in my department told me an anecdote about a student who dreamed of understanding quantum mechanics but ended up in a mental asylum, I gladly shut up and started to calculate.

Many years later, in January 2009, I found myself confronting my old demons in the Spinelli cafe at NUS’ University Hall while I nervously gripped a cup of coffee . The demons had materialized in the form of a young and ambitious scientist from Poland, Dr Marcin Pawlowski, whom I invited to CQT after a brief conversation with my collaborator Tomek Paterek. Perhaps if I had listened more carefully to Tomek I would have found out that Marcin, like me, would have earned my former Professors’ warnings. Now it was too late…

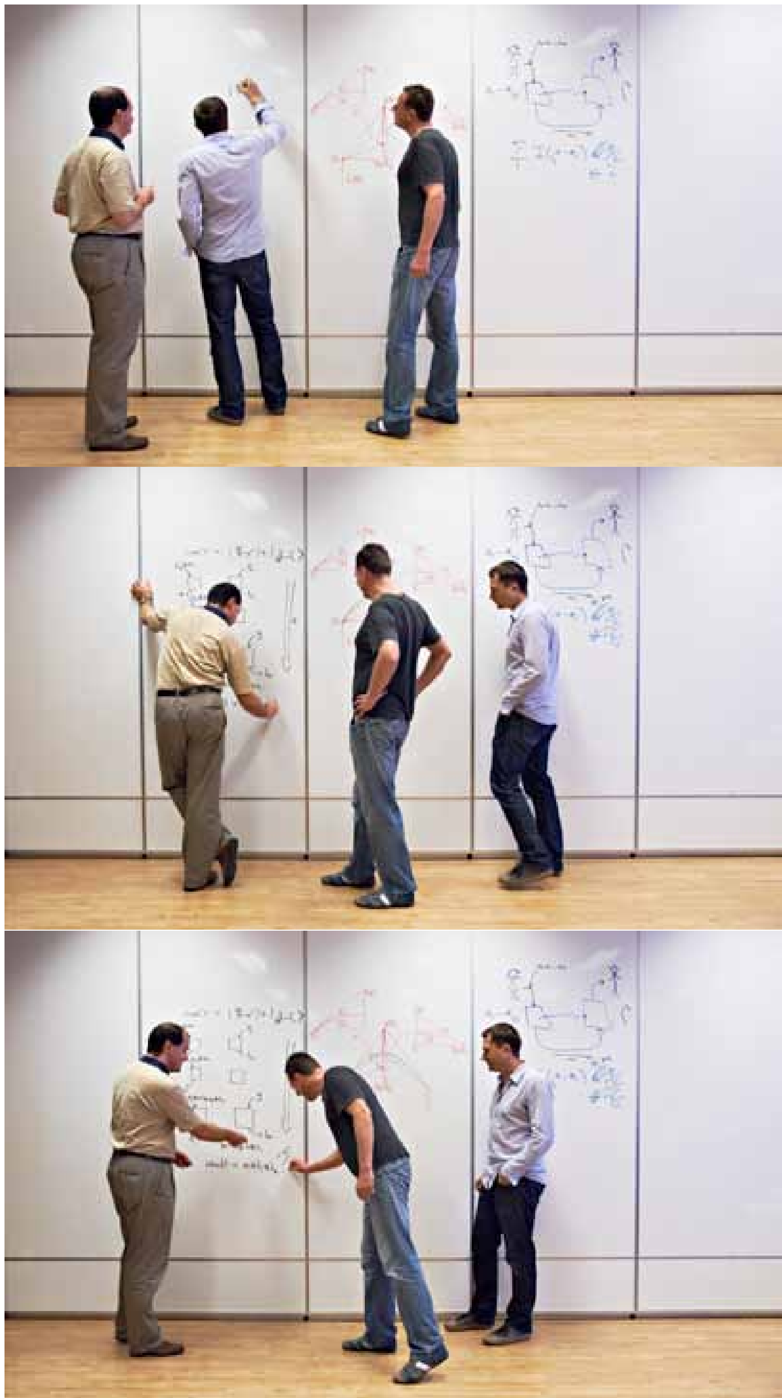
Over the next few weeks, Marcin would draw me back into the search for an intuitive understanding of quantum mechanics. And it wouldn’t only be me. By the end, there would be six of us straining for insight into quantum correlations, the connections that quantum mechanics lets exist between particles. I am pleased to say right away that far from driving us crazy, this story comes to a happy close. We identified a principle that could be a defining one for quantum laws.

Bit talk

With unruly hair, a casual dress-sense and an absent-minded air, Marcin, from the University of Gdansk in Poland, conforms to the stereotype of a scientist. He seems to be thinking about science 24/7, and not only thinking about science but also talking about it. As soon as I’d shaken his hand that day in the Spinelli cafe and offered a pointless “How are you?”, he started to talk about his ideas about quantum information theory with the speed of a machine gun. All of his ideas related to a better understanding of quantum theory. “Oh, gosh”, I thought.

After spending a few days sifting through Marcin’s ideas, we decided to concentrate on the question of how much information one person can make accessible to another by sending m classical bits of information. We call these two people Alice and Bob, following convention in quantum physics, and we wanted to look at whether sharing physical correlations changes how much information they could exchange.

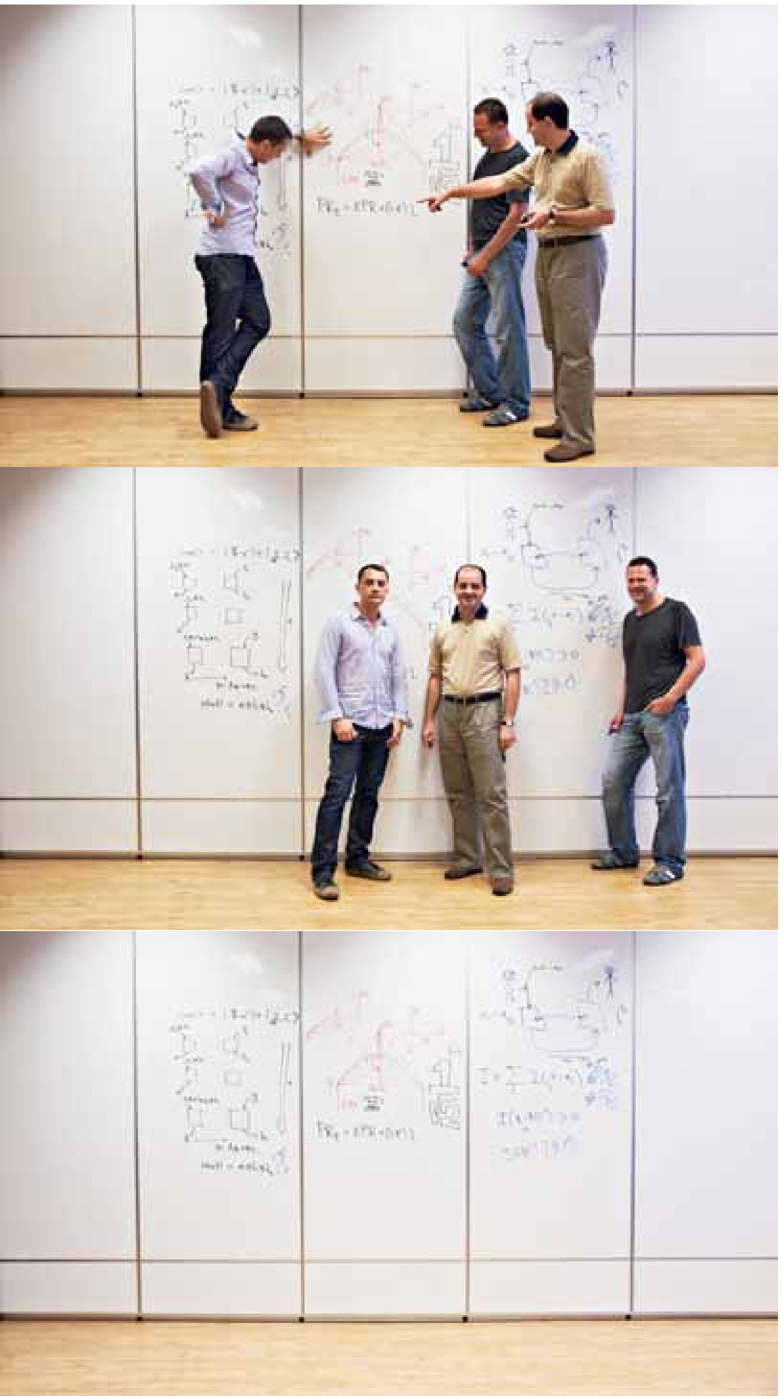
To better understand the concept, let us imagine that Alice has a book about Singapore that contains M bits of information. It could be one of those Lonely Planet books that contain information about good food, what to see, where to find interesting nightlife, etc. Knowing that Bob likes to eat well, Alice scans and emails him the pages about food. These pages contain m bits of information. Bob, who is actually much more into clubbing and thought Alice should know so, is disappointed and wishes instead to have the pages about nightlife, which also contain m bits of information. However, Bob finds that he is too late because Alice is offline. In this example, Bob



is clearly stuck with the information about food that Alice sent him. But what if Alice and Bob's computers were somehow linked, or correlated: could Bob choose which pages he got to see when he opened his attachments? Marcin had a gut feeling that if Alice and Bob shared correlated quantum particles, and Alice were allowed to send Bob m classical bits of information about M bits in her possession (here M is larger than m), Bob could still learn no more about Alice's M bits than the m bits she chose to send. At first I thought that Marcin's intuition was wrong and that the whole problem was silly. It was "obvious" to me that sharing some physical correlations will definitely allow Bob access to more than those m bits, and I could not see why one should be interested in this kind of nonsense. How wrong I was.

