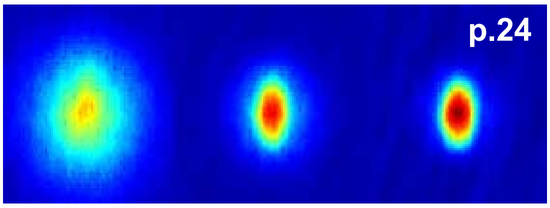
Centre for Quantum Technologies

CENTRE FOR QUANTUM TECHNOLOGIES
ANNUAL REPORT
09

NUS National University of Singapore

Contents



Cover Design by Dixon Chan © 2009.
Photos D. K. L. Oi © 2009 p. 4 left, botton, 5 middle, 10-11, 12 top, 17, 19, 21, 26, 28, 29, 37-41, 43.
Centre for Quantum Technologies website:
www.quantumlah.org

"Piled Higher and Deeper" by Jorge Cham

WWW.PHDCOMICS.COM

From the Director

So, how is the Centre doing? I keep hearing this question over and over again; it resonates in my head like a well rehearsed mantra. It invariably comes within the first ten minutes into any official, or even casual, lunch or dinner. It is asked by friends and colleagues, by people from academia, government agencies, industry and even by my diving buddies. And you know what - I do not mind being asked. I mean it. This is because I do not have to repeat the same story over and over again, so I am never bored. I believe the Centre is doing well simply because there is always something new, something exciting to talk about. It is only the second year of our existence and yet there are many highlights to choose from.

So I can tell people how we took our quantum cryptographic kit to Las Vegas to expose it to the hardcore hackers at one of their annual gatherings. How our home-made Bose-Einstein condensation elevated the Centre to the status of the coolest place on the Equator (give or take one degree of latitude) and how quantum phenomena can help birds in their navigation skills (no, I am not kidding). Sometimes the topic may be very elusive and esoteric, say a conjecture that was defeating the community for ten years and was finally resolved by one of our researchers, or perhaps elucidation of intricate connections between information causality and some wacky correlations. Still, even then, there is always a thrill of discovering something new, and that is easy to convey.

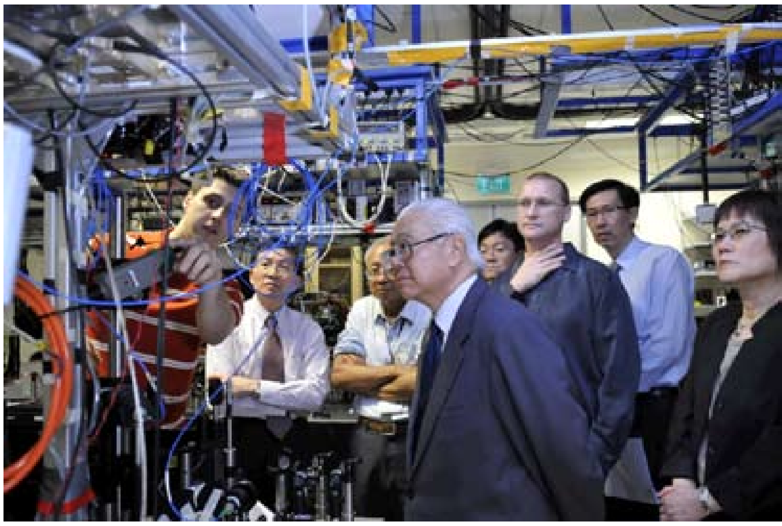
And one should never forget to mention that behind all these interesting results there are fantastic people - our researchers, students, technical and administrative support - who in their own way contribute to our unique research environment and make good science happen.

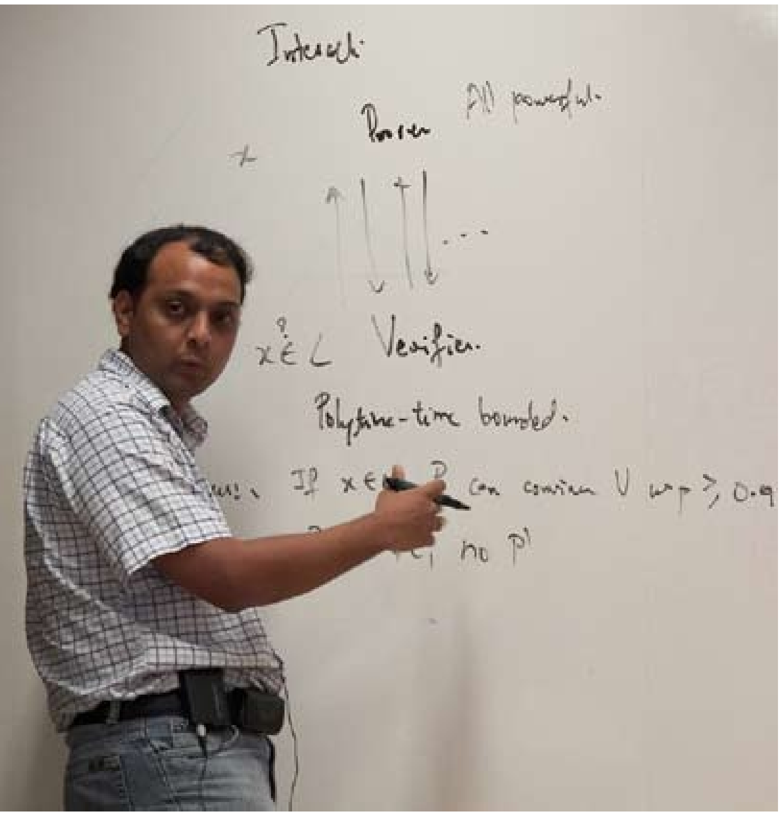
So, how the Centre is doing? Please, read on and you will get a glimpse of what kept us busy this year. This report is aimed to be both informative and readable. I hope you will enjoy it.

Artur Ekert

Research Highlights

We are the coolest place in Singapore. Now it is official! The lowest temperature registered at CQT was less than one millionth of a degree above the absolute zero. Probably the coolest spot anywhere near the Equator. In order to reach such low temperatures Murray Barrett and Kyle Arnold had to use a combination of state-of-the-art laser cooling, trapping and evaporation techniques, not to mention their patience and perseverance. Atoms in their sample gradually slowed down to only a few millimetres per second and then lost their individual identities and started behaving like a single quantum entity, known as the Bose-Einstein condensate (BEC). For CQT this experiment is only a beginning. The condensate is just a tool for interesting experiments to come. Read about the Singaporean BEC on page 24.

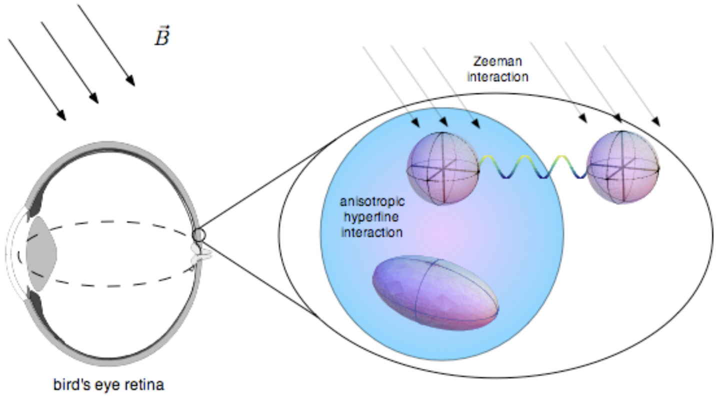




Computer scientists interested in computational complexity study how difficult it is to solve a problem, or how hard it is to verify that a proposed solution is indeed correct. Computation is a physical process hence whenever we discover new laws of physics we may improve the efficiency of computation. Indeed, our interest in quantum computation is mostly due to the fact that projected quantum computers will be capable of efficiently solving some problems for which there is believed to be no efficient classical algorithm. However, Rahul Jain of CQT, in collaboration with other researchers, has proved that, in some important scenarios, quantum physics does not help. In his recent breakthrough paper, he showed that quantum interactive proof systems provide no more computational power than classical ones. This solves a long standing open problem in the theory of quantum computation. Rahul explains the essence of his work on page 26.

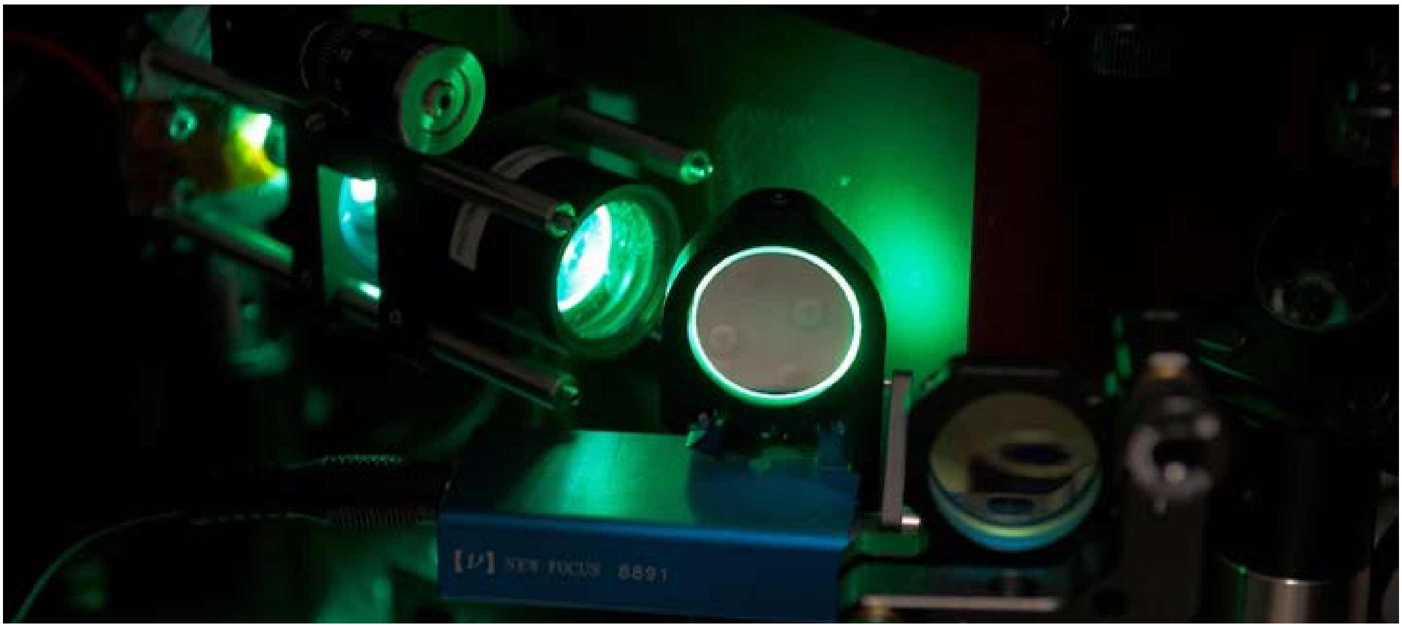
The consequences and implications of last year's breakthrough in the theory of quantum information, namely showing that entangled inputs can enhance capacities of memoryless quantum channels, are currently under intense investigations. CQT researchers made significant contributions to the original result and several new results by Andreas Winter are regarded as seminal to our understanding of quantum channel capacities. Andreas outlines some of his research on page 28.

How do migrating birds manage to navigate from Northern Europe to Africa and back? Why is energy transfer in photosynthesis so efficient? Is quantum physics behind it all? While very little is known about quantum phenomenon in biological systems, its relevance is fast becoming evident from the growing experimental data. Indeed, our researchers are among the first to examine this intriguing connection. Vlatko Vedral and Elisabeth Rieper explain on page 33.

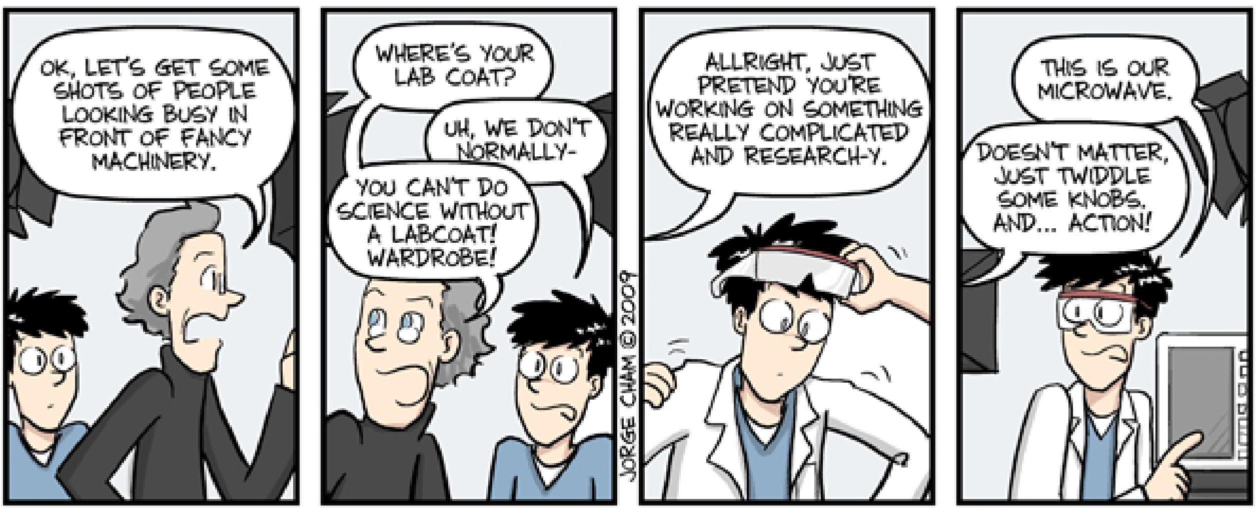


Yet again we join forces with our colleagues from the National Institute of Standards and Technology in the US to present our quantum cryptography kit to the hackers of the world. Our vintage parametric down conversion source, producing highly entangled photons, was the centre of attention at the two major hacker conferences - DEFCON 17 in the US and HAR2009 in the Netherlands. Antia reports on page 36.

Quantum cryptography is certainly one of our strengths, both in theory and practice. Indeed, a recent special issue of the New Journal of Physics devoted to quantum cryptography featured four (out of twenty) articles authored by CQT researchers. Our contributions ranged from technological developments to futuristic proposals for device-independent cryptography.



When the media calls...



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AMO Physics Center, National Institute of Standards and Technology

Principal Investigators

Quantum Optics

Assoc. Prof. Christian KURTSIEFER

In 1997, after completing his doctorate in experimental physics in Konstanz, Germany, Christian joined IBM Almaden Research Center in California, where he worked on an ion trap experiment. Between 1999 and 2003, while a research staff at the at Ludwigs-Maximilians-Universität München, 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 is chiefly responsible for the development of experimental quantum optics in Singapore. (National Science Award 2008).