Marcin showed us that if his intuition were correct, we could derive the Tsirelson bound in a new way. The Tsirelson bound is a very important result in quantum physics. In short, it puts a limit on the strength of the bi-partite correlations that are allowed by quantum theory. The "problem" with this bound is that its standard derivation is very technical and relies on the properties of Hilbert space, which is a complicated mathematical structure (and something that nobody understands). Technical derivations are not satisfying for hardcore physicists who always want to have some kind of intuition about why things are as they are.

Dagomir, Valerio and Andreas discussing their latest results.



After hearing Marcin's explanation, my jaw dropped (I am almost sure that I also saw Tomek's jaw dropping but I can't be certain). It was simply brilliant! If Marcin were right, we had an explanation of the unexplainable. If he were right, it would mean that Feynman's famous phrase should be re-interpreted and that curious PhD students need not worry about their sanity. But what if Marcin was not right?

From intuition to proof

Immediately, Tomek and I set out to prove Marcin's intuition mathematically (Marcin went on holiday, setting off to climb some mountains in Asia). In spite of our best efforts, after two weeks of hard work we still did not have a proof. To get a fresh perspective, I approached Valerio Scarani, knowing that he had been doing similar research and is a very curious chap. He got hooked on the problem momentarily. We also decided that Marek Zukowski from Poland should join the team because Marcin's idea had been born of discussions with him. Now we were a bunch of friends working on an intriguing problem, which is a physicist's idea of paradise.

Days passed and we still couldn't find a complete solution. We knew intuitively that Marcin was right and we knew the way to prove it but we were missing various bits and pieces necessary to close all the loopholes in the reasoning. It was exasperating. Suddenly I realized we had one more chance: Andreas Winter.

Andreas is one of the smartest chaps I know. He is also one of those very few famous scientists who have time to discuss physics and have a cup of coffee with you. Some time ago I was stuck with a problem, approached Andreas and made a 50 buck bet with him that he wouldn't be able to solve it. The next day I said goodbye to the money. Yes, Andreas was our last chance. When I presented this problem to him he simply said "Beautiful". Next morning he had the full proof. It's not a joke, he really did it overnight. Moreover, his solution was a real beauty.

The end game

So we had it. We proved that if Alice has M bits of information, shares with Bob quantum correlations and sends to Bob some m bits of information, Bob has access to at most those predetermined m bits. One of the consequences of this theorem, which we call "information causality", is that one can recover the famous Tsirelson bound in a very intuitive way, without invoking Hilbert space formalism. More than just being a principle that quantum mechanics happens to respect, information causality might be a requirement that physical laws have to follow: information causality is a candidate for an underlying principle of nature.

When Marcin came back from his Asian voyage, it was time to sit down and write a paper about information causality, which is easier said than done. We wanted to aim for publication in the high-level journal Nature, where articles on fundamental aspects of quantum theory appear once in a blue moon or even less often. The paper needed not only to describe what we did but also to describe it in an appealing way. We called on the expertise of Valerio, who has lots of experience in writing articles and books popularizing science. It took us some time to arrive at a final version of the paper – Marcin and Andreas left Singapore and we had to work via email – but in the end we got it published. The article “Information causality as a physical principle” appeared in Nature in August 2009.

And here begins a new story. Information causality has generated lots of interest in the quantum information community and opened new avenues of research, which is what good ideas are about. There’s just one piece of unfinished business for our collaboration after the fun and excitement of discovering a tiny bit of the infinite puzzle of the universe: we still haven’t had our celebratory champagne.

Drawing by Haw Jing Yan, Undergraduate, NUS Physics

A Bit More Formally...

Valerio Scarani

Information causality states a limit on how much information one party can gain in a communication from another. To formalize the idea, let us consider a scenario in which one person, Alice, sends another, Bob, some bits of information. We also introduce a distributor, Dago.

Imagine that Dago sends Alice two bits, i.e. one of the four pairs (0,0), (0,1), (1,0) or (1,1). Let us denote these bits by (a_1, a_2). Now Dago sends Bob one bit, b=1 or b=2, which tells Bob to output a_1 or a_2, respectively. How do the odds for Bob to give the right answer, 0 or 1, depend on the number of bits that Alice sends Bob?

Let us describe first what happens in the classical world, where everything behaves in a familiar way. If Alice can send Bob two bits, which we write m=2, obviously Bob can give the right answer whichever bit Dago tells him to output because Alice will just send a_1 and a_2 and then Bob knows their values. If Alice can send no bits at all (m=0), Bob is reduced to sheer guessing, with a 50% probability of getting the answer right. If Alice is allowed to send one bit (m=1), Bob’s optimal strategy is to always output the value of that bit. If Alice had sent a_1, Bob’s output would always be right when Dago sent him b=1 and would be correct with 50% probability if Dago sent him b=2.

Casting these odds in a different form, using conditional mutual information, we can define a quantity I that in the classical world obeys:

$$I \leq m.$$

This is the formal expression of information causality: if Alice sends m bits, Bob’s information (suitably measured) cannot be larger than m bits.

In quantum information, we are accustomed to the idea that the outcomes of “games” we design for Alice and Bob can differ in the quantum and classical worlds. Sometimes, by sharing entangled quantum states, Alice and Bob can do better than classical rules allow. But in the example described here, entanglement does not help. This is what Andreas conclusively proved: information causality also holds if Alice and Bob share entanglement.

You may think this is obvious, following from the fact that entanglement is non-signaling. “No-signaling” means that Alice cannot send information to Bob by measuring her half of a shared entangled state, and that much was known already. However, this intuition is wrong – and here comes the remarkable part, the fact that Marcin had noticed and that started the whole project: some no-signaling resources do allow Bob to do better than he could in classical or quantum physics. In fact, if entanglement were any "stronger" than allowed by the Tsirelson bound in quantum physics, the odds for Bob to guess bits correctly would increase, and I could exceed m.

Microtraps Ready to Give New Results

Murray Barrett provides an update on his group's experiments in trapping atoms and ions

The two labs I manage in the microtrap group are on the cusp of an exciting new phase of research. Years of careful work since we moved our equipment into the CQT building have brought our experiments to the point where we can start pursuing original research.

Our research focuses on cavity quantum electrodynamics (QED) and its application to quantum information processing. In very general terms, we want to manoeuvre atoms or ions into a cavity – a small space enclosed by mirrors – and then communicate with them using light. The mirrors enhance the interaction between the light and the trapped particles. If we think ahead to applications, the atoms or ions are potential bits, or "qubits", for a quantum computer or quantum simulator, and photons are a way to address them and move information between them. Our experiments also deal with creating entanglement – connections between the quantum states of particles – which is important to information processing applications.

We have three main focus areas:

Neutral atom cavity QED
An atom trapped in a cavity may undergo a change in energy level known as a Raman transition, emitting a photon in the process. The idea is to use these cavity-assisted transitions to provide entanglement between the atom and the outgoing photon. This is a key component in establishing entanglement between remotely located atoms. Our system also has the flexibility to allow us to investigate multi-atom dynamics and quantum phase transitions.

Ion trap cavity QED
Ions are more easily trapped than atoms, benefiting from high confinement and long trapping lifetimes. Photons emitted by trapped ions provide a means to interface multiple ion trap processors. A few traps holding a few qubits each can be linked in a bigger computational scheme. Combining ion traps with cavity QED should drastically improve existing remote entanglement protocols based on spontaneous emission — remote ions could be entangled at a rate of one event every ten milliseconds instead of every ten minutes, say. Ion traps are also an important technology for precision metrology with applications in frequency and time standards and tests of fundamental physics.

Micro-cavities
We are exploring possibilities to miniaturize our cavities. Having smaller cavities would make it easier to incorporate them into other setups (such as an ion trap) and increase the strength of the coupling between the atom and cavity.

On all fronts, good progress has been made.

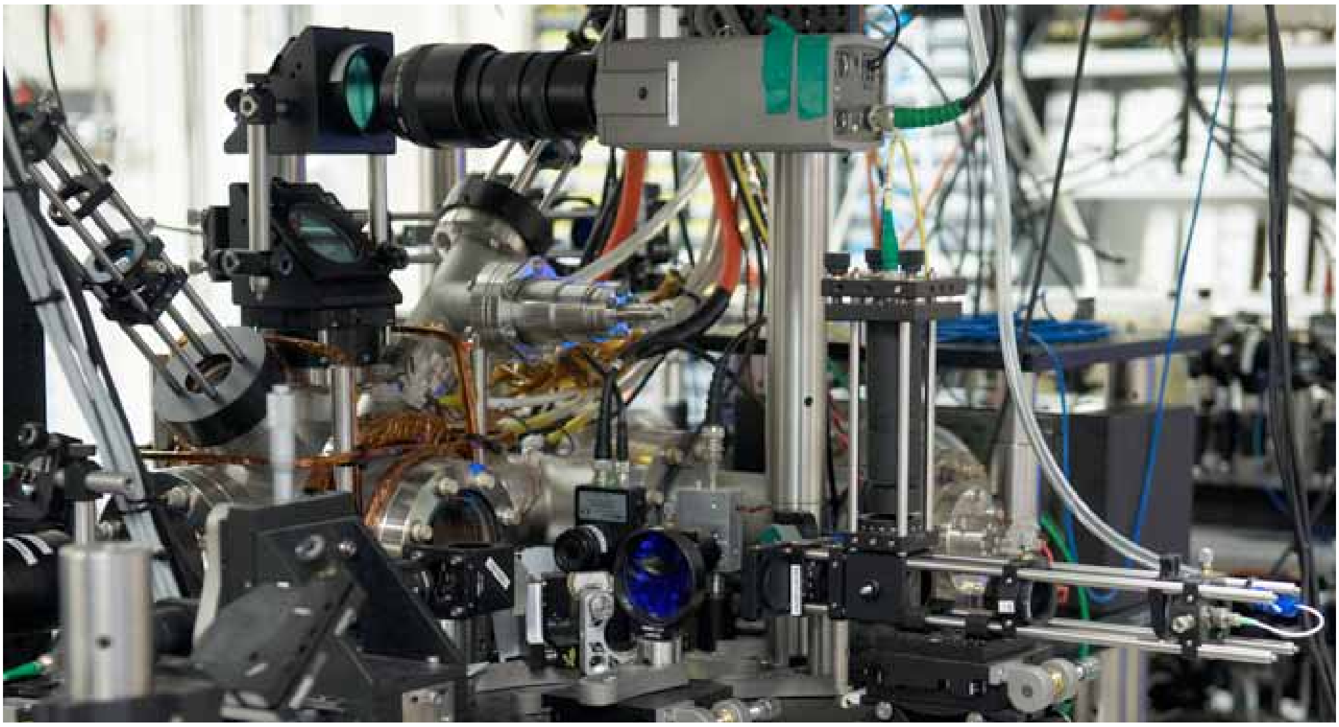


Figure 1: Cavity QED Experiment. An ultra-high vacuum chamber is surrounded by a phalanx of lasers, cameras and other optical components. These serve to trap and cool atoms to close to absolute zero. An extremely high precision cavity enhances the interaction of light with the atoms. This could form the basis of a distributed quantum computer.

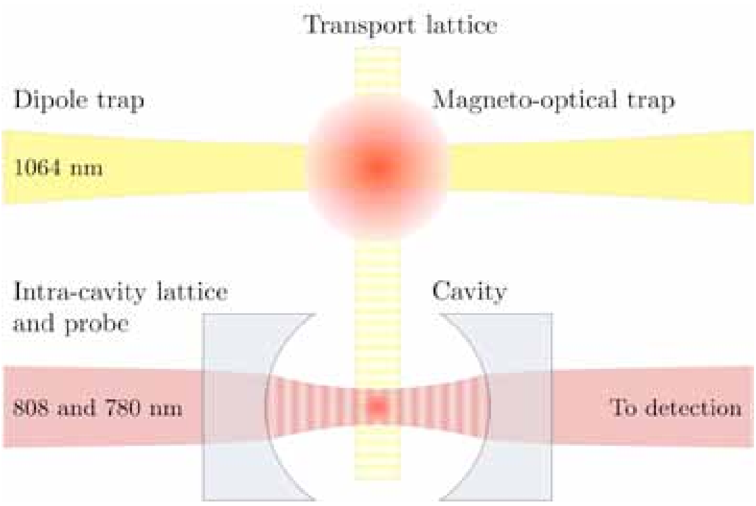


Figure 2: A magneto-optical trap located ~1cm above the cavity uses light and magnetic fields to confine a cloud of neutral atoms, which are then loaded into a transport lattice of laser light to be carried into the cavity. Within the cavity, confinement is provided by a red laser and a horizontal lattice potential.

Neutral atom cavity QED

Our neutral atom cavity system is now very well established. The setup for trapping and conveying atoms into the cavity is pictured (Fig 2). From a diagram like this, it is hard to appreciate just how difficult the experiment has been to build: just to get everything lined up is a challenge. Consider that the zone in the cavity where the atoms need to be placed is only as wide as a human hair. The laser beam that transports them there and the one that holds them there have to intersect this spot precisely.

Initially, we have concentrated on testing our setup with a number of standard cavity QED protocols, such as observing splitting in the energy level of the trapped atoms thanks to strong atom-cavity coupling (data shown in Fig 3). From this testing stage, we already have one unexpected result to explain. Atoms in our cavity appear to be held for around 3 seconds before they escape the trap, a period which we refer to as their intra-cavity lifetime.

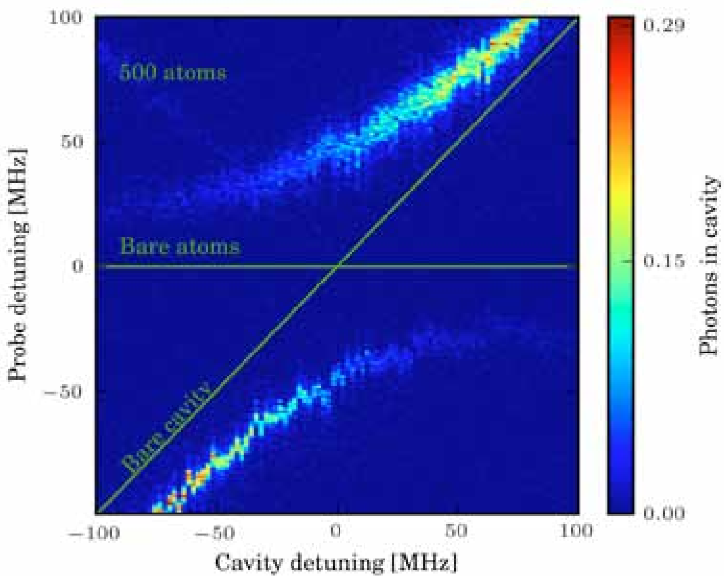


Figure 3 :Experimental data shows the splitting of the cavity resonance, as probed by an interrogating laser beam. The anti-crossing behaviour of the resonances, which appear as bright areas in the plot, indicates that the atoms and the cavity's fields are coupled.

Similar experiments elsewhere have had to add another layer of cooling to reach lifetimes this long, whereas we seem to be getting it "for free". During our testing phase we also observed extended probing times which is a strong indicator that the atoms are being cooled by the cavity interaction and we will be investigating the limitations of this cooling method in the upcoming months. With everything apparently behaving well, the PhD students working on this project with me, Kyle Arnold and Markus Baden, and I are talking to theorists about the experiments we intend to start.

For now, we plan to focus on single atom dynamics, specifically interfacing photonic and atomic qubits. However our system has the flexibility to look at multi-atom dynamics including cavity-based cooling schemes and quantum phase transitions. The optical dipole trap part of our system was used in 2009 to establish a Bose-Einstein condensate — an exotic phase of quantum matter that forms when the atoms are cooled to less than a millionth of a degree above absolute zero. This was both a result to celebrate on our route to establishing the experiment, and proof-of-principle that we can in future explore the interaction of a condensate with the cavity field.

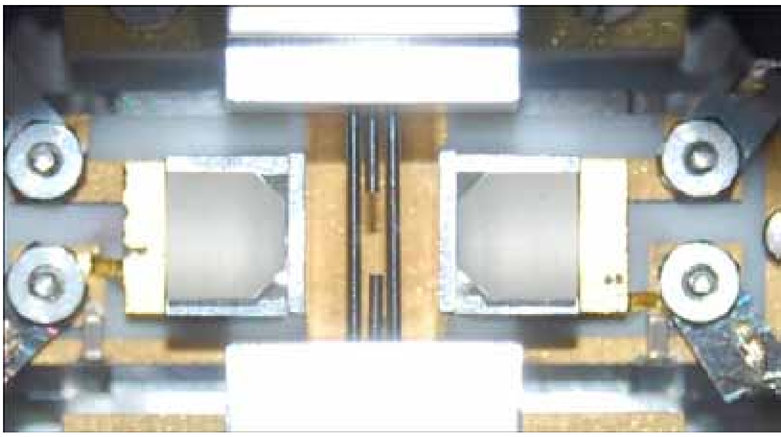


Figure 4: A view from above of the ion trap showing the cavity placement (left and right) about a standard four rod Paul trap (centre), which creates electric fields to hold the ions in place. Each cavity mirror is shielded using a metal insert which has a small 0.5mm hole to allow the cavity mode through. The setup limits the size of the cavity, with the length constrained to about 5mm.

Ion trap cavity QED

As this annual report is being put together, we are preparing for a major milestone in this experiment: getting ions into the cavity. We have tested the ion trap and cavity separately; all that remains is to get them working together (see Fig 4). Implementing cavity QED with ion traps is really a technical problem. In order to provide the strongest coupling to the ion, the cavity has to be small. This brings the cavity mirrors close to the ions and the dielectric surface is known to cause heating problems and charging effects. Moreover, mirror surfaces are easily contaminated during the loading process, and this is after we have painstakingly selected each mirror for the cavity under a microscope, screening them for imperfections.

We had one early set-back when, in the process of testing a cavity, we accidentally destroyed it. A leak in the vacuum system had gone unnoticed and this led to the voltage we applied across the cavity causing a plasma

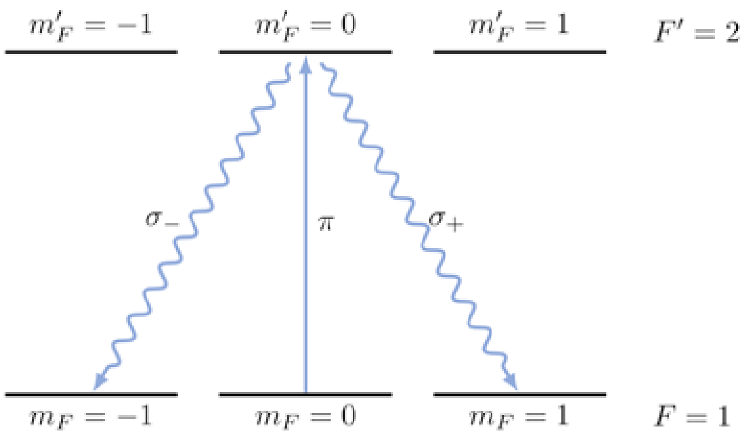


Figure 5: Here we show the basic atomic level scheme for generating atom-photon entanglement via spontaneous emission. The m_F=±2 upper states have been omitted. A driving laser pulse places an atom initially in the F=1, m_F=0 state into the F=2, m_F=0 state. The atom then decays into either F=1, m_F=±1 states emitting a right or left circularly polarized photon, respectively, in the process. Since each possibility is equally likely, the joint state of the atom and photon is highly entangled.

discharge — the gas in the system started to glow. It's a dramatic effect that I now use as a demonstration in teaching, but it wasn't good for the mirrors. Now we can laugh about it because the experiment is back on track. Our replacement cavity has a cavity finesse of 70000, a linewidth of 400kHz, and a single atom cooperativity greater than unity. The finesse measures the efficiency of the cavity in trapping light. Our cavity linewidth will enable us to resolve the vibrational levels of the trapped ion which should allow us to cool the ion to the ground state of motion via the cavity, and the high single atom cooperativity means that emission into the cavity mode is enhanced.