Asst. Prof. Antia LAMAS-LINARES

Originally from Galicia, in northern Spain, Antia studied optics at Imperial College, London and University of Oxford, 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 spending some time at the University of California in Santa Barbara, she joined NUS as an Assistant Professor . Her current research interests involve quantum communication, cryptography and the foundations of quantum physics. (National Science Award 2008).

Assoc. Prof. Valerio SCARANI

Valerio, our European polyglot, received his PhD in 2000 from Ecole Polytechnique Federale de Lausanne (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. 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)

Computer Science

Prof. Miklos SANTHA

Born and educated in Budapest, Hungary, Miklos moved to France in 1980 and received his Ph.D. 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 the 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 from 1990 to 1991. Since 2008 he is also a Visiting Research Professor at NUS, in charge of building up the Computer Science component at CQT. His research interests include quantum computing, randomized algorithms and complexity theory.

Asst. Prof. Rahul JAIN

Rahul obtained his PhD in Computer Science from Tata Institute of Fundamental Research, Mumbai, India in 2003. He was a post doctoral fellow for two years at University of California at Berkeley, USA (2004-2006) and for two years at Institute for Quantum Computing (IQC), University of Waterloo, Canada (2006-2008). In 2008, he joined NUS as Assistant Prof. in the Computer Science Department and concurrently with CQT as a Principal Investigator. His research interests are in the areas of Information Theory, Quantum Computation, Cryptography, Communication Complexity and Computational Complexity Theory.

Interdisciplinary Theory

Prof. OH Choo Hiap

Born in Sabah, Malaysia. Selected under the Colombo Plan to study in New Zealand, where he completed his Ph.D. (University of Otago, 1972), returned to serve at 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 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).

Prof. Berthold-Georg ENGLERT

Born and educated in Germany, Berge was a postdoc at UCLA after receiving his doctorate in 1981. He taught at the University of Munich 1985-1995, and then became a “physicist at large” until arriving at NUS late 2002, becoming a professor 6 months later. He contributed to semiclassical atomic physics, to quantum optics, to the foundations of quantum physics, and to 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)

Assoc. Prof. 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. He has been with CQT since 2007. His research interests are in the foundations of quantum theory and in the properties of entanglement, in particular in many-body systems. (National Science Award 2006)

Prof. Andreas WINTER

Andreas Winter received his Ph.D. in Mathematics from the University of Bielefeld in 1999. Since then he has been at the University of Bristol, first as a post-doctoral 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. His research interests cover quantum information theory, discrete mathematics, and statistical physics.

Prof. Vlatko VEDRAL

After undergraduate studies and PhD at Imperial College, London, in 1998, Vlatko went to Oxford as a JRF at Merton College. From 2000-2003 he was Governor’s lecturer at Imperial College and promoted to Reader in 2003. He became a Professor at Leeds in 2004 and at NUS in 2007. He has held visiting professorships in Vienna and at Perimeter Institute in Canada. Vlatko has written 2 textbooks: on Quantum Optics and Quantum Information and has published more than 140 research papers in quantum mechanics and quantum information.

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

Microtraps

Asst. Prof. Murray BARRETT
Murray Barrett received his PhD from the Georgia Institute of Technology, Atlanta, Georgia in 2002. His PhD work resulted in the first ever production of a BEC by pure optical means. He then spent 2 years in Dave Wineland's group as a Post-doc. 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 Oct. 2006 and is currently working on integrating microtraps and cavity QED for quantum information applications.

Asst. Prof. Björn HESSMO
Björn Hessmo obtained his undergraduate degree from Uppsala University and Ecole Polytechnique in Paris, and his doctorate in Quantum Chemistry from 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 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 Vienna he continued his work on atom chips and photonics. In 2009 he joined the CQT team at NUS to lead the experimental activity on microtraps for neutral atoms."

Quantum Matter

Assoc. Prof. Kai DIECKMANN
After completing his German Physics Diploma at the University of Konstanz Kai Dieckmann 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) as an individual Marie Curie fellow. He went on as a postdoctoral fellow in the group of Prof W. Ketterle at the Massachusetts Institute of Technologies. 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. Since late summer 2009 he is in transition to Singapore bringing along his Munich experimental setup on mixed ultracold Fermi gases, and engaging in a new collaboration to realize fermionic quantum gases in optical lattices.

Asst. Prof. Wenhui LI
Born and educated in China, Wenhui worked on experiments with cold Rydberg atoms during her Ph.D. studies at University of Virginia, USA. After receiving her doctoral degree in 2005, she moved to Randy Hulet's group at Rice University 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.

Research Staff

Research Fellows

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David Paul Maxime WILKOWSKI
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Syed Muhamad ASSAD
TAN Ting Rei
Dario POLETTI
DAO Hoang Lan
Ravishankar RAMANATHAN
POH Hou Shun
Mile GU
FANG Yiyuan Bess
Elica Sotirova KYOSEVA
CHUAH Boon Leng
CHNG Mei Yuen, Brenda
Aarthi Lavanya DHANAPAUL

PhD Students

Student	Supervisor
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ARUN	Prof. Englert
Markus BADEN	Asst. Prof. Barrett
Adam Zaman CHAUDHRY	Assoc. Prof. Kaszlikowski
Eilidh GUDGEON	Prof. Winter
HAN Rui	Prof. Englert
HUO Mingxia	Assoc. Prof. Kwek
Siddarth JOSHI	Assoc. Prof. Kurtsiefer
Nicholas LEWTY	Asst. Prof. Barrett
LI Ying	Assoc. Prof. Kwek
NG Tien Tjuen	Assoc. Prof. Kurtsiefer
Attila PERESZLÉNYI	Asst. Prof. Jain
Elisabeth RIEPER	Prof. Vedral
Ritayan ROY	Asst. Prof Hessmo
SYED Abdullah Aljunid	Assoc. Prof. Kurtsiefer
Giovanni VACANTI	Prof. Vedral
WANG Yimin	Assoc. Prof. Scarani
Marta Joanna WOLAK	Prof. Englert
Penghui YAO	Asst. Prof. Jain

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Arthur TADENA
IT System Engineer

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FANG Yiyuan Bess
Librarian

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CHIA Zhi Neng Bob
Technical and Lab Support

GAN Eng Swee
Technical and Lab Support

KWEK Boon Leng Joven
Technical and Lab Support

Mohd Imran Bin Abdol RAMAN
Technical and Lab Support

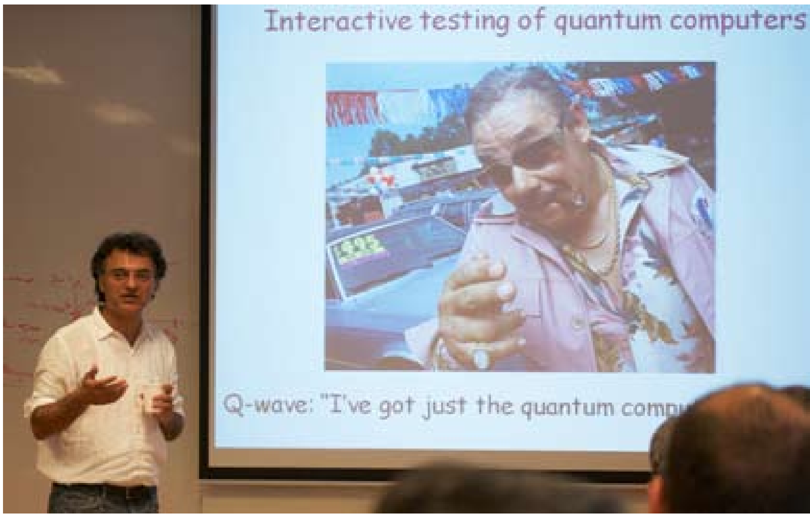
CQT Member Profile

Principal Investigators	15
Visiting Research Staff	13
Research Staff	43
CQT PhD Students	19
Technical Support	6
Admin	13
Total	**109**

90 researchers from 24 countries

Singapore	21
China	17
United Kingdom	10
Germany	10
India	9
Malaysia	7
Italy	6
France	5
Poland	3
Hungary	2
Israel	2
New Zealand	2
Switzerland	2
USA	2
Vietnam	1
Austria	1
Phillipines	1
Russian Fed.	1
South Korea	1
Spain	1
Greece	1
Sweden	1
Bulgaria	1
Pakistan	1

Calendar of Events



Umesh Vazirani, Scientific Advisory Board member, giving an overview of the state of Quantum Computer Science at the SAB meeting in August 2009

Colloquia

Date	Speaker	Affiliation	Title
20-Jan-09	Seth Lloyd	Massachusetts Institute of Technology	Quantum algorithm for solving linear systems of equations
5-Feb-09	Wolfgang Behr	University of Zurich	Ciphering Classical Chinese
12-Feb-09	Ian Walmsley	University of Oxford	The photon and the vacuum cleaner
26-Mar-09	Patrick Hayden	McGill University	Black holes as mirrors
2-Apr-09	Serge Haroche	ENS and Collège de France	Exploring the quantumness of light in a cavity
16-Apr-09	Jörg Schmiedmayer	Atominstitut der Österreichischen Universitäten	AtomChips: Integrated circuits for matter waves

Congratulations

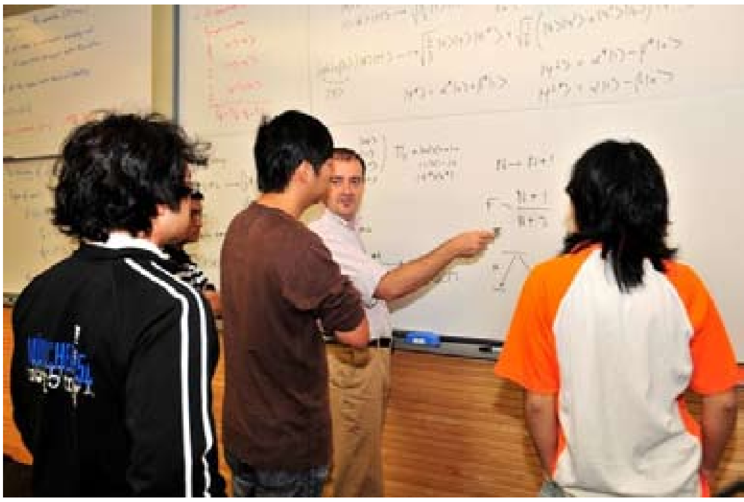
Raymond **Cai** Yongqin (Ugrad)– NUS Outstanding Undergraduate Researcher Prize (OURP) for his work on "Finite Key Analysis for Quantum Cryptography" supervised by Valerio Scarani
Teoh Yong Siah (Ugrad)- Best academic project in Physics, Faculty of Science, NUS, "Symmetric, informationally complete POVMs in finite-sample tomography", supervised by Berge Englert
Tey Meng Khoon (PhD)- Wang Gungwu Medal & Prize 2009 for the Best PhD thesis in the Natural Sciences, supervised by Christian Kurtsiefer

Workshops and Schools

Event	Date
First Workshop on "Quantum Technology in Biological Systems	Jan 10 - 17, 2009
Les Houches School of Physics in Singapore Ultracold Gases and Quantum Information	June 29 - July 24, 2009

Social Events

Date	Event
20-Jan-09	Welcome 2009 Lunch @ CQT Quantum Cafe
9-Feb-09	Chinese New Year Reunion Lunch Gathering
20-Mar-09	Southern Ridge Walk
14-Apr-09	Easter Celebration - Eggs Painting Competition and Easter Lunch
21-Apr-09	CQT Basketball Friendly Match
29-May-09	Dumpling Festival - Dumpling Tasting and Movie Screening
12-Aug-09	Movie Screening and Pizzas Lunch



Valerio Scarani explaining Quantum Cloning at the Les Houches School of Physics in Singapore

Visitor Talks

Date	Speaker	Affliation	Title
7-Jan-09	Antonio Badolato	Swiss Federal Institute of Technology	"Solid State Cavity Quantum Electrodynamics: Quantum Dots coupled to Photonic Crystals Microcavities"
16-Jan-09	David Hallwood	University of Oxford	Ever larger quantum system - An investigation using a rotating ultra-cold atomic system
19-Jan-09	Sir John Enderby	University of Bristol	Physics and its Funding in the UK
30-Jan-09	Dan Browne	University College London	The computational power of multi-party correlations
19-Feb-09	Leonid Krivitsky	Data Storage Institute, A*STAR	Correlation Measurement of Squeezed Light
11-Mar-09	Julien Degorre	Laboratoire d'Informatique de Grenoble	A combinatorial approach of non locality
12-Mar-09	Ke Li, Carl	University of Science and Technology of China	Nonadditivity of the Private Classical Capacity of a Quantum Channel
13-Mar-09	Elena Rufeil Fiori	Universidad Nacional de Cordoba	Non-Markovian decay beyond the Fermi Golden Rule: Survival collapse of the polarization in spin chains.
13-Mar-09	Daniel Terno	Macquarie University	Non-completrely positive maps and their use
25-Mar-09	Ming-Shien Chang	University of Maryland	Trapped Ion Q. Computation with Transverse Phonon Modes
1-Apr-09	Serge Haroche	ENS & Collège de France	Public Lecture
14-Apr-09	Karoline Wiesner	University of Bristol	Natural information processing and structure in quantum systems
21-Apr-09	Bill Rosgen	Institute for Quantum Computing	Distinguishability of Quantum Channels
23-Apr-09	Christophe Couteau	LNIO, Universite de Technologie de Troyes	Q. information processing with semiconductors - I
27-Apr-09	Lana Sheridan	Institute for Quantum Computing	Simulating Continuous Quantum Evolution of Unitary Black Boxes
28-Apr-09	Christophe Couteau	LNIO, Universite de Technologie de Troyes	Q. information processing with semiconductors - II
29-Apr-09	Roger Colbeck	ETH Zürich	The impossibility of partially local hidden variable models for quantum theory
30-Apr-09	Achim Kempf	University of Waterloo	Reconciling Spacetime Continuity and Discreteness using Tools from Information Theory
14-May-09	Thomas Decker	McGill University	Hidden Polynomial Function Graphs
20-May-09	Ming-Shien Chang	University of Maryland	Trapped Ion Q. Computation and Q. Simulation
28-May-09	Hendrik Weimer	University of Stuttgart	Q. critical behaviour in strongly interacting Rydberg gases
9-Jun-09	Frederic Hebert	INLN	Introduction to quantum Monte-Carlo simulation for Fermi(Bose)-Hubbard model
2-Jul-09	Hans A. Bachor	ARC Centre of Excellence for Quantum-Atom Optics	Spatial multi mode entanglement
24-Jul-09	Martin Aulbach	University of Leeds	Max-Ent. Symmetric States of the Geometric Measure
28-Jul-09	Ben Varcoe	University of Leeds	Laser Physics, Precision Measurements and Q. Information
30-Jul-09	Frederic Chevy	LKB, ENS, Paris	Weighing a particle immersed in a Fermi sea
11-Aug-09	Jaewoo Joo	University of Calgary	Error-correcting one-way quantum computation
12-Aug-09	Tony Leggett	University of Illinois	Majorana anyons in (p+ip) Fermi superfluids:an attempt at a particle-conserving description
14-Aug-09	Tristan Farrow	University of Cambridge	Telecom wavelength single photon emitting diodes based on InAs/GaAs quantum dots
14-Aug-09	LOOI Shiang Yong	Carnegie Mellon University	Types and Location of Information