The emission scheme we will be working with is illustrated in Fig 5. It deals with photons emitted by ions in an excited state. It has been demonstrated that making an interference measurement between photons emitted by ions in different traps can create entanglement between the remotely located ions. Since the scheme is based on spontaneous emission, however, the photons are not in a well defined mode and the process is extremely inefficient — the chance of success being less than one in a million. We are investigating cavity QED as a means to substantially enhance the efficiency of the process — with our cavity, we anticipate being able to achieve efficiencies well above 50%. Chuah Boon Leng and Nick Lewty are my collaborators on this project.

Micro-cavities

Both the neutral atom and ion trap efforts would benefit from a reduction in the dimensions of the cavity which would increase the atom-cavity coupling. Arpan Roy, Nick Lewty and I have explored a number of possibilities for miniaturizing our cavities including silicon processing, laser machining both quartz and fibres, and reflowing glass under appropriate conditions.

The most successful approach to date has been reflowing glass, and the basic scheme is illustrated in Fig 6. The resulting glass surfaces are almost perfectly spherical, clean and defect-free, making them very suitable as a substrate for a high finesse mirror. Mirror curvatures in the range 0.5-5mm have been produced. Atomic force microscopy and optical profiling indicate surface roughness of a few Angstroms (10^{-10} metres), which is at the limit of the measurement techniques. This roughness is expected to limit the cavity finesse to about 10^5 (for light of wavelength 780nm) and 10^4 should be easy to achieve.

Cavities constructed from these miniature mirrors will reach the strong coupling regime of cavity QED at a much reduced finesse, and single atom cooperativities of approximately 30 should be easily obtainable. Moreover, their size should make them easy to incorporate into experiments, particularly with ion trap technology. We are currently working with a commercial company to establish a coating process for the small curvatures involved.

Outlook

As we look forward to collecting new results, some of our colleagues in the microtraps group are starting new experiments. Björn Hessmo and his collaborators are establishing a new lab, but that's news for next year's annual report.

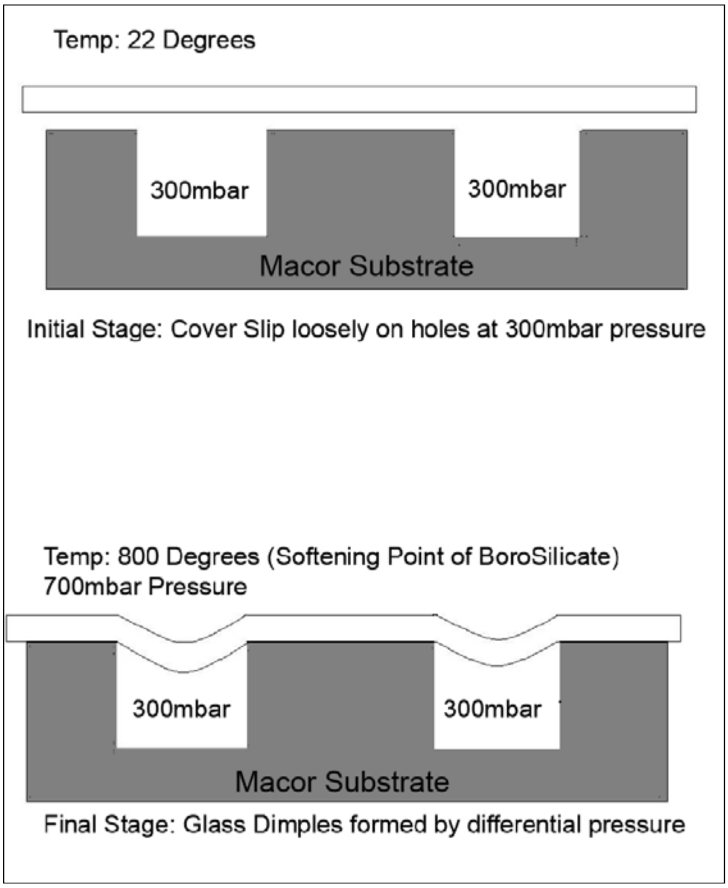
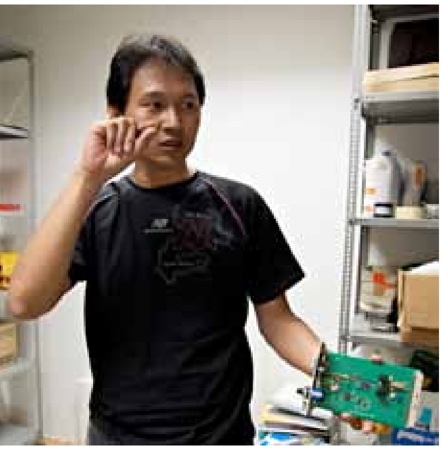


Figure 6: This graphic illustrates the processing steps for creating small curvature mirrors. A glass cover slip is placed over a ceramic substrate with small holes in its surface. The air pressure is less than one-third normal atmospheric pressure leading to a part vacuum in the holes. The glass cover and ceramic substrate are then heated up to 800°C, which is the softening temperature of the glass used. The external pressure is increased and the pressure difference depresses the glass over the holes, leading to a spherical concave surface. These can then be treated to produce extremely high-quality optical cavities.

The CQT Technicians

Meet the people behind the scenes

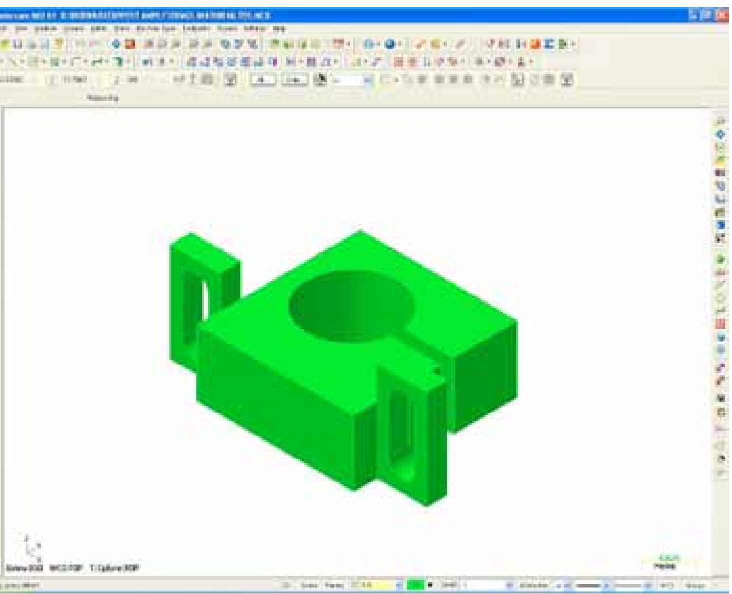


Eng Swee with a finished electronics board

The office that technician Mohammad Imran shares with his colleague Bob Chia Zhi Neng is home to an unusual memento of his past year's work: a giant bean bag. In September 2009 and again in February 2010, Imran travelled to Germany to help coordinate the move of a large and complex quantum experiment from a lab in Munich, where its hundreds of pieces were carefully taken apart, to CQT in Singapore. That experiment, led by researcher Kai Dieckmann, is now taking shape again in a room down the hall from Imran's office. When complete, the setup will be used to study the intermingling of three different types of ultra-cold atom (see p.33). The bean bag? It was packing: a soft cushion for the experiment's vacuum chamber during the equipment's transit.

Imran and Bob, together with Gan Eng Swee and Joven Kwek Boon Leng, are CQT's research support staff. Shifting an experiment from one side of the world to the other is something they're rarely called upon to do, but the team of four technicians, headed by Eng Swee, are still busy all the time. They support the Centre's growing experimental program, solving engineering problems and making parts in their orderly workshop on the ground floor of the CQT building. Their work forms a crucial basis for successful experiments. Depending on the experiments' needs, they provide printed circuit boards, machine aluminium and other materials and, when circumstances call for it, they even offer renovation services.

A CAD model of a collimator mount



This year has been particularly hectic for them with four new experimental labs getting started at the Centre. These new labs will bring the total number of labs at CQT to nine.

Imran showing a modified heat exchanger

A day in the life

In their day-to-day work, each member of the team has a different speciality. Eng Swee is an electronics engineer. He worked on quantum experiments even before CQT was established, transferring with quantum optics and microtrap experiments from the NUS physics department. If an experiment needs a printed circuit board (PCB) to control, for example, the performance of a laser, Eng Swee can help. He says that a complex circuit may take up to six months to implement as a PCB – see overleaf "How a printed circuit board comes to be". Sometimes the researchers present him with a design, other times it is only a set of specifications and their requirements can be tough – for example, needing very stable performance at very high currents.

For now the electronics lab shares space with the mechanical tools, which are Bob's department. Bob joined CQT from the aerospace industry, swapping a long commute for the responsibility and variety of the lab technician's role. One day he may be dealing with a request from a student asking for modifications to a small metal fixture, another day rising to the challenge of recreating from photos and drawings a part of the Munich experiment that had to be left behind. His workhorse is a computer numerically controlled (CNC) 3-axis milling machine that is used to shape components, often mounts for instruments, with a precision of 10 to 20 microns.

Bob operating his CNC machine

Testing a laser pulse controller

The machine runs automatically, even changing tools as it drills and cuts, following instructions derived from a computer model of the component to be made. From experience, Bob knows tricks to make best use of this machine – he recommends double-sided sticky tape for securing metal pieces during milling. The workshop also has a lathe, modified to wind wires into coils used in experiments to generate magnetic fields.