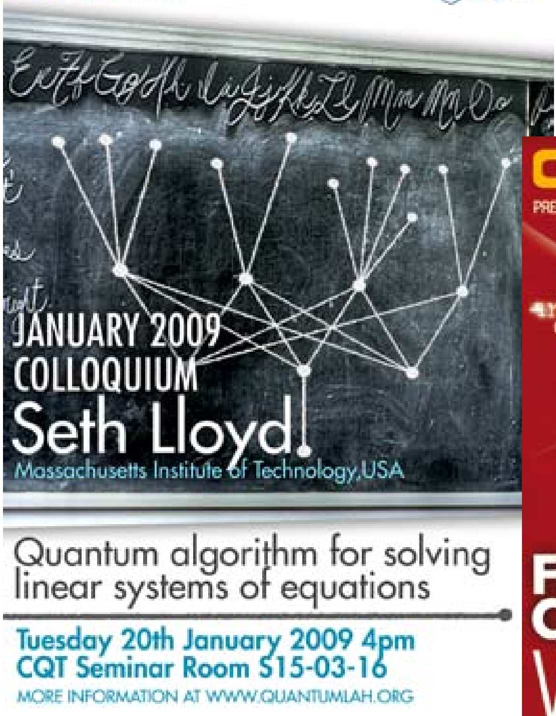
Outreach Activities

Date	Activity	Who	Audience	Additional Information
24.8.09	Visit to CQT	V. Scarani, D. Kaszlikowski, T. Paterek, Y.S. Teo, C.W. Lim, T.P. Le	VIP@NUS	Visit of Lord Martin Rees
21.8.09	Judging in scientific competition	C. Kurtsiefer	Secondary school students	SAMC (Secondary school students)
31.7.-2.8.09	The Bellometer and public hacking of a QKD system	I. Gerhardt, A. Lamas-Linares, C. Kurtsiefer	Geeks, Larger public	Quantum Lounge @ DEFCON17, Las Vegas
23.5.09	Open House Faculty of Science	K. Arnold, B. Chng, G. Maslennikov, T.T. Ng, V. Scarani Y.S. Teoh	NUS prospective students	Participation in the Physics booth and visits to the labs
22.5.09	Posters on CQT	E.Tan, V. Scarani	Large public	Decoration of CQT
22.5.09	Media event	M. Barrett, K. Arnold, A. Ekert, C.T. Chan, E.Tan, V. Scarani	VIP@NUS	Visit of Tony Tan and presentation to the media of the recent results of CQT
18.5.09	Visit to CQT	A. Ekert, Lai C.H., Oh C.H., V. Scarani	VIP@NUS	Visit of Prof Lee Lou-Chang, Minister of National Science Council of Taiwan
7.5.09	Visit to CQT	Lai C.H.	VIP@NUS	Delegation of Zhejiang University
24.4.09	Talk on quantum physics	V. Scarani	Secondary school students	Students of Meridian JC
8.4.09	Visit to CQT	Lai C.H.	VIP@NUS	Delegation of Jiao Tong University, Shanghai
2.4.09	Visit to CQT	Li Wenhui	VIP@NUS	Delegation of Sheffield University, UK
1.4.09	Popular Science Talk by Prof. Serge Haroche	C. Miniatura (organizer)	Large public	Co-organized with NUS Faculty of Science, Agora and French embassy
27.3.09	Quantum physics talk	V. Scarani	Secondary school students	Students of Victoria JC
19.3.09 (starting)	Exhibit	C. Kurtsiefer	Large public	Photon-pair source exhibited in the Singapore Science Centre
2.3.09	Quantum physics talk	V. Scarani	Secondary school students	H3 students of Victoria JC
27.2-15.3.09	Exhibit	C. Kurtsiefer	Large public	80th anniversary Science Faculty
31.1.09	Straits Times Article	V. Vedral	Media	The Straits Times, page B8
22.1-11.3.09	Judging in scientific competition	D. Kaszlikowksi, L.C. Kwek, V. Scarani	Secondary school students	SSEF
14.1.09	Cafe scientifique by Prof. Paul Davies	V. Vedral, E. Tan, D. Gosal (organizers)	Large audience	Singapore Science Centre
9.1.09	Visit to CQT	V. Scarani, A.A. Syed, M. Barrett	NUS students	Visit of the labs for NUS Physics majors
6.12.08	Straits Times Article	A. Ekert, V. Scarani	Media	The Straits Times, page D6

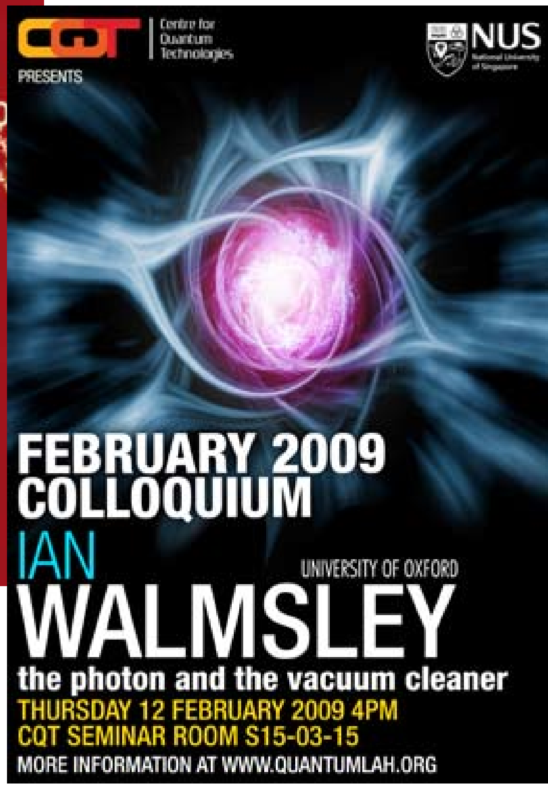
Other Events

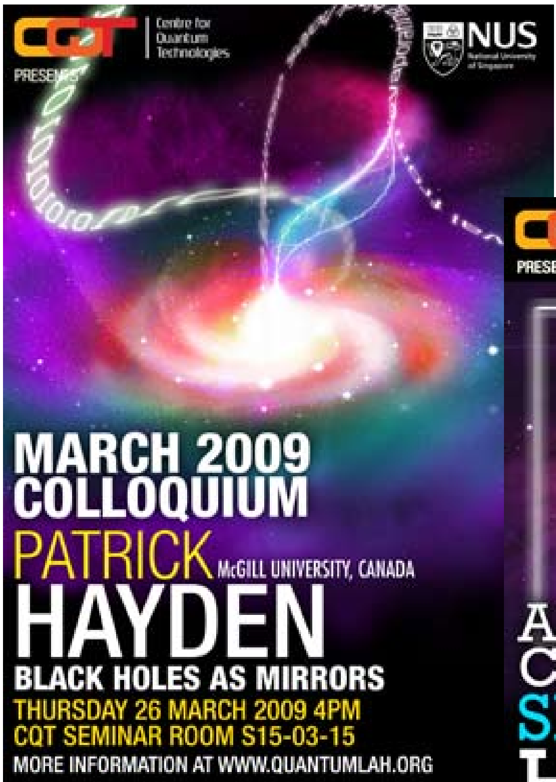
Date	Event
19-Dec-08	Governing Board Meeting
7-Jul-09	Governing Board Meeting
24-28 Aug-09	Scientific Advisory Board Meeting

Lord Martin Rees, President of the Royal Society of London, visiting the CQT


JANUARY 2009
COLLOQUIUM
Seth Lloyd
Massachusetts Institute of Technology,USA
Quantum algorithm for solving linear systems of equations
Tuesday 20th January 2009 4pm
CQT Seminar Room S15-03-16
MORE INFORMATION AT WWW.QUANTUMLAH.ORG


Centre for Quantum Technologies
PRESENTS
NUS National University of Singapore
FEBRUARY 2009
COLLOQUIUM
Wolfgang
BEHR
UNIVERSITY OF ZURICH, SWITZERLAND
CIPHERING CLASSICAL CHINESE
THURSDAY 5 FEBRUARY 2009 4PM
CQT SEMINAR ROOM S15-03-15
MORE INFORMATION AT WWW.QUANTUMLAH.ORG


Centre for Quantum Technologies
PRESENTS
NUS
FEBRUARY 2009
COLLOQUIUM
IAN
UNIVERSITY OF OXFORD
WALMSLEY
the photon and the vacuum cleaner
THURSDAY 12 FEBRUARY 2009 4PM
CQT SEMINAR ROOM S15-03-15
MORE INFORMATION AT WWW.QUANTUMLAH.ORG


Centre for Quantum Technologies
NUS
MARCH 2009
COLLOQUIUM
PATRICK
McGILL UNIVERSITY, CANADA
HAYDEN
BLACK HOLES AS MIRRORS
THURSDAY 26 MARCH 2009 4PM
CQT SEMINAR ROOM S15-03-15
MORE INFORMATION AT WWW.QUANTUMLAH.ORG


Centre for Quantum Technologies
PRESENTS
NUS
APRIL 2009
COLLOQUIUM
SERGE
ENS and Collège de France
HAROCHE
Exploring the quantumness of light in a cavity
THURSDAY 2 APRIL 2009 4PM
CQT SEMINAR ROOM S15-03-15
MORE INFORMATION AT WWW.QUANTUMLAH.ORG


Centre for Quantum Technologies
PRESENTS
NUS
APRIL 2009
COLLOQUIUM
JÖRG
Atominstitut der Österreichischen Universitäten, TU-Wien
SCHMIEDMAYER
AtomChips: Integrated circuits for matter waves
THURSDAY 16 APRIL 2009 4PM
CQT SEMINAR ROOM S15-03-15
MORE INFORMATION AT WWW.QUANTUMLAH.ORG

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

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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Fax: +65 6516 6897
Email: cqtphd@nus.edu.sg

CQTPhD.QUANTUMLAH.ORG

Graduate Programme

Back Row L-R: M. Baden, A. Chaudhry, A. Pereszlényi, S.Joshi, P Yao, R. Roy, A. Syed. Front Row L-R: M. Wolak, E. Rieper, R. Han, Y. Wang, G. Vacanti

CQT Academic Committee

Prof. Berthold-Georg Englert (Chair)
Prof. Vlatko Vedral (CQT)
Assoc. Prof. Christian Kurtsiefer (CQT)
Asst. Prof. Rahul Jain (CQT)
Prof. Ji Wei (Faculty of Science, NUS)
Prof. Mark Breese (Dept of Physics, NUS)

Student	Supervisor
Kyle ARNOLD	Asst. Prof. Barrett
ARUN	Prof. Englert
Markus BADEN	Asst. Prof. Barrett
Adam Zaman CHAUDHRY	Assoc. Prof. Kaszlikowski
Eilidh GUDGEON	Prof. Winter
HAN Rui	Prof. Englert
HUO Mingxia	Assoc. Prof. Kwek
Siddarth JOSHI	Assoc. Prof. Kurtsiefer
Nicholas LEWTY	Assoc. Prof. Barrett
LI Ying	Assoc. Prof. Kwek
NG Tien Tjuen	Assoc. Prof. Kurtsiefer
Attila PERESZLÉNYI	Asst. Prof. Jain
Elisabeth RIEPER	Prof. Vedral
Ritayan ROY	Asst. Prof. Hessmo
SYED Abdullah Aljunid	Assoc. Prof. Kurtsiefer
Giovanni VACANTI	Prof. Vedral
WANG Yimin	Assoc. Prof. Scarani
Marta Joanna WOLAK	Prof. Englert
Penghui YAO	Asst. Prof. Jain

The Centre for Quantum Technologies attracts highly talented students from around the world to undertake PhD studies, and offers top-class education in a vibrant environment. Supported by a generous scholarship, research and training at CQT are multidisciplinary, with each student having a focus in Science, Computing, or Engineering.

The Centre for Quantum Technologies is committed to producing high-caliber graduates. For this purpose CQT has put in place a programme for graduate studies by which the selection of excellent candidates, their supervision at CQT, and the monitoring of their progress are ensured. These students receive a competitive scholarship from CQT. Research and training at CQT are multidisciplinary, with each student having a focus in Science, Computing, or Engineering.

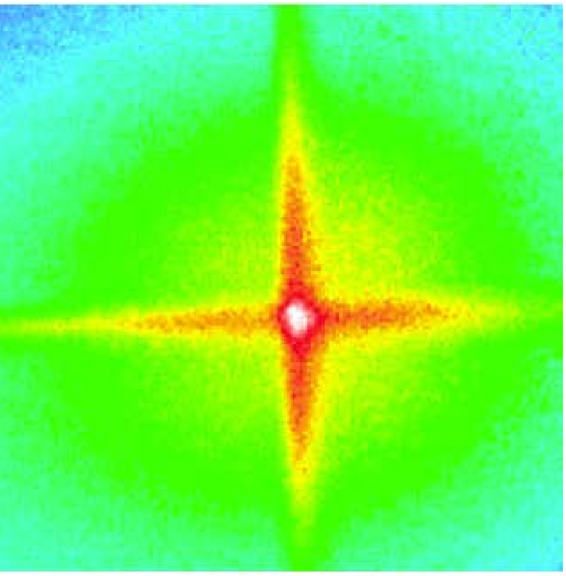
The aim of the PhD@CQT Programme is to train approximately 80 PhD students over 10 years in all disciplines in which research is carried out in the Centre. In order to achieve this, an intake of 8 students per year is planned with 30 to 40 students in the programme when fully launched. The programme had its first intake in August 2008 and there are presently 19 students in the programme and more candidates under consideration.

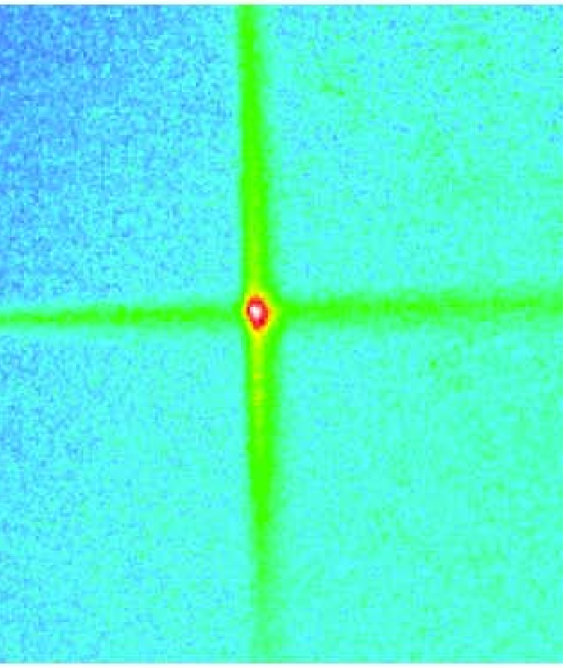
In addition to the students under the PhD@CQT programme, principle investigators at CQT also supervise students funded from other sources, such as the Faculty of Science or NGS. Currently, there are 13 PhD students and 7 MSc students conducting their research projects at CQT with funding from external sources.

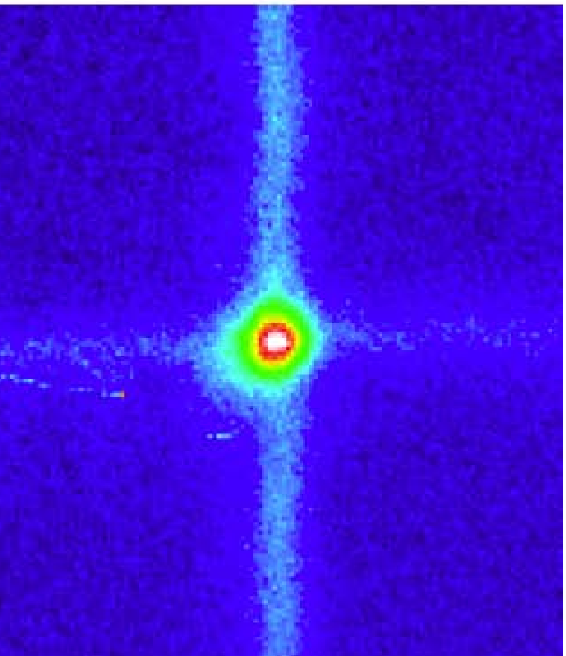
By now, three doctoral students have received their degrees from research at CQT. Dr Alex Ling completed a PhD in Quantum Optics and has joined the Joint Quantum Institute and University of Maryland as a post-doctoral research fellow. Dr Janet Anders completed a PhD in Theoretical Quantum Information and is now a Dorothy Hodgkin Research Fellow at the University College, London. Dr Tey Meng Khoon completed a PhD in Quantum Optics and is now a research fellow at the Institute for Quantum Information and Quantum Optics in Innsbruck, Austria.

Research Report

Adapted from the Scientific Advisory Board Report







Overview

The CQT has a wide research program that embraces most of the research areas in Quantum Information Science. On the one hand, it develops several research projects on experimental physics, mostly in atomic, molecular and optical physics. Three experimental groups cover a broad area including single and entangled photons, single atoms, ions, cavity QED, ultracold atoms, and superconducting devices. This research is supported by several groups working on theoretical quantum optics spanning a wide range of collaborations.

On the other hand, there is a very strong component of other theoretical activities in computer science, as well as on information theory. The first develop new algorithms and protocols for communication and computation that exploit the extraordinary features offered by quantum mechanics, whereas the latter aim at developing the mathematical theory underlying this new area of research. This combination of broad research activities under the same umbrella at the highest scientific level provides a very productive and collaborative environment, making CQT a strong component of the international effort.

The center has a wide range of activities to support research and to increase its visibility in the international context. First of all, it has launched a graduate program in order to train students in the field as well as to attract international researchers. It has a very strong visiting program, which has already brought to Singapore many of the leading scientists in Quantum Information Science. Through its partial appointments, it has managed to establish several world-class research subgroups in the center, supervised by some of the most prominent young scientists working abroad, who spend a considerable time in CQT.

The organization of several international events, like conferences and summers schools, has made the scientific community aware of the firm commitment of the center to play a central role in the international context. Collaborative programs, like the one with the CNRS in France, has allowed the CQT scientists to start new theoretical and experimental projects. Finally, the outreach activities have established a connection to other research centers in Singapore as well as helped to improve the scientific education of the youngest generations in the country.

The scientific accomplishments reviewed by the Scientific Advisory Board during their visit in August 2009 and they were very satisfied in general. In particular, there have been several breakthroughs which have had an enormous impact in the quantum information community. Examples include the solution of a long-standing problem in computer science regarding the equivalence of two computational complexity classes (QIP and PSPACE), which has been proved by Rahul Jain and collaborators, and the establishment of the relationship between the field of communication complexity and the maximal quantum correlations encapsulated in quantum states by Andreas Winter, Dagomir Kaszlikowski, Valerio Scarani and collaborators. This last work has been featured in Nature, and has already stimulated new work in many groups worldwide.

From the experimental side, the group of Christian Kurtsiefer has observed very efficient interaction between light and a single atom. This elegant experiment contributes importantly to a growing area of interest worldwide in efficient qubit/photon coupling and the fundamental aspects of atom/radiation interaction and has been recognized internationally and exemplifies the connection between good basic science and potential practical applications. In particular, it helps open up the possibility of implementing quantum information protocols with single atoms without high-Q cavities.

In the following we briefly review the most important activities carried out during the last year in each of the areas of research.

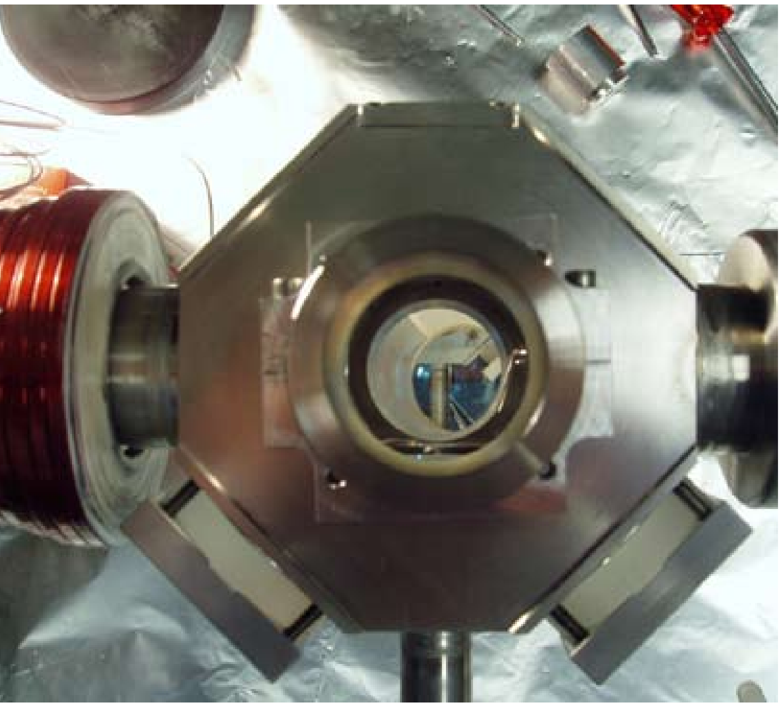
Theory

The research of the interdisciplinary theory group spans a very wide range of activities. On the one hand, they develop fundamental concepts and mathematical tools in order to establish a theory of Quantum Information. On the other, they study specific physical implementations in which one could observe quantum phenomena and build quantum communication and computation devices. The overall quality of the theory group is really outstanding, as it is illustrated by the number of high-impact publications that have appeared during last year.

In the first category, there have been several highlights during the last year. First of all, Andreas Winter, Dagomir Kaszlikowski, Valerio Scarani and collaborators have been able to show certain laws of quantum mechanics naturally arise just by imposing a very natural constraint on how much information can be transferred between two locations. This was a long-standing problem which several scientists in the field had tried before. The results have been accepted in the journal Nature. The groups of Andreas Winter and Dagomir Kaszlikowski have obtained many other important results regarding additivity of quantum channels, classification on multipartite entangled states, mutually unbiased basis, t-designs, etc. In particular, the amount and quality of results reported by the group of Andreas Winter is really outstanding.

The groups of Berthold Englert, Valerio Scarani, and Vlatko Vedral have also been very active in this first category. We give a few examples. Englert and colleagues have continued work on establishing new properties of bipartite entangled states, and finding applications in the field of quantum cryptography. Scarani and colleaguges have continued developing the formalism of finite-key analysis in quantum cryptography: with his student Raymond Cai, he has provided rigorous finite-key bounds for practical implementations. Vedral and collaborators continue work on entanglement in many-body quantum systems, proposing original ways of detecting and establishing that property in many different situations. They have also co-founded an emerging field, so-called quantum biology, which promises to find important applications of quantum information in remote areas such as life sciences or chemistry.

In the second category, also important results have been obtained. For example, new ways of performing quantum computations using cluster states and different experimental set-ups have been put forward and thoroughly analyzed by Simon Benjamin, Dieter Jaksch and collaborators. Quantum simulations of different kinds of



many-body systems have been proposed using qubits connected by cavities, a work led by Dimitris Angelakis and Kwek Leong Chuan. Timothy Liew and Valerio Scarani have provided the theoretical description of the measurements of extinction and phase shift induced by a single atom in a propagating beam, as measured by the quantum optics group. Topological quantum computation with atoms in lattices and other devices has been theoretically studied by the group of Oh Choo Hiap. Furthermore, detailed proposals to observe Dirac's dynamics and other intriguing many-body phenomena have been put forward by the group of Berthold Englert, as well as by Dieter Jaksch. This work is done in close collaboration with experimentalists, and we expect that this strong bond between theory and experiment will become very fruitful in the coming years.

Computer Science

Last year Miklos Santha started the effort towards building a quantum computer science group. At the time of the last SAB meeting CQT was in the process of hiring Rahul Jain, a young star in quantum communication complexity, as a faculty member in the computer science department.CQT has continued to build on the momentum it started last year, and in addition to having a steady flow of researchers visit CQT, has established a first-rate group of researchers based at CQT (consisting of Jain and long-term visitor Hartmut Klauck, "medium-term" visitors Iordanis Kerenidis and Zhang Shengyu, 2 PhD students, and 2 recently arrived postdocs).

Rahul Jain and collaborators were responsible for one of the most important results in the theory of quantum information in the past year, resolving a fundamental question that has been open for over a decade. Their proof that QIP = IP = PSPACE completely characterizes the power of quantum interactive proofs, and shows that quantum interactive proof systems are exactly as powerful as classical interactive proof systems. Hartmut Klauck and Rahul Jain have already established an excellent working relationship and have collaborated on three publications in this short period.

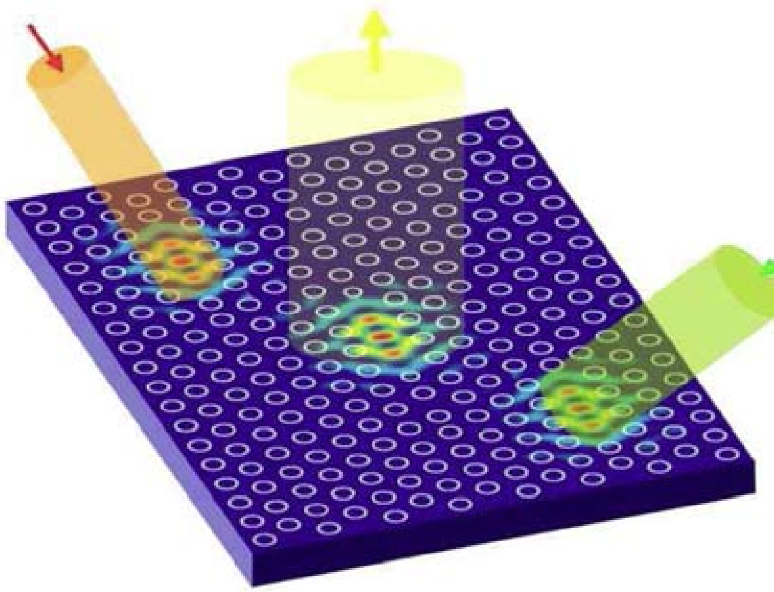
Overall, the pace of progress towards establishing a quantum computer science group is quite impressive, and CQT already has the nucleus of an excellent group in quantum complexity theory. The group is cohesive and meets frequently for lectures and study group meetings. There is an excellent opportunity to leverage the current momentum towards building one of the top groups in quantum algorithms and complexity, through further strategic hiring of additional faculty as well as attracting postdocs, students and visitors.

Experimental

The experimental activities focus predominantly on quantum optics and atomic physics.

Quantum Optics Group:

The group of Christian Kurtsiefer has co-initiated the emerging field of studies of strong couplings between a focused optical field and a single trapped atom. The highlight of the experimental efforts in this new field is the measurement of a nonlinear phase shift of a weak coherent field induced by a single trapped atom. This experiment constitutes a major step towards the realisa-



tion of a cavity-free conditional dynamics of travelling photonic qubits. Antia Lamas-Linares has focused mainly on parametric down-conversion and experimental key distribution. Quantum cryptography has been traditionally the strength of the Group. The demonstrations of security attack scenarios is quite interesting and worthy further investigations.

Microtraps Group:

The cold atoms/cavity-QED project of Murray Barrett is progressing quite well with the accomplishment of an all-optical BEC and the ability to transport the sample over macroscopic distances. The group is well on their way towards obtaining some new interesting results on cold-atom/cavity-QED within the next several months, which will establish them upon the international stage.

Though affected by fabricational delays outside the group's control, the ion trap experiments are progressing. The basic laser hardware and trap apparatus is in place and initial trapping appears to be imminent which would establish an important milestone in the ion experiments, and will serve as a spring- board for the planned experiments on ion-based cavity QED, micro-mirror detection and similar efforts.