Imran joined CQT after a brief stint at a photo studio. Like Bob he has also worked in the aerospace industry. He describes himself as the person the Centre's researchers go to for ad-hoc jobs. For example, for Kai's experiment, Imran and Eng Swee helped route the cables and optical fibres that connect the equipment up and through the lab's ceiling panels. This hides what would otherwise be a lot of clutter: attached to just one of the experimental racks are 264 different cables. Imran knows them well because one of his jobs in Germany was to check and document every connection before the wires were unplugged. More recently he has turned his hand to plumbing, working with researchers Kai and Wenhui Li to build a customised water-cooling system for the equipment arriving in their new quantum matter lab.

The only one of the team not involved with the new labs is Joven, who is trained in electronics. He primarily supports Murray Barrett's group, which does research on atoms and ions held in microtraps (see p.27). The two labs run by this group are well established – in 2009 Murray and his colleagues successfully trapped and cooled atoms to create Singapore's first Bose-Einstein condensate – but students are starting new experiments all the time, and Joven assists in modifying the set-up. When not building electronics components or making prototypes, he also helps maintain the lab space, updates the website and upgrades his technical knowledge. Being dedicated

A tour of the quantum matter lab

Components ready and waiting to be placed on PCBs

to one group means that he can provide more specialised support, he says, because it takes time to master an experiment's control circuitry.

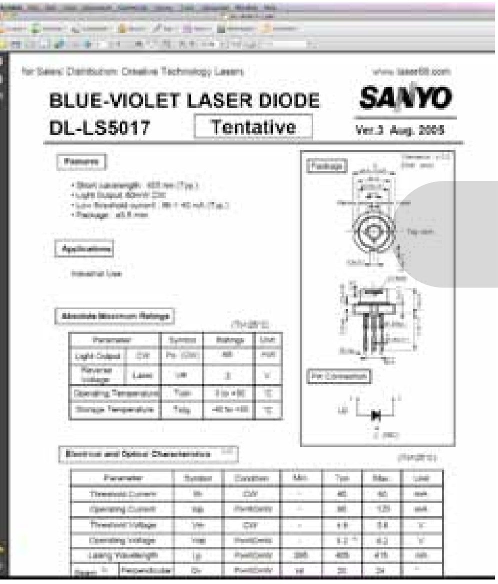
Expansion plans

As the new labs come online, the research support team will grow. Eng Swee says the plan is to recruit five new support staff for the Centre: two technical support people, a machinist, one mechanical designer and one electrical designer or building engineer. Two of these posts are confirmed. The workshop will also grow. Electronics is moving up a floor into a room of its own and mechanical is expanding in the current space with the installation of a second, speedier CNC machine. The technicians joke that they have many bosses because they support everyone from students to principal investigators. With their new recruits, the technicians will match their many bosses with many hands to get the work done.

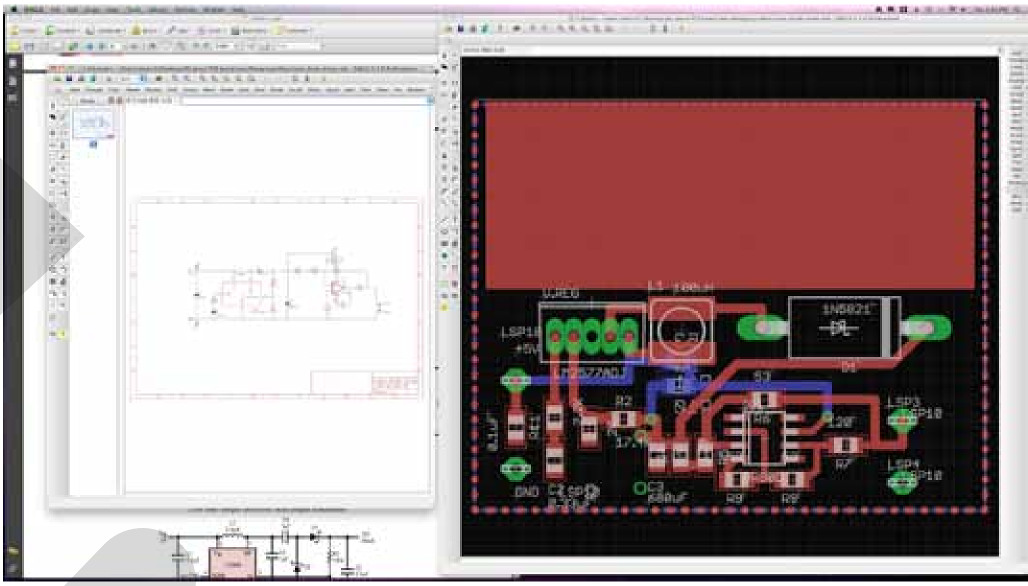
The technicians also receive support. They would like to thank their cleaner who tidies up the workshop every Friday. Additional thanks also go to the procurement team, Chin Pei Pei, Tan Lay Hua, and Mashitah, who ease their workload in obtaining equipment and supplies vital for the operation of the workshop.

Imran making sure all of the 264 cables are connected properly

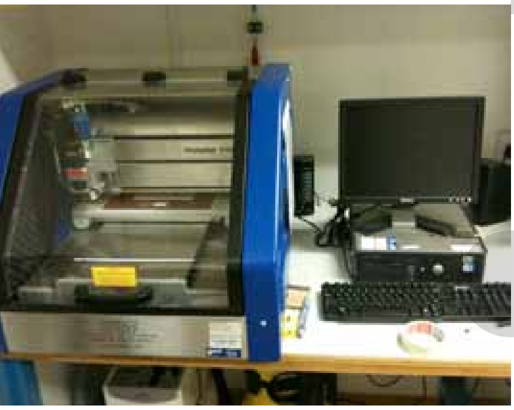
How a Printed Circuit Board Comes to Be



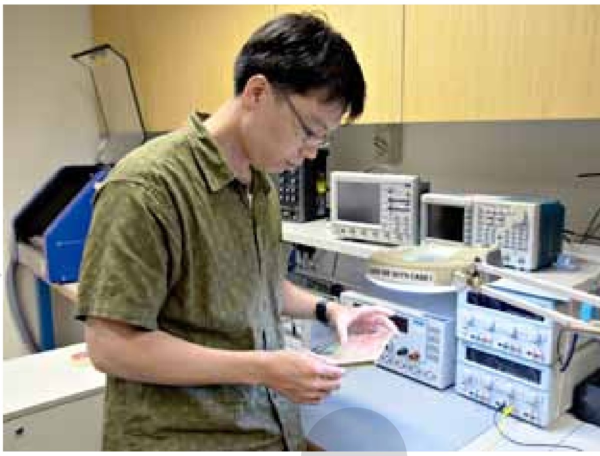
1. First the technicians and researchers discuss the required design specifications. The pictures illustrate the development of a driver for a blue-violet laser, to be operated by rechargeable batteries.



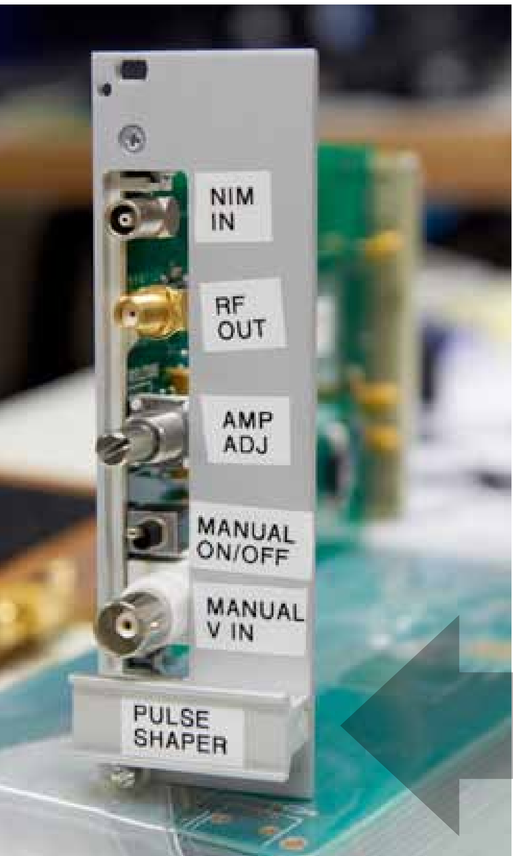
2. A circuit diagram is the next step in the design of a PCB. It shows the components required and how they should be connected to perform the PCB's desired function. The circuit for the laser driver includes a 'boost converter' containing a voltage regulator and an amplifier. Special software converts the schematic diagram to a layout for the wiring of the PCB.



3. This layout is fed into a machine in the technicians' workshop that creates a prototype.



4. Joven examining his handiwork. Components are connected to the prototype board by hand. This may take up to a week for the most complex of circuits, with the assembler using a magnifying glass to position the pieces before soldering them in place.



7. A happy ending: the PCB ultimately takes its place in an experiment.

6. The finalised PCB design is manufactured by a commercial firm. It is not practical for the workshop to buy and host the equipment required to produce such boards to industrial standards.

5. Next the completed PCB is put through tests. A period of trouble-shooting and redesign follows if the PCB is not working as it should. For example, the boost converter had to be rethought because it became unstable when the battery supply exceeded 5V, risking damage to the laser.

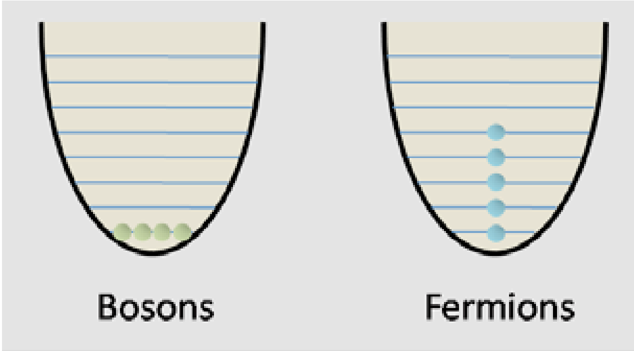
Quantum Matter

New experimental projects landed at CQT, by Kai Dieckmann

I was excited when Artur Ekert first pointed out to me the possibility of moving my research on ultra-cold atoms to Singapore. That was in January 2007. I was then based in Germany, and it was only one day after Artur had presented his ideas for a new quantum research centre to the Singapore funding agencies. I was intrigued by the idea of joining an emerging scientific institute that promised not only to be strong in theory, particularly in quantum information science, but also to offer good conditions to conduct experimental projects.