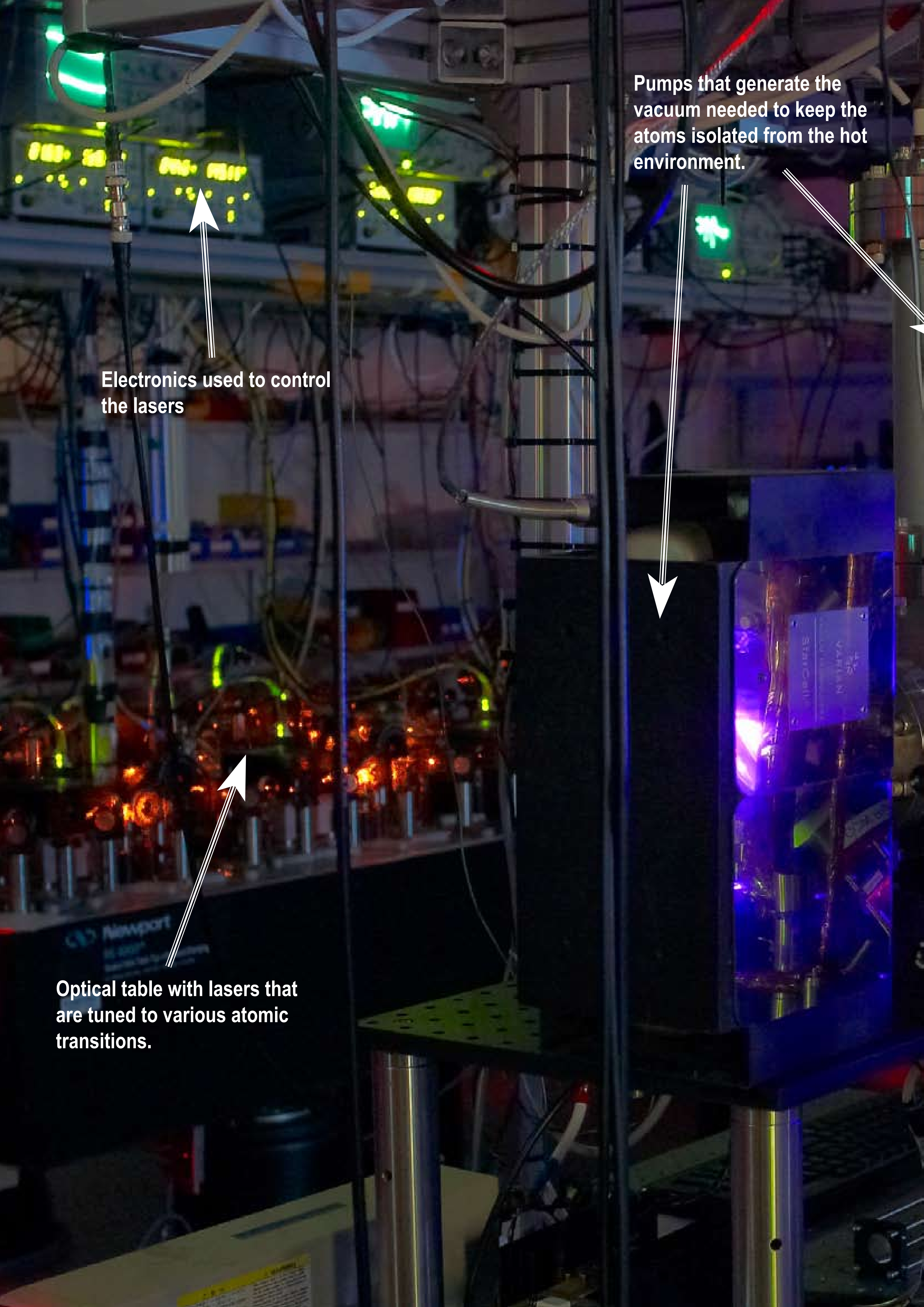
New Principal Investigators in the Area of Cold Atoms:

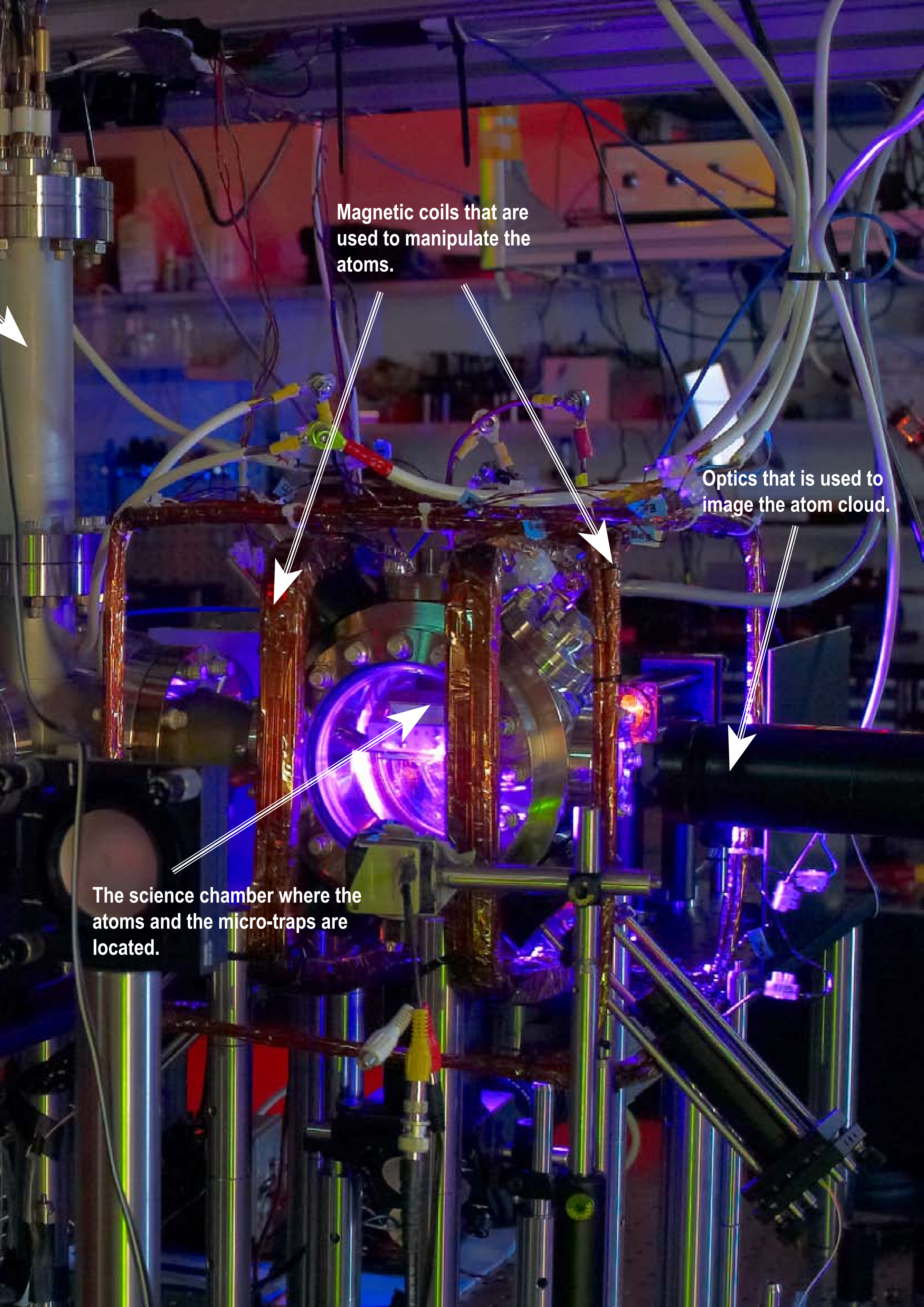
Kai Dieckmann, Wenhui Li, and Björn Hessmo are impressive and enthusiastic young researchers that will undoubtedly add considerable strength to the experimental efforts. Just being able to bring in this group of talented young researchers is an important accomplishment by the CQT. These researchers have already proven themselves in their past work and are starting projects in areas that appear quite rich in terms of future results.

Overleaf

If you are a theorist, be it a computer scientist or a physicists, or just a casual visitor to our labs, you may find all our experiments look the same. Optical tables with zillions of lenses and mirrors, a mess of wires and cables, glow of oscilloscopes, hum from some unidentified metal boxes, bits and pieces of electronics scattered all over the place, flashes of laser light, mysterious coils here and there. Once you saw one such a lab you saw them all.

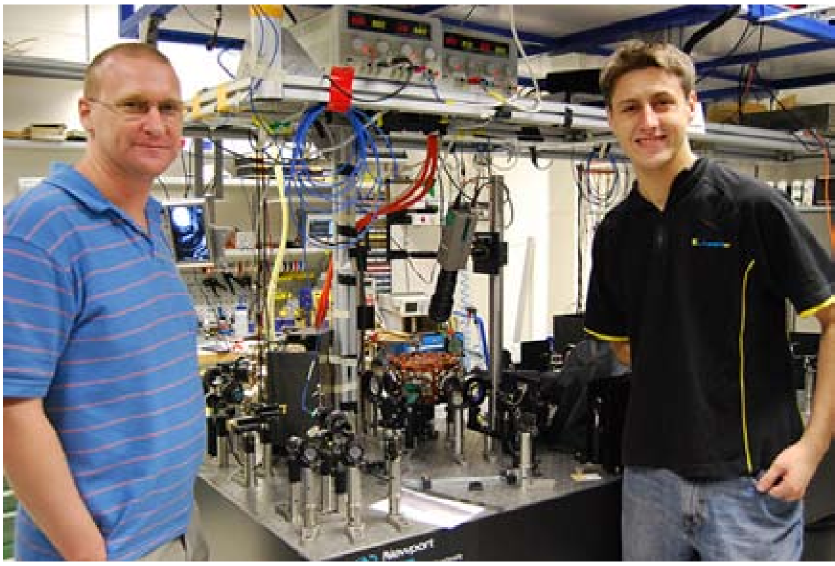
Well, not quite. Experimentalists assure us that they are all different. You just have to know what to look at and what to appreciate. As the first step in the never ending efforts to bridge the gap between theory and experiment - as you know, in theory there is no difference between theory and practice but in practice there is - we invite you to take a peek into one of the Microtrap Group's lab. This is the place where Björn Hessmo and his colleagues experiment with atom chips. In the centrefold you will find a picture of his experimental apparatus -dominated by the steel vacuum chamber - and some basic explanations of what is what.


Pumps that generate the vacuum needed to keep the atoms isolated from the hot environment.
Electronics used to control the lasers
Optical table with lasers that are tuned to various atomic transitions.



Magnetic coils that are used to manipulate the atoms.
Optics that is used to image the atom cloud.
The science chamber where the atoms and the micro-traps are located.

The Coolest Place on the Equator



Murray Barrett and Kyle Arnold have achieved the lowest temperature on the equator in creating an exotic state of matter, the Bose-Einstein Condensate.

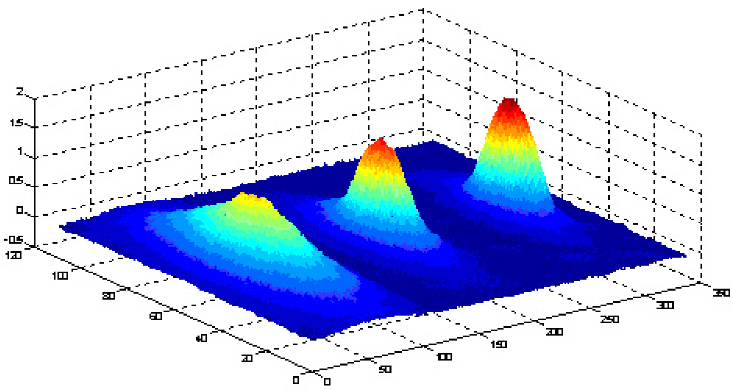
Microtraps

Murray Barrett and Kyle Arnold, have successfully achieved a state of matter that is as cold as the fundamental laws of physics allow. This ultra-cold collection of atoms is called “Bose-Einstein condensate”, from the names of Satyendra Nath Bose and Albert Einstein, who predicted it back in 1924. Its first realization in a laboratory dates only from 1995, the achievement that was recognized by the Royal Swedish Academy of Sciences with the Nobel Prize in Physics in 2001.

The reason it took over seventy years to produce the condensate is the enormous technological difficulty involved in cooling atoms. Even today such condensates are produced only in the world most advanced laboratories. The CQT experiment is a remarkable local achievement; it promotes Singapore to the premier league of experimental atomic physics and provides local researchers with the most sophisticated tools to investigate the quantum properties of matter. In any case, it gives us tangible experimental evidence that we live in the coolest place on the Equator!

Cool Matter

But what exactly is a Bose- Einstein condensate and how is it different from any other state of matter? If we think of a gas of atoms or molecules, such as air, we might consider them as basically a collection of “billiards balls” bouncing off each other. Our familiar notion of temperature is a measure of how energetic or fast moving the molecules are. In most everyday situations, this description is accurate enough. Quantum physics, however, allows for a very different picture, provided the conditions are just right.



Formation of a Bose-Einstein Condensate. As the temperature of the atoms decreases (left to right) the atoms suddenly all start behaving as one and settle down into the lowest state and condense into a narrow peak.

In the peculiar world of quantum physics it is impossible to obtain precise knowledge of both the position and speed of an atom at the same time: the better we know the position, the less we can know about its speed and, conversely, the better we know the speed the less we can know about its position. At everyday temperatures and conditions this has very little consequence. For example, molecules in the air have velocities of a few hundred meters per second – roughly the speed of a bullet from a low powered rifle. In this situation the rules of quantum mechanics limits knowledge of position to a very small fraction of the typical separation between atoms. Thus atoms maintain their individuality and our crude billiard ball picture remains accurate.

The billiard ball description breaks down when the atoms reach a critical temperature. They become so cold that the uncertainty in their position is comparable to the separation between atoms. This means several atoms can occupy the same region of space at the same time and this is something that billiard balls simply cannot do! At this critical temperature, all the atoms condense into the lowest energy state available; they lose completely their individuality and behave as single quantum entity: the Bose-Einstein condensate.

Snail-Paced Atoms

How cold is cold enough? Physicist measure temperature on an absolute (Kelvin) scale where 0 K = -273.15 degrees C, or absolute zero, is the temperature at which all motions would cease. To reach the critical temperature needed to achieve Bose-Einstein condensation, atoms typically need to be cooled down less than one millionth of a degree above absolute zero. At such temperatures, the velocity of the atoms is only a few millimetres per second – roughly the speed of a healthy garden snail. To reach such temperatures in their laboratories, physicists utilize a combination of state-of-the-art laser cooling, trapping and evaporation techniques.

For Murray Barrett and Kyle Arnold, who is a PhD student at CQT, this is only a beginning. The condensate is just a tool for more interesting experiments to come. Some of them will provide better insights into the world of collective behaviour of ultra-cold atoms, and some may lead to new technologies for information processing and metrology. The quantum world is full of surprises and one never knows what may come out of it. Quantum physics gave us transistors and lasers, but, it seems, with better understanding and control over quantum phenomena, there is much more to come.

QIP=PSPACE=IP

Rahul Jain explains interactive proofs

Vive La (Information) Revolution!

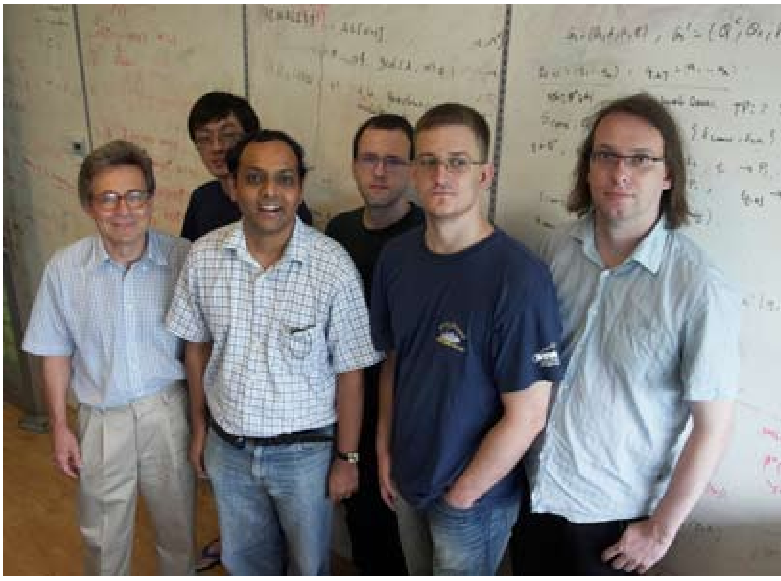
In the last couple of decades, computers have become integral part of our lives. On line shopping, banking, travel planning, weather prediction, google, wikipedia, facebook, twitter.. the list goes on. We are all very thankful of these things that computers can do well, however we should be equally thankful for some of the things that computers cannot do or are not known to do efficiently! For example computers are not known to determine 'prime factorization' of large integers fast and this fact is used crucially in order to carry out secure transactions over the Internet like transfer of money and credit card transactions.

It's Complicated

Factoring is just the tip of the iceberg and there are a whole lot of other problems which are perceived to be much harder to solve using current day computers. An example is what is referred as the 'Travelling Salesman Problem' which is to determine the shortest route for a travelling salesman who wants to cover all the given cities. This is one of the very well studied problems in the field of study called as 'Complexity Theory' which tries to study the inherent 'hardness' of different problems. The hardness of a problem is counted in terms of the amount of 'time' and 'space' (memory) needed to solve it using a standard computer called the 'Turing Machine'. The class of problems that can be solved efficiently in time is referred to as PTIME. The class of problems that can be solved efficiently in space is referred to as PSPACE. It is easily argued that PTIME is contained in PSPACE since in unit time a machine can only use unit space.

Prove It!

One of the great mysteries in the complexity world is that if time competes with space, that is if PTIME is equal to PSPACE or strictly contained in it? In fact it is widely believed that PTIME is not equal to PSPACE. Now let us try to provide some extra powers to PTIME to help it compete with PSPACE. Let us begin by giving PTIME the extra power of 'randomness'; that is we allow 'probabilistic computations' with 'small error' in the answer.



Left-Right: Mikos Santha, Penghui Yao, Rahul Jain, Thomas Decker, Attila Pereszlenyi, Hartmut Klauck.

Let us call the class of problems that can be solved efficiently this way as Pr-PTIME (for probabilistic PTIME). It can be argued that Pr-PTIME is contained in PSPACE; however it is not known if Pr-PTIME is equal to PSPACE and again it is widely believed not to be the case. Let us make another try and provide a different power called as 'non-determinism' to P. The power of non-determinism is captured by letting the PTIME machine, hence referred to as 'Verifier', take help from an 'all powerful Prover' who is willing to help but can possibly cheat and hence its claims need to be verified. For example consider the decision version of the Travelling Salesman Problem, that is if the shortest route covering all cities is less than 100 km. If such a route exists then the Prover could provide the Verifier an 'evidence', that is a valid route of total length less that 100 km which the Verifier can efficiently verify. If such a route does not exist then the Prover cannot fool the Verifier since any route provided by it would not be valid and the Verifier will reject while checking it. The class of problems that can be solved efficiently using such non-determinism is referred to as N-PTIME (for non-deterministic PTIME) and it can be argued that N-PTIME is contained in PSPACE. However again N-PTIME is not known to be equal to PSPACE and widely believed not to be the case.

An Aside

I cannot help but mention a side track to our story: it is not known if PTIME is strictly contained in N-PTIME or equal to it and this is arguably the biggest problem of all times for Complexity Theorists to solve! Clay Mathematics Institute of Cambridge, Massachusetts, USA (CMI) has declared it as one of the seven 'millennium problems' and a prize of one million US Dollars for its solution! Let me dare to add that not many are hopeful that it will be solved this century!

The Space-Time Comptinium

Coming back to our main track, let us make a final attempt and provide both the powers of randomness and non-determinism to PTIME. In such a situation it also makes sense to allow for 'interaction' between Prover and Verifier, that is allow exchange of several messages between them. This is like a student-teacher interaction in which the student learns by asking several different questions to the teacher in a question-answer sequence. The class of problems having such 'Interactive Proofs' is referred to as I-PTIME (for interactive PTIME). Indeed I-PTIME can finally catch up with PSPACE; this was shown back in 1992 when it was shown that I-PTIME = PSPACE. This is how finally time caught up with space in the Complexity Theory World! Are there some bells ringing in the mind on what Einstein said about time and space?!

Quantum Enters the Stage

Now that we have made PTIME catch up with PSPACE, let us see if we can make it beat PSPACE by giving it a further extra power of the 'Quantum'. Quantum computers use the 'Superposition Principle' of 'Quantum Mechanics' which in a sense provides them massive parallelism in computation and hence they can perform some tasks much better than conventional classical computers. Peter Shor in 1995 famously showed how to factor large integers efficiently using quantum computers! So if quantum computers become a reality then a large part of the current day cryptography collapses but with them also comes new cryptography which is much more robust, relies on no assumptions like hardness of factoring etc., and is secure as long as quantum mechanics is correct! After Shor's algorithm for factoring, there was a great deal of excitement generated about finding out what else quantum computers can do efficiently. It was shown that quantum computers can search large databases better, and in some models like 'Communication Complexity' and 'Walks on Graphs' they can perform exponentially faster than classical computers.

It Doesn't Matter

OK, so let us come back to our story and consider the quantum analogue of I-PTIME, known as QI-PTIME (for quantum interactive PTIME), in which now the Verifier is an efficient 'Quantum Turing Machine' exchanging quantum messages with the Prover. It is easily argued that I-PTIME, and hence PSPACE, is contained in QI-PTIME, since a classical verifier is also a quantum verifier. It was an open question for about a decade now, since QI-PTIME was first defined, as to whether QI-PTIME strictly beats PSPACE or QI-PTIME equals PSPACE? We settle this long standing question and show that QI-PTIME is also contained in PSPACE and hence QI-PTIME = PSPACE = I-PTIME. So no quantum leap for Interactive Proofs; such is the world, we got to live in it! Also in different words, 'quantum verification efficiently in time' equals 'classical solution efficiently in space'.

The Meaning of it All

So what does it really mean? For ardent quantum fans it is a surprising result and possibly a bit disappointing too; after all they hoped better from the power of the quantum! However for good old Classical Complexity Theorists, this further increases their love and admiration for PSPACE, a very robust class that stands firm in all weathers! For many, this result is not so much a statement on the limitation of the power of the quantum but more on the already vast power of PSPACE and I-PTIME which does not further increase even with the quantum help. The techniques used while settling this question are also interesting in their own right; in our solution we exhibit 'fast parallel algorithms' for solving a certain class of 'semi-definite programs'.

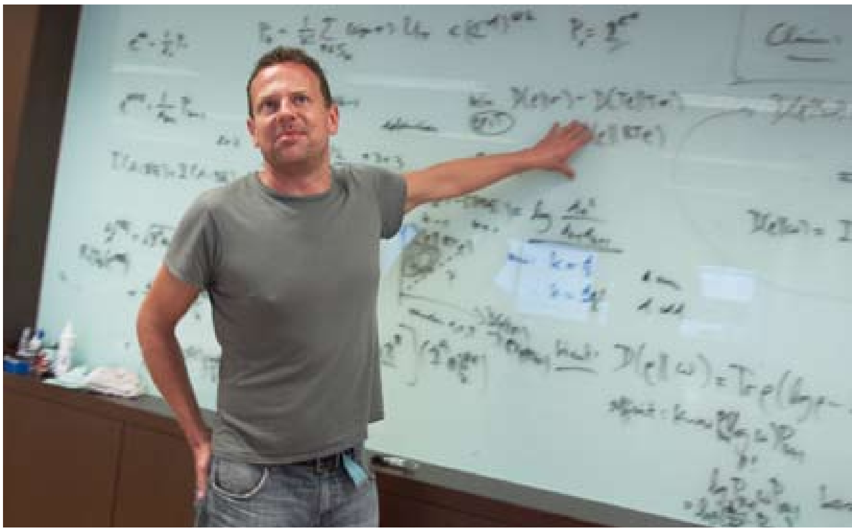
But leaving this technical mumbo jumbo aside, the common man on the street asks; is our world going to be better or worse after this result? Neither is the answer, at least not that I know of! For now we can all continue to sleep as peacefully as before!

Acknowledgements

The work described above is done in collaboration with Zhengfeng Zi (Perimeter Institute of Technology, Waterloo, Canada), Sarvagya Upadhyay and John Watrous (Institute for Quantum Computing, University of Waterloo, Canada).

In Theory

Andreas Winter presents four snapshots of the latest developments in Quantum Information Theory



Beyond No-Signalling

Without a cause there cannot be an effect, or in information theory language: without communicating anything one cannot send a deliberate message. This "non-signalling" principle is obeyed by all modern physical theories, including quantum mechanics, but it encompasses also much wider classes of toy theories. In our work (L. Pawlowski et al., to appear in Nature), we extend this to bound *how much* information can be obtained after receiving a limited communication - assuming that some elementary ways of reasoning about mutual information hold (which they do in quantum mechanics). On the other hand, many generalised non-signalling theories don't obey the bound. Turning this around, and postulating the information bound as a fundamental property of nature, excludes large swathes of "trans-quantum" correlations, right to the boundary of the quantum mechanically accessible ones.

Capacity from incapacity

Quantum channels allow in general the transmission of all sorts of information: quantum bits (qubits), classical bits (cbits), or private information (pbits), giving rise to three separate capacities C, Q and P. The quest for usable formulas for these numbers, as well as the understanding of their properties as functions of the channel is one of the central objectives of quantum communication theory. After Hastings (Nature Phys. 2009), brilliantly building on work by AW, P. Hayden &AW, and T. Cubitt et al. (Comm. Math. Phys. 2008), showed recently that a long-conjectured candidate for C is actually strictly smaller in general, no computable expression is currently known for either of the three capacities. In extension of their work, G. Smith & J. Yard (Science 2008) showed dramatically that Q is really strange: the combination of two zero-capacity channels may have positive capacity. In variation and extension of their work, K. Li & AW & X-B. Zou & G-C. Guo (to appear in Phys. Rev. Lett.) proved that there are channels, one of which has small *classical*, the other zero *private* capacity, but in combination they can have enormous *quantum* capacity. It is wide open how to interpret these phenomena, and whether the effect also exists for the classical capacity.

Randomness for random states

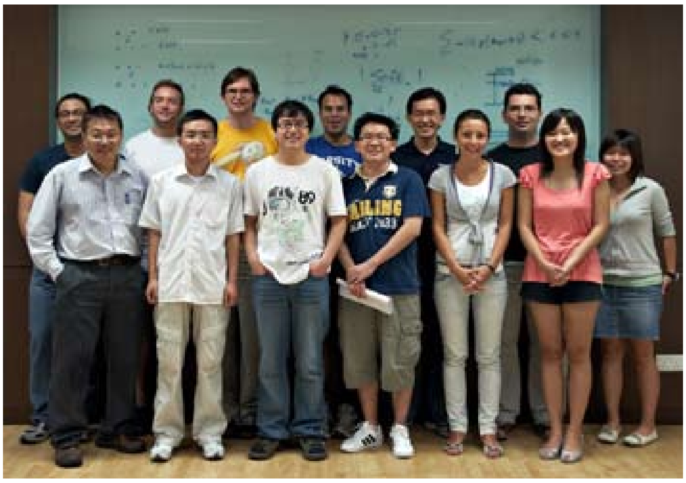
Which states are useful for one-way quantum computation? In that model, the quantum power is neatly represented in the correlations of a multi-party state, plus a (typically very simple) classical control governing how this state is measured qubit by qubit. The first good states for the purpose were so-called cluster states, but actually it is easier answer which states are useless! Indeed, the resource state has to be sufficiently entangled to offer a quantum advantage. Complementing this elementary insight, we show (M. Bremner & C. Mora & AW, to appear in PRL) that many correlations are not good either. Namely, the typical sample from sufficiently large families of states is of no greater use to a bounded classical control than a source of unbiased random coin flips.

Classical Hash

Not all is quantum, especially in cryptography: Markus Grassl helped crack a long-standing proposal for a classical scheme of so-called hash functions; these are compression maps to convert a long bit string into a short "digest" - this is used in authentication and digital signatures. Markus and his co-authors showed that a proposal by Tillich and Zemor (CRYPTO 1994) is not resistant to malicious attacks -- by a classical adversary!

Photons and Atoms

Dimitris Angelakis explains how to get photons talking



The Group: H. Reslen , L.C. Kwek, S. Benjamin, L. Dai, D. Browne, Y. Li, H. Cable, CL Ching, Setiawan, E. Kyoseva, D.G. Angelakis, M. Huo, E. Tan,

Our newly formed "Quantum Simulators and Distributed QIP" group is exploring the rich physics found in the interaction of atoms and photons. In quantum simulators, we work towards the understanding of complex quantum phenomena found in real solid state materials; and in Distributed Quantum Information Processing (DQIP) towards realistic schemes for quantum computation implementations.