The potential in Singapore for experimental success in quantum science was already proven by the Quantum Optics group that would join CQT from the NUS physics department. What's more, quantum optics and work on ultra-cold atomic gases – my speciality – traditionally exist in partnership in quantum labs. They have an underlying common interest: gaining perfect control over the quantum mechanical behaviour of atoms and photons. On the basis of such quantum technologies a deepened theoretical understanding of quantum systems can be obtained.

Before committing to so big a move, I had several issues to consider. At the time, the project I had been setting up in Ted Hänsch's group in Munich, at the Ludwig-Maximilians University of Munich and Max-Planck Institute of Quantum Optics, was just becoming productive and we needed to harvest our results. Also, it was a scary prospect, both logistically and in terms of time lost in a competitive research situations, to think of transporting from one continent to another a complicated machine that had grown over years. But after we obtained several important results, Ted Hänsch generously supported the purchase of the experimental setup by CQT, and the jump from Germany's Alps to Singapore's Kent Ridge was made possible during 2009 and 2010 thanks to many helping hands. There's more about the move in the following page (see box "Carefully packed").



Bosons, fermions and what we can do with them
Particles such as atoms or electrons have a fundamental property called spin. Particles that have half-integer values of spin are called fermions and particles with integer values, bosons. In practice, the difference in spin means they behave differently when choosing what quantum states to occupy. Bosons are happy to share, fermions aren't.

Cool a bunch of bosons down to just above absolute zero and they drop into a single quantum state. Physically, this means the cloud of atoms condenses into a small volume and behaves like a wave – a quantum phase of matter known as a Bose-Einstein Condensate. Fermions, when cooled, won't all occupy the same lowest-energy quantum state. Instead, they stack up in states of ever-increasing energy, as though ranged on the rungs of a ladder.

Collections of ultracold fermionic atoms are particularly interesting to study as analogues of physical systems in which it's the quantum behaviour of electrons (themselves fermions) that governs the properties – such as high-temperature superconductors. Quantum matter experiments let researchers tweak the interactions of atoms to understand what controls many-body behaviour in a way that's not possible to do with electrons in real materials.

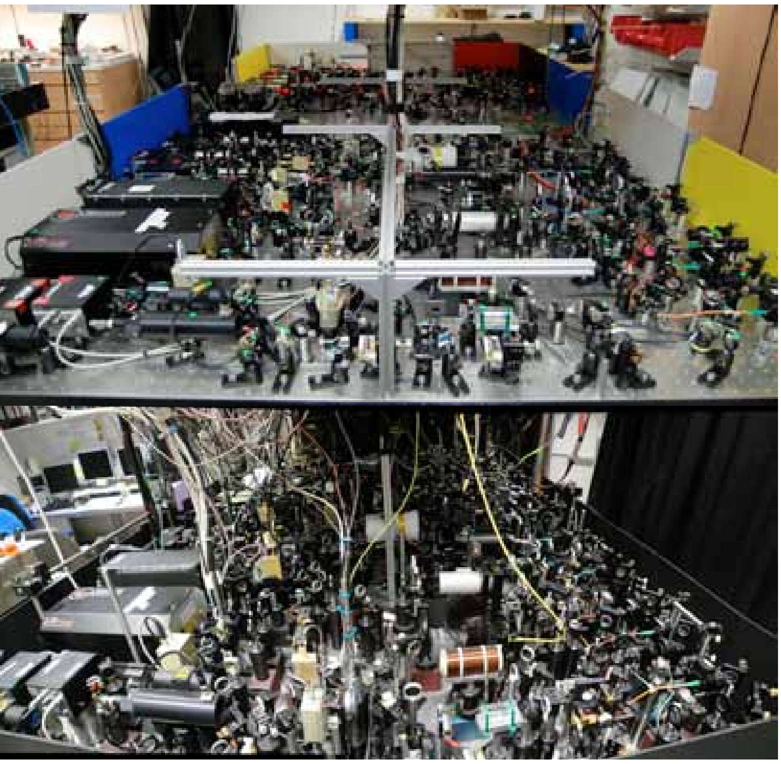


Figure 1: Spot the differences: (top) laser table before the move in Munich, (bottom) replica after the move in Singapore

One important factor in my decision to move to Singapore was that CQT offered an opportunity to set up a second experimental project with ultra-cold fermions, as a Principal Investigator. The experiment in Munich was being used to study mixtures of two types of fermions (see box "Bosons, fermions and what we can do with them"). The research goals of a second project established at CQT would be oriented towards ideas formulated in the theory group of Berge Englert. In collaboration with Christian Miniatura and David Wilkowski from CNRS (the French Centre National de la Recherche Scientifique), he put forward the idea of studying the physics of graphene with fermionic atoms in a hexagonal optical lattice. This raised the prospect of an in-house collaboration between theorists and experimentalists emerging.

Figure 2: Cold atom vacuum chamber (with glass parts covered) dangling from the carrying rack moments before touch down into the transport box. (from right: Wolfgang Simon, Charlie Linner, Mohammad Imran, Gan Eng Swee)

The most compelling feature of the second fermion project was the opportunity to collaborate with experimentalist Wenhui Li, who joined CQT as Principal Investigator in early 2009. Wenhui came from the well known group of Randy Hulet at Rice University and brings strong expertise on research with fermions. Last year, Wenhui also received funding to start her own project on Rydberg atoms.

All three projects target tailoring of the quantum behaviour of many body systems. They have a common goal to study the general aspects of quantum matter realized with ultra-cold atoms in analogy with other quantum systems. The supreme experimental control of such quantum simulators can be used to extend knowledge in fields such as high temperature superconductivity and offers the possibility of exploring transitions to new types of quantum phases.

Carefully Packed

Moving the experimental setup brought together people who do not often get the chance to experience international work environments as researchers do. Chan Hean Boon Thomas and Chin Pei Pei from CQT's finance and procurement team paved the way, visiting Munich to view the equipment and negotiate the purchase contract. This allowed the team to itemize and purchase in a timely fashion the basic bits and pieces that were not going to be redeemed from Munich. At the same time, a lab at CQT was renovated in order to accommodate the setup to be shipped. When the move eventually happened, CQT technicians Gan Eng Swee and Mohammad Imran (see p.30 for an article on CQT's technicians) showed up in full gear to do the job of documenting, unplugging and uninstalling the equipment with confident concentration, as if they had worked for years in foreign laboratories.

It was a delight to see the local technicians, students, and people from the moving company working in a friendly and efficient atmosphere. Fig. 2 shows a group of us practicing a drill to manoeuvre a fragile vacuum chamber from the optical table into the soft pillows inside the moving box. Remarkably, after the 4 tons of equipment arrived in arrived in Singapore, we found almost no damage at all.

Rebuilding a complicated machine takes time, but we have made great progress with the help of research assistant Tarun Johri. He spent time in Munich before the move so he could document the laser systems used for cooling and contemplate improvements for setting up the replicas at CQT. Two mechanical engineers from the Munich lab also came to Singapore to help set up the laser system, and the locals offered hospitality that made this counter visit an unforgettable Singapore experience for them.

Fermi-Fermi Mixture

Parts of the setup that arrived from Munich are shown in Fig. 1 and Fig. 2. What's special about this experiment is that it can handle three atomic species at once: rubidium, lithium and potassium. Rubidium atoms, which are bosons, are cooled to form a Bose-Einstein condensate. This condensate acts as a refrigerator to cool two different fermionic species, lithium and potassium, into quantum degeneracy.

Our main research interest is the Fermi-Fermi mixture. The strength of the interactions between the two types of fermionic atom can be controlled by varying the strength of an ambient magnetic field (Fig. 3). On one side of the so-called Feshbach resonance, the atoms form loose pairs and behave as a superfluid, on the other the fermions tightly pair to form bosonic molecules. The goal of studying this crossover is especially interesting in our system because the masses of the two species are mismatched, and an unmatched superfluid has been searched for in the solid state physics community for decades.

While the setup was running in Munich, we created the biggest sample of heteronuclear molecules (i.e. molecules made of two different species) seen in any such experiment so far. We also verified our long standing prediction of long molecular lifetimes for molecules composed of two fermions as opposed to two bosons. Our most recent measurements on elastic scattering [1] resulted in the first studies of many body effects for the case of a narrow scattering resonance. These results were the fruits of months of measurements, completed just two weeks before the machine was packed into boxes, very much to the relief of the graduate student Louis Costa. He can now follow Arne Voigt, who successfully defended his PhD thesis on the heteronuclear molecules in fall 2009.

Now that we're getting established in Singapore, the next goal on our list is to obtain Bose-Einstein condensation of our heteronuclear molecules. Heteronuclear molecules in their absolute vibrational ground state exhibit a strong electric dipole moment. The long range and non-isotropic character of the dipole-dipole interaction makes the study of the quantum phases of such a gas a rich and so far unexplored area. Especially, creating such a dipolar gas with next-neighbour interactions in optical lattice potentials is a long-standing goal of the scientific community. Graduate student Hannes Brachmann is currently preparing a new laser system for transferring the molecules to the ground state. We will need very precise control of the laser wavelengths, and to achieve this we are planning to purchase a frequency comb system. As we also identified a high demand for such precision among other experiments at CQT, for example in the Microtrap Group and in Wenhui's new lab, the frequency comb will be installed as a shared facility. In future, having this tool available could open new research directions.

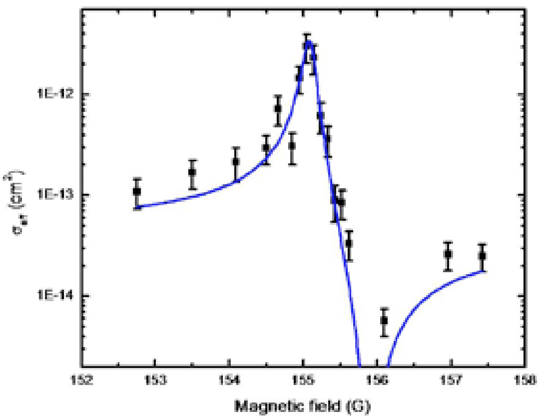


Figure 3: Feshbach resonance of ^{6}Li and ^{40}K. The interaction can be conveniently tuned by a magnetic field. Plot taken from [1].

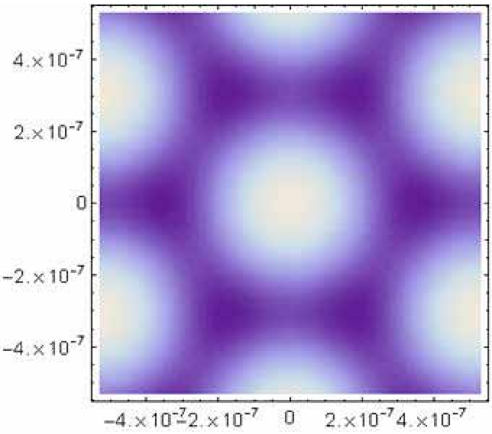


Figure 4: Optical lattice structure. Atoms can be trapped in the dark regions of low laser intensity (dark purple) that form a hexagonal pattern. (scale in m)

Fermions in Optical Lattices

The second project will place fermionic lithium into optical lattices, structures of laser light that impose some spatial order on the position of the atoms. The idea is to make a "quantum simulator" of condensed matter systems, such that quantum phase transitions such as the recently observed fermionic superfluid to Mott insulator transition can be observed. The lattice forces the atoms to mimic the arrangement of atoms or electrons as in the original condensed matter material. Lithium atoms have a broad and easily controllable Feshbach resonance which allows the interactions between these atoms to be tuned.

Berge Englert's group suggested such an experiment at CQT and proposed simulating graphene in a hexagonal optical lattice structure (Fig. 4). Graphene is a material consisting of a single layer of carbon atoms arranged in hexagons, which has among other properties exceptional strength and electric conductivity. The discovery of easy ways of making graphene sheets led to rapid growth of a new research area, and was granted the Nobel Prize in Physics in 2010. A new research centre on graphene physics was recently initiated at NUS.

With cold fermionic atoms in the non-interacting regime, one can study transport phenomena analogous to massless Dirac fermions, while in the interacting regime one can observe a phase transition from a metallic to an anti-ferromagnetic ordered state. Further, transforming the lattice symmetry from hexagonal to triangular would allow studying phenomena of interaction in the presence of disorder.

For a lattice experiment, modern experimental methods such as blue-detuned lattices, lattice rotation, and importantly single site optical resolution detection are desired. It is therefore important to push forward the evolution of chamber designs (the chamber holds the cold atoms during the experiment) that can facilitate such advanced methods. Moreover, as the experiment is starting from scratch and competition is expected in studying graphene type of lattices, it is good practice to create flexibility by defining intermediate goals. As pointed out by Wenhui Li after a visit to Randy Hulet´s group at Rice University, where she did her postdoc, one possibility to simplify the chamber design and cold sample production process might arise from laser cooling of lithium on a narrow transition in the UV domain. A UV magneto-optical trap has never been tried before, and will help overcome the shortcomings in laser cooling specific to lithium. Moreover, high resolution imaging will benefit from using this optical transition at short wavelength. We have embarked on building a new experimental setup (Fig. 5) by adapting ideas from the Munich experiment, which lets us hope for fast progress.

The initial stage of the project was conducted with much help from visiting Associate Professor David Wilkowski, who was involved in conceptual discussions in the beginning and in setting up laser systems. David's expertise on narrow band cooling of strontium was an important factor in us deciding to test this cooling method for lithium. Jimmy Sebastian recently joined the team as a postdoc after receiving his PhD from a renowned cold atom lab in Germany.

Rydberg Atoms

With the third new project, Wenhui is launching CQT into the very exciting research field of Rydberg atoms, which are atoms in highly excited quantum states with strong electric dipole moments. The plan is to study rubidium atoms, and the project is entering the design phase now that the laboratory renovation has been completed. The new machine will be designed and built from scratch. To meet this challenge, Wenhui can draw from her first-hand experience as a PhD student in one of the pioneering labs in the field of Rydberg atoms, run by Tom Gallagher at the University of Virginia.

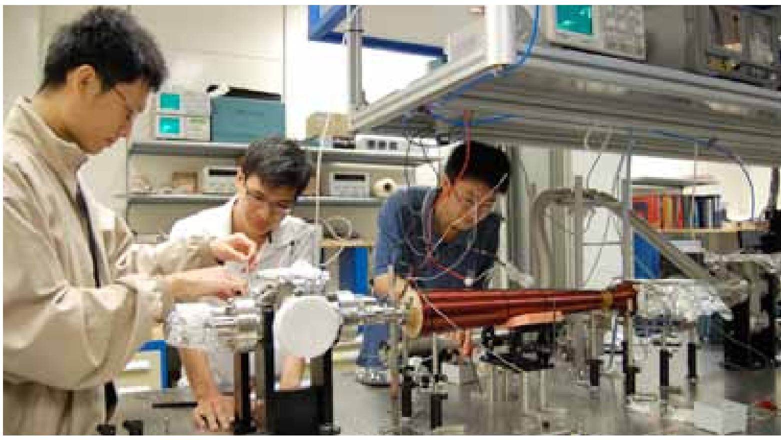


Figure 5: Lim Chin Chean, Wang Jianxin, and Wang Yibo assembling the new lithium vacuum chamber with the central Zeeman slower magnetic field coil.

Scientifically, the long-range nature of the dipole-dipole interaction has dramatic effects on a dense gas of such atoms. Take for example the case of the dipole blockade. It has been experimentally demonstrated that exciting a single atom in a small ensemble invokes such a strong interaction that the remaining atoms are shifted out of resonance with the excitation field: excitation of all other atoms is blocked by the excitation of just a single one. Studying quantum phase transitions in such a gas is an intriguing goal, and Wenhui is collaborating with the theory group of Dieter Jaksch, a visiting research professor at CQT, on this research direction.

[1] S-Wave Interaction in a Two-Species Fermi-Fermi mixture at a Narrow Feshbach Resonance, L. Costa , H. Brachmann, A.-C. Voigt, C. Hahn, M. Taglieber, T. W. Hänsch, and K. Dieckmann, Phys. Rev. Lett., 105, 123201 (2010).

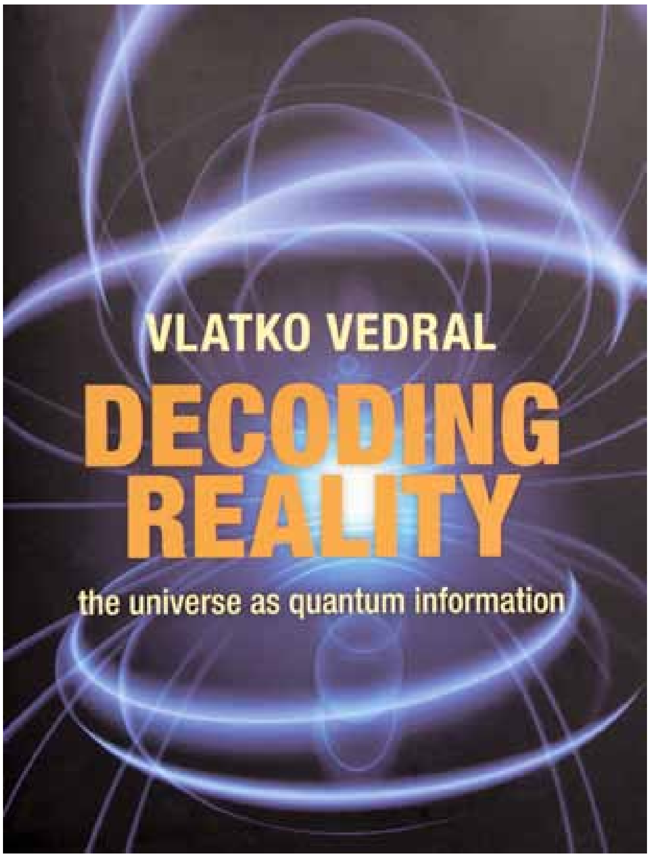
Surfing the Waves

Hyper-fast computers

*This is an extract from Chapter 9 of the book **Decoding Reality** by Vlatko Vedral. Reproduced with permission of Oxford University Press.*

If you want to have 100 useful quantum bits in your computer, then you have to build a 1000-qubit large quantum computer. This means that for every one qubit, you have an additional nine copies of that qubit, so, if the occasional one decoheres, you can still make a majority decision over the remaining nine. Quantum superpositions can thus be protected, and whilst there are more optimal ways of adding redundancy, this in essence is the key concept.

As I write these lines (summer 2008) we are already moving towards producing quantum computational microchips. Furthermore, this is happening right now and right here in Singapore (I say this as I am sitting down and sipping a double espresso in Spinelli's on the National University campus). On these microchips, experimental physicists are trying to integrate components involving super-cold atoms and coherent photons in small numbers. Microengineering has progressed so much in the last 20 years that it is amazing to see how much stuff can be packed onto a very small area of a two-dimensional chip. Making a fully quantum computational unit can easily take some 5–10 years to complete, but so much ingenuity has gone into the research here that the possibility of large quantum computers is a very real prospect!