Quantum Simulators

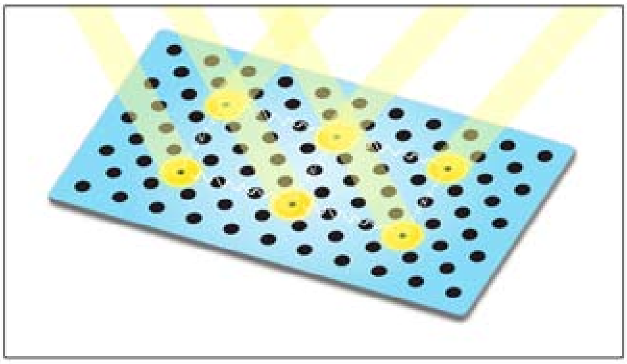
Simulating even the most modest of quantum systems requires enormous classical computing power. Richard Feynman in the 80s proposed to use one "easy to manipulate" quantum system to simulate another complex one. People have suggested using neutral atoms trapped by laser beams in an optical lattice by Jacksh, Greiner and collaborators. However it is difficult to individually examine each atom which is necessary for efficient quantum simulation. We are trying to use photons to overcome these difficulties. One way to achieve this is to get photons to do things they don't usually want to, i.e., strongly interact with each other. When photons talk, in this case through a mediator such as an atom or a quantum dot, we may be able to reproduce and study a range of complex many-body phenomena found in real materials, but now in well controlled laboratory conditions.

Getting Photons Talking

Building upon our earlier work in 2006 we now investigate networks of strongly interacting photons as follows: Imagine a hair-thin membrane of a dielectric material like silicon, with an array of microscopic holes. Each hole when slightly deformed creates a so-called defect cavity, a tiny area a millionth of a metre in diameter that can store photons for a long time. By placing a few atoms in the defect or growing artificial atoms (quantum dots) in it, our calculations show that a so-called "Mott insulator state for photons" could be created. In this case photons behave like electrons in an insulator and literally bounce off each other when they get close enough. In addition, a so called "Quantum Phase Transition" between this strongly correlated photon phase and their usual non-interacting selves, can be observed by tuning external fields. This way we can simulate what is happening inside real materials and understand why and when they change from conductors to insulators for example.

The Future

We have started studying even more complex condensed matter phenomena such the Fractional Hall Effect and steady state entanglement, magnetism and spin canting. We are also studying many-body quantum correlations in photonic systems and efficient implementation of fast quantum algorithms. We would also like to explore the versatility of these systems for simulating even more exotic phenomena of matter like high-temperature superconductors and magneto-electric materials. In collaboration with the Microtraps experimental group in CQT we plan to realize specific experimental implementations of the above theory results using atoms in low temperatures interacting with photons.



Getting photons to talk to each other might provide the tools for deeper understanding of the behaviour of matter at the atomic scale and for the design of new materials with exotic powers for computation

Trusting the untrustworthy

CQT attracts both long and short term visitors from all over the world. Sometimes even a brief visit to the centre results in some excellent work. Joe Fitzsimons explains the results of his visit.

The Quantum Way

For more than a century quantum mechanics has provided us with some of the most astounding and counter-intuitive phenomenon in physics, and in the process has perplexed generations of physics students. More than any other branch of physics, quantum mechanics describes a world totally alien to us. Years of interacting with the environment around us has allowed us to form an intuition for physics. This intuition serves us well on the typical scales we are use to: dealing with objects ranging in size from ants to skyscrapers. When we go down to the scale of atoms and molecules, however, this intuition breaks down.

On small scales quantum effects become apparent, and the classical physics of our intuition fails us. In order to make accurate predictions we need to abandon the physics of Newton and Galileo in favour of quantum mechanics. According to quantum mechanics there are some properties of particles which we cannot simultaneously know. An example of this is the relationship between the position of a particle, such as an electron, and its momentum. Our intuition would have us believe that these are independent properties, since we can easily measure both the position and momentum of a bowling ball. Why shouldn't the same be true of electrons?

Uncertainty

Strangely, this is not the case. Making a measurement of one of these properties disrupts the other in such a way that we can never learn both, no matter how sophisticated or precise our measurement instruments are. There is a fundamental trade-off between how well we can simultaneously measure each of these properties. This is the famous Heisenberg uncertainty principle, and is one of the most counter-intuitive aspects of quantum mechanics.

In fact, this uncertainty principle is not simply limited to position and momentum. For any property of a quantum system that we can measure, it is possible to come up with another property which cannot be simultaneously measured.

This may sound like a depressing result, placing fundamental limits on our knowledge, but it does not have to seen this way. This very property of quantum mechanics which limits our ability to measure systems opens the door to a range of new technologies and ways to process information. Computers operating using quantum effects could be harnessed to solve problems intractable on even the most powerful of our current computers.

Computing by Measurement

In 2001, Robert Raussendorf and Hans Briegel, then both at Ludwig-Maximilians University in Munich, proposed a revolutionary new way of performing computation with quantum systems. Rather than using physical interactions between the quantum bits which make up such a computer to perform computation, as had been done up to that point, they proposed using specially chosen measurements to drive the computation. If the system was initially prepared in a special state these measurements could be used to implement the basic logic gates that are the fundamental building blocks of any computation. This model of computation is purely quantum: It is impossible to construct a measurement based computer according to classical physics.

Measurement based computation can be seen as equivalent to simply rolling some dice and then measuring the result. Normally this would lead to a random result, and so is not sufficient to perform a meaningful calculation. If the dice behave quantum mechanically, however, the result is very different. Quantum mechanics allows for a more general set of correlations between the dice, known as entanglement, which can be exploited to perform the computation. If the dice are entangled then the measurement outcome of one dice effects the next. A more general set of measurements is also possible, and so by adapting the choice of measurement to the previous result it is possible to perform calculations.

This new model of measurement based computation opens many promising routes for building large scale quantum computers. Indeed, researchers at the Centre for Quantum Computing Technologies here in Singapore are currently working on architectures for distributed quantum computers based on this model which may lead to large scale quantum computers.

A New Way of Thinking

For me, however, measurement based computation is not simply a way to build better computers, but rather a new way to think about computation. Over the past two years I have been working with Anne Broadbent (University of Waterloo) and Elham Kashefi (University of Edinburgh) to exploit techniques based on measurement based computation in cryptography. One question was of particular interest to us: Can you trust a computer you do not control?

In particular what we wanted to know was whether or not it was possible to perform a blind computation on a remote computer. For a computation to be blind it must be impossible for someone with access to that computer to learn the input, output or the calculation being performed.

This may seem like rather an odd question to ask, but in a world where we digitizing our most sensitive information maintaining the secrecy of sensitive material is more important than ever. Time on supercomputers is often rented, and so it is essentially impossible to insure that nobody has interfered with the system. The problem becomes even more acute when we consider quantum computers, which will likely appear initially in only very limited numbers.

Surprisingly, this problem has no solution in classical computer science. Not only are there no encryption schemes for performing arbitrary calculations blindly, but it has been proved impossible to ever construct such a scheme using only classical computers.

Quantum Blind Computation

Our recent work has shown that the case is quite different for quantum computers. The uncertainty principle allows for more information to be encoded in a quantum state than can be accessed through measurements. As measurement based computation allows quantum computation to be constructed from measurements on quantum states together with a classical rule for adapting subsequent measurements, we found that by using subtly different initial quantum states for the computation different logic gates could be implemented. Each possible initial state is chosen in such a way that they yield identical results for any possible measurement, but yet each nudges the computation in a different direction. As a result, it is possible to perform arbitrary calculations blindly.

In fact, this can be taken one step further. By adapting techniques usually used to detect errors in quantum computers, it is possible to detect any interference with the blind computation. Taken together these results provide for us to with a way to ensure that our computation remains private and correct without needing to trust the computer or those who have access to it.

Though it may seem surprising, in this age of computer viruses, hackers and spyware, computers can once more gain our trust. The catch? You can only trust the quantum ones.

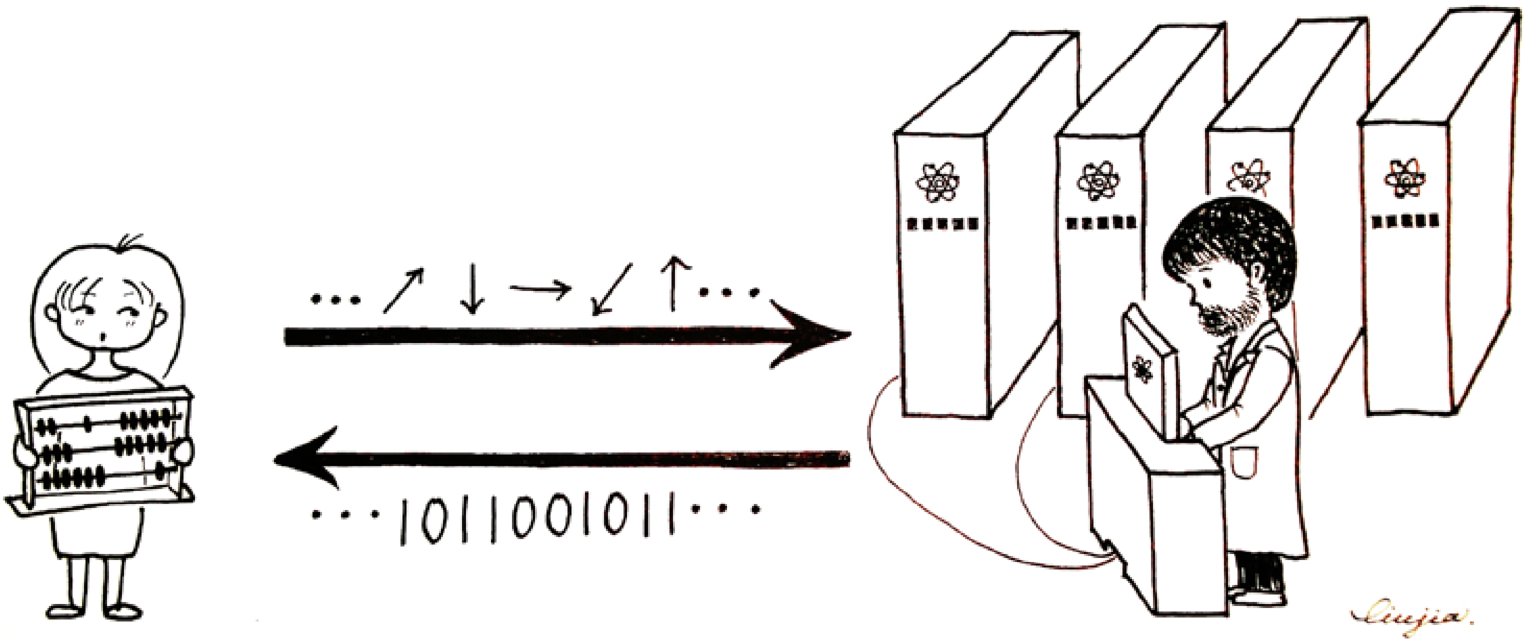


Figure 1. Alice would like to use Bob's supercomputer to run her program. Unfortunately, she does not trust Bob to not peek at her data and thus would like a way of sending instructions to Bob with revealing any information about what she trying to calculate. This task is impossible if they are restricted to classical communication and computers. However, if alice is allowed to send quantum signals to Bob who has a quantum computer, then so-called Blind Computation can be achieved. Illustration by Liu Jia.

Quantum Technology in Biological Systems

Vlatko Vedral and Elisabeth Rieper explore quantum processes in biology

Living matter, while not eluding the 'laws of physics' as established up to date, is likely to involve 'other laws of physics'… It is, in my opinion, nothing else than the principle of quantum theory over again.
Erwin Schrödinger, "What is life"

What is Life

The application of Quantum Mechanics in Biology seems at first sight ridiculous. While the first deals with small systems at low temperatures, the second is about large systems at high temperatures. Nevertheless there is a long successful story about physicists engaging in biology. Meanwhile modern biology highly depends on, both on the experimental and theoretical side, using physics. Indisputable is the importance of using QM for explaining molecular properties, like energy levels or the chemical mechanism of H-bonds. But the last years of research within Quantum Information Theory (QIT) showed that there are quantum effects without classical a counterpart. The most famous one are superposition and entanglement, which lead to exciting applications, such as the ability to teleport a quantum state or a quantum computer running in parallel with the help of superposition.

The big question is: Is Nature engaged in any kind of Quantum Technology? It is tempting to argue that biological systems, master of nanodesign, found after millions of years of trial and error evolution ways to implement QIT for optimizing efficiency. After all, recently, biologists have begun to realise that classical laws cannot explain everything. Therefore Vlatko Vedral and Elisabeth Rieper organized an interdisciplinary workshop on the topic 'Quantum Technology in Biological Systems' from January 11th-16th 2009 on Sentosa, Singapore. Topics ranged from Introduction to Quantum Mechanics to Photosynthesis Unit, Avian Navigation and Spin Chemistry and non trivial Quantum effects in molecules.

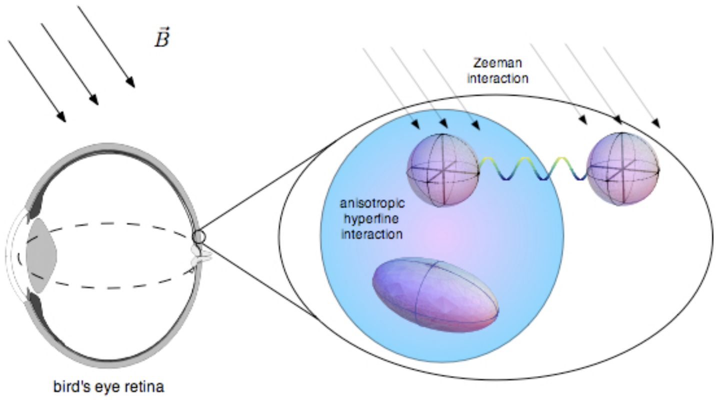


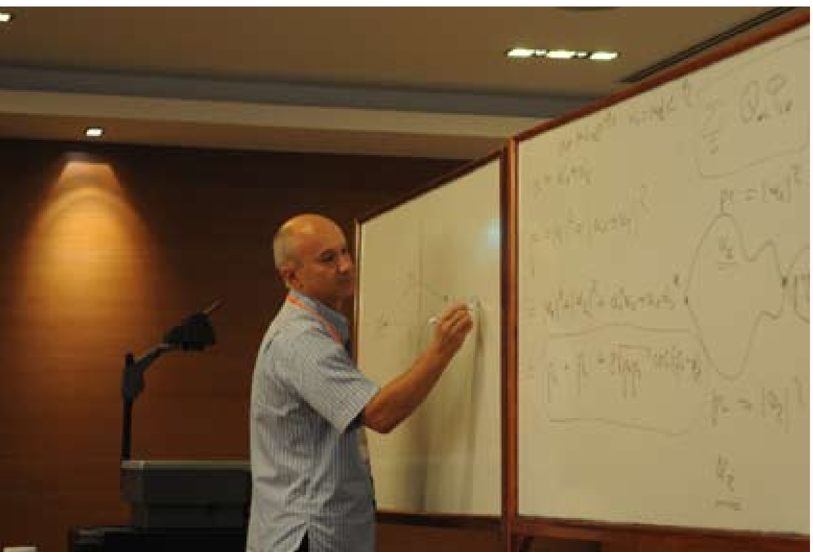
Figure 1. Schematic of a bird's eye. The back of the eye contains numerous molecules, fixed with a specific orientation. In the simplest Radical Pair model, each such molecule involves three crucial components (see inset): two electrons, initially photo-excited to a singlet state, and a nuclear spin coupled to *one* of the electrons. This coupling is anisotropic, so that the molecule has a directionality to it. The angle of magnetic field with the molecule influences the relative ratio of the production of chemicals in the retina of birds.