As with living systems, the battle to build a quantum computer is ultimately a battle against entropy. The lower the overall entropy of an arbitrary physical system the higher the chances that its constituent atoms may be entangled. Typical atoms useful for quantum computation usually need to be at a temperature close to absolute zero (around 1 billionth of a kelvin). Furthermore, given that the temperature in the rest of the laboratory is 300 billion times higher than that, it's a constant battle. This is a kind of Maxwell's demon scenario, where a process needs to reduce the entropy of the system in order to get some useful information processing done. A striking piece of evidence to show how quantum effects can be seen in some macroscopic objects was demonstrated by Syantani Ghosh and her colleagues in 2003. Ghosh showed that quantum superpositions between many atoms exist in a piece of salt involving billions of atoms and at temperatures of a few millikelvin. This was a huge shock because it showed that quantum phenomena, whose power was thought to be confi ned to the infi nitesimal world of subatomic particles, can produce effects that remain measurable on macroscopic scales.

This discovery was so momentous, it was difficult for anyone to believe. In a paper I submitted in 2000 to Nature, the premier scientific journal, I made similar predictions and was duly laughed off the court. The fact that the prediction has now been borne out by Ghosh's experiment catapults the mystery of quantum information into the wider arena. Nature kindly sent me Ghosh's paper as they thought I would be pleased to know that one of my predictions turned out to be correct (it doesn't happen too often). Even better still, since Ghosh's results, a number of other results have demonstrated similar effects in other materials, some of them being at much higher temperatures than this (even, startlingly, at room temperature!).

We are now realizing that advanced quantum effects are much more ubiquitous in macroscopic systems and this gives us hope that one day we may find that Nature has already provided us with a quantum computer and all that is left for us to do is to program it. After all, Nature has already invented many tricks before us humans. Radar and error correction by redundancy are just two out of many such tricks used by living systems. Might it therefore be that somewhere there is a living system which harnesses the speed-up advantages of quantum computation? Even better, perhaps quantum computation is so ubiquitous that it takes place in every living cell.

Decoding Reality
The Universe as Quantum Information
Vlatko Vedral
Oxford University Press
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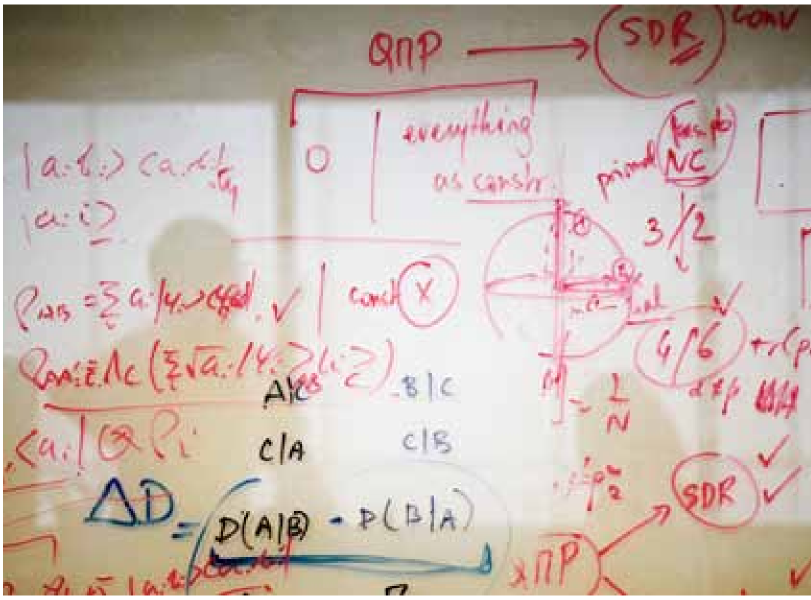

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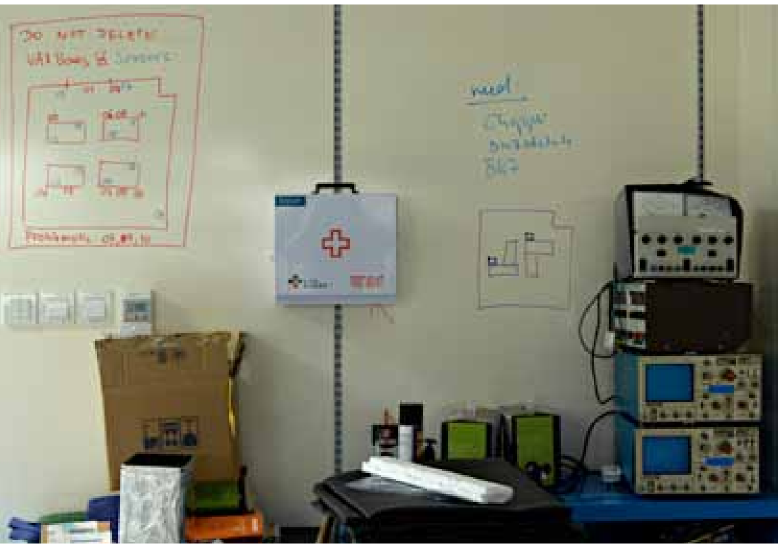

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Martin Aulbach	University of Oxford
Joonwoo Bae	Korea Institute for Advanced Study
Michael Banks	PhysicWorld
Crispin Barnes	University of Cambridge
Kristian Baumann	ETH, Zurich
Florian Baumgaertner	Imperial College
Jacob D. Biamonte	University of Oxford
Nicholas Bigelow	University of Rochester
Sergio Boixo	California Institute of Technology
Cyril Branciard	University of Queensland
Michael Bremner	University of Queensland
Andrew Briggs	University of Oxford
Michael Brooks	NewScientist
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Benjamin Brown	Imperial College
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Money Matters

We spent some money

CQT Expenditure

	Dec'07 to Aug'09	Sep'09 to Aug'10	Cumulative Total
Expenditure on Manpower (EOM)	8,379,894	8,041,992	16,421,886
Equipment	3,478,618	2,414,334	5,892,952
Other Operating Expenditure (OOE)	10,196,696	7,455,972	17,652,668
Total SGD$	**22,055,208**	**17,912,298**	**39,967,506**

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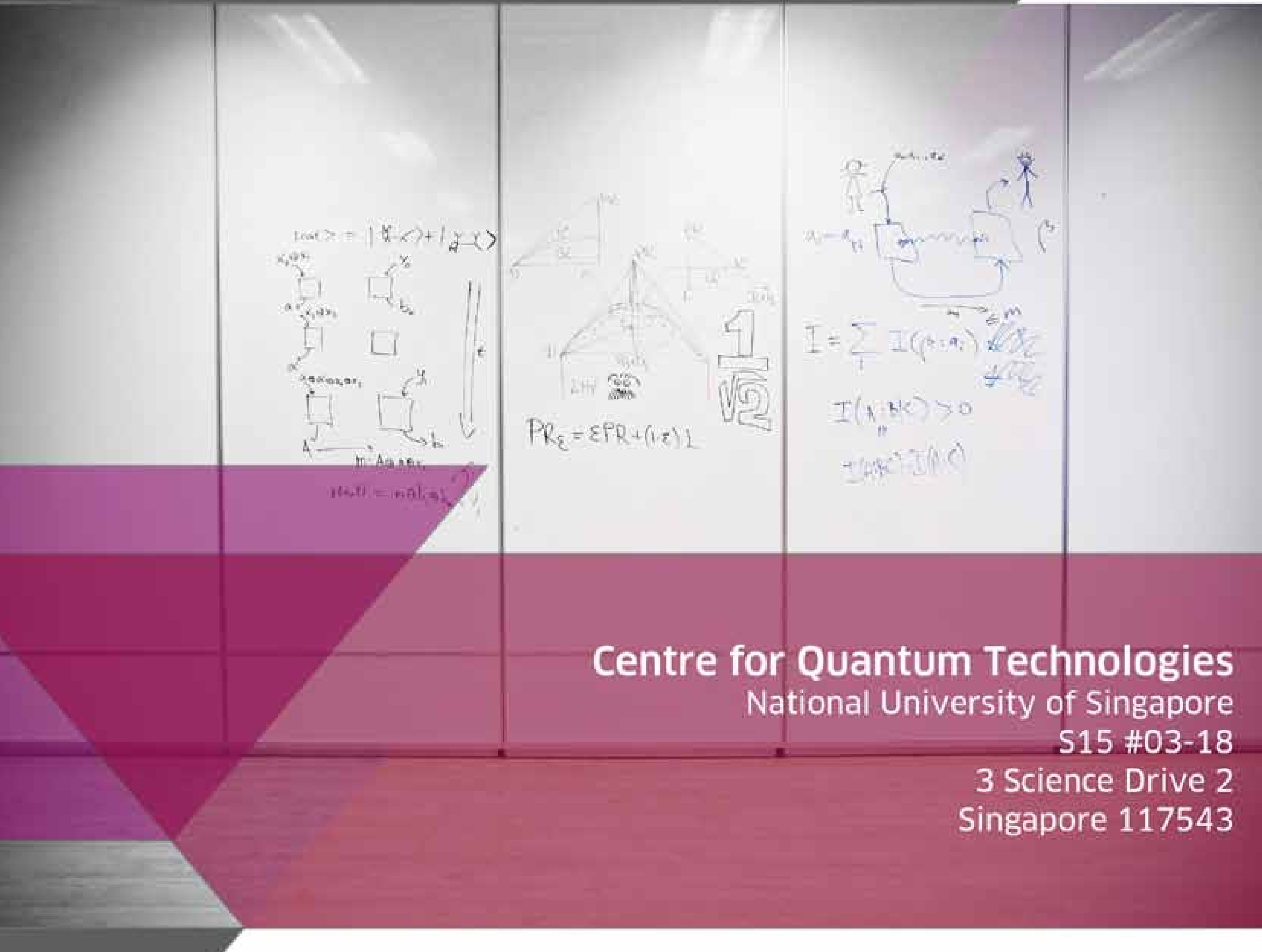

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