Photosynthesis

Photosynthesis is one of the most important processes for life, as it converts solar energy to 'sugar', which allows efficient long term energy storage. Meanwhile the molecular structure of the photosynthetic unit is discovered. Most of the photosynthetic unit is used to capture light. This excitation is then transmitted to a reaction centre. Until recently theoretical models were not able to predict the highly efficient energy transfer from the light harvesting units to the reaction centre. The energy transfer mechanism was described by semi classical models that use excited state hopping from one site to the next.

Participants of the Quantum Technologies in Biological Systems Workshop, 11th-16th January 2009, Sentosa, Singapore. (Left to Right) Francois Fillaux (CNRS Thiais),Mile Gu (The University of Queensland), Wolfgang Wiltschko (University of Frankfurt), Graham Fleming (UC Berkeley), Vlatko Vedral (CQT),Vasily Ogryzko (Institute of cancerology Gustave Roussy, Paris), Chris Rodgers (University of Oxford),Judith Klinman (University of Berkeley),Tony Leggett (University of Illinois at Urbana-Champaign), Bruno Sanguinetti (University of Leeds), Anita Goel (University of Harvard),Nathan Babcock (University of Calgary), Libby Heaney (Centre for Quantum Technologies, NUS), Paul Davies (Arizona State University),Frances Wang (University of Illinois at Urbana-Champaign), Elisabeth Rieper (CQT), Janet Anders (University College London),Juan Pablo Paz (Ciudad Universitaria, Buenos Aires), Philip Walther (University of Vienna), Kavan Modi (CQT, visitor), Richard Cogdell (University of Glasgow). Other participants not present in the photo: Simon Benjamin (University of Oxford), Artur Ekert (Centre for Quantum Technologies, NUS), Nicolas Gisin (Université de Genève), Kiminori Maeda (University of Oxford), Thorsten Ritz, (University of California, Irvine), Valerio Scarani (Centre for Quantum Technologies, NUS)

A recently conducted experiment at Berkeley started the idea of using coherent electron transport instead of the classical model. As a light wave is by far larger than a typical photosynthetic unit, a single excitation is spread out coherently over many electrons. This coherence brings a speed up in searching for the 'correct' final site, where the excitation is transformed into 'sugar'. Research conducted at MIT showed that in order to achieve high transfer efficiency, one has to consider both the coherent speed up and Anderson localization effects, which definitely count as non trivial quantum mechanics.



CQT Director, Artur Ekert, giving the Quantum Theory 101 introduction for the benefit of non-physicists.

Spin Chemistry

It is already known that entanglement, although defined on a microscopic level, has macroscopic effects. For example the magnetic properties of certain states of solids cannot be explained without entanglement. Another such effect is provided by the interaction of spins with an external magnetic field. It turns out that by this microscopic interaction a chemical reaction can be controlled. This is of relevance for biology, as birds navigate along magnetic field lines.

The intriguing idea behind the Radical Pair (RP) Model is that birds 'see' the geomagnetic field. Orientated molecules, embedded in the eye's retina, form a signal pattern dependent on the inclination of Earth's magnetic field (see Fig.1).

The formal workshop sessions were punctuated by informal discussion over local cuisine.

The simplest RP model describes the spin of two electrons and one nucleus of the molecule. Absorption of a photon and subsequent transfer of one electron to an acceptor part of the molecule gives rise to the radical pair. Due to the spatial separation it now becomes meaningful to talk about electron spin entanglement.

Without the hyperfine interaction both electrons would precess around the same magnetic field, leaving the singlet state invariant. With the nuclear interaction present, the singlet state is no longer an eigenstate of this Hamiltonian leading to an angle dependent singlet-triplet oscillation. In other words, both electrons are subject to different local operations. Recombination occurs either from the singlet or triplet state, leading to different chemical end products. The concentration of those products constitutes a macroscopic chemical signal, which, due to the HF interaction, is sensitive to the orientation of the molecule with the magnetic field.

Using recent experimental observations together with the well developed 'radical pair' model of the avian compass, one can employ a master equation with generic decoherence operators in order to examine the system's vulnerability to environmental noise. Remarkably, the room temperature noise tolerance in this natural system appears greater than that of the best man-made molecule, i.e. N@C60 (a single nitrogen atom encased in a buckyball). Researchers at CQT and Oxford find that entanglement, though probably not an essential feature of this process, appears to persist to tens of microseconds, or more.

Participants at the workshop discussed many different ideas, bringing together expertise from any disciplines.

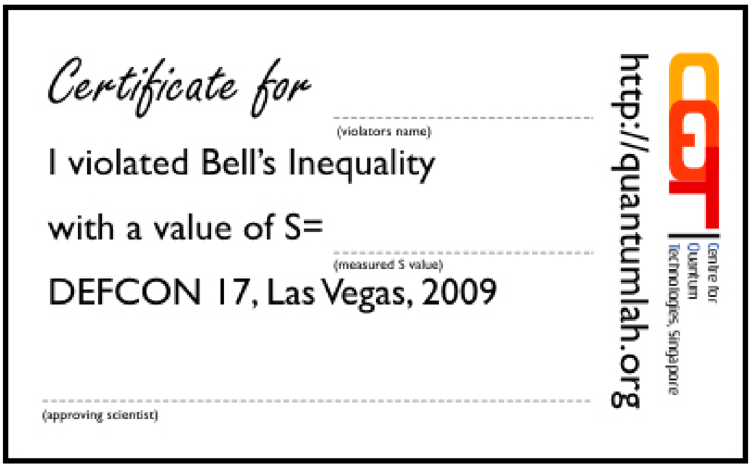
On the Road

The Quantum Optics Lab exposed their hardware in Las Vegas and the Netherlands to hardcore hackers

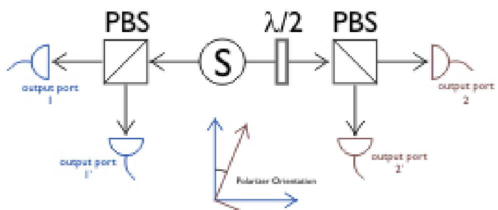
Back on the road with the vintage parametric down-conversion (PDC) source! Again we went to Vegas to show some hardware together with the NIST guys. We showed the basics of how to fool a single photon detector into "clicking" at the request of an eavesdropper and set up a fun fair competition for the DEFCON17 participants to see who could achieve the highest violation of a Bell inequality by carefully aligning the measurement basis. The Golden Handles were connected to a very fiddly polarization controller. After that Ilja joined up with Vadim in the Netherlands and presented the hacking setup to yet a different audience in Hacking at Random (HAR2009).

Golden Handles. Participants would use these controls of the polariser settings to try to achieve the maximal violation of Bell's Inequalities.

Hacking Kit in a Box. On display at HAR2009



Participants in the Bell competition were given signed cards with their degree of "non-classicality", i.e. how far above 2 they managed to get the Bell value S.

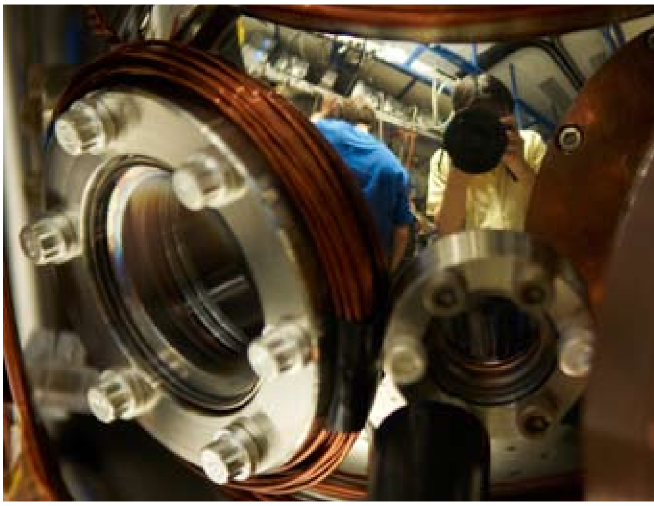


$$-2 \le E(a,b) - E(a,b') + E(a',b) + E(a,b) \le 2$$

$$E = \frac{N_{12} + N_{1'2'} - N_{1'2} - N_{12'}}{N_{12} + N_{1'2'} + N_{1'2} + N_{12'}}$$

Entanglement source and analyser. The angles of the polarising beam splitters could be adjusted via "Golden handles"

Publications



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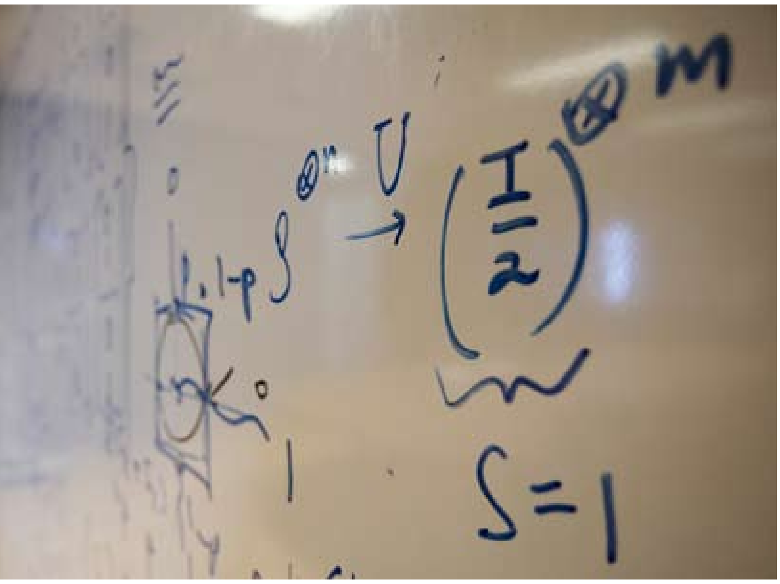

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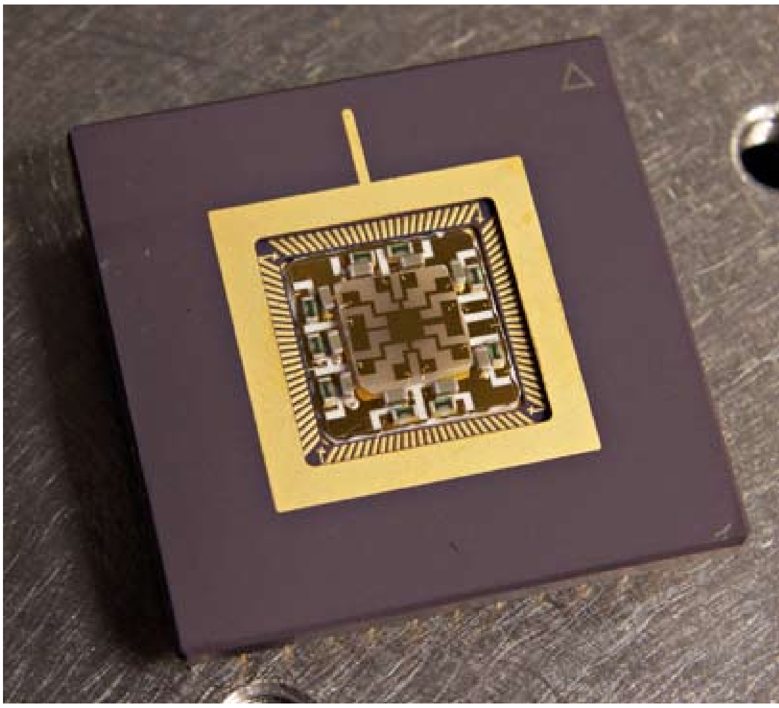

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Visitors to the CQT

Name	Institute
Antonio Acin	The Insitute of Photonic Sciences, Spain
Mafalda Almeida	The Insitute of Photonic Sciences, Spain
Andris Ambainis	University of Latvia
Seyed Massoud Amini	Universiti Putra Malaysia
Janet Anders	University College London
Martin Aulbach	University of Leeds
Nathan Babcock	University of Calgary
Hans A. Bachor	ARC Centre of Excellence for Quantum-Atom Optics, The Australian National University
Antonio Badolato	ETH Zürich
George Batrouni	INLN, University of Nice
Wolfgang Behr	University of Zurich, Switzerland
Dan Browne	University College London
Caslav Brukner	University of Vienna, Vienna
Dagmar Bruss	University of Düsseldorf
Earl Campbell	University College London
Daniel Cavalcanti	The Institute of Photonic Sciences
André Chailloux	LRI, Université Paris-Sud
Ming-Shien Chang	University of Maryland
Frederic Chevy	LKB, ENS, Paris.
Jaeyoon Cho	Belfast
Matthias Christandl	University of Munich
Tom Close	University of Oxford
Judith Cogdell	University of Berkeley
Richard Cogdell	University of Glasgow
Roger Colbeck	ETH Zürich
Paul Davies	Arizona State University
Thomas Decker	McGill University
Julien Degorre	Universite de Paris
Dominique Delande	National Center for Scientific Research, France
Du Jiangfeng	University of Science and Technology of China
Jacob Dunningham	University of Leeds
Sir John Enderby	IOP Publishing, United Kingdom
Marie Ericsson	Uppsala University
Juergen Eschner	Institute of Photonic Sciences
Tristan Farrow	Cambridge, UK
Francois Fillaux	CNRS Thiais
Elena Rufeil Fiori	Universidad Nacional de Córdoba
Joseph Fitzsimons	University of Oxford
Graham Fleming	UC Berkeley
Aurelien Fragniere	Ecole Polytechnique Fédérale de Lausanne, Switzerland
Erik Gauger	University of Oxford
Thierry Giamarchi	University of Geneva
Nicolas Gisin	Université de Genève
Hsi-Sheng Goan	National Taiwan University
Mark Oliver Goerbig	LPS, University Paris 11
David Guéry-Odelin	LCAR, University of Toulouse
Michal Hajdusek	University of Leeds
David Hallwood	University of Leeds, united Kingdom
Serge Haroche	College de France and Ecole Normale Superieure, Paris
Patrick Hayden	McGill University
Frédéric Hébert	INLN
Heng Fan	Chinese Academy of Sciences
Peter Hoyer	University of Calgary
Jiazhong Hu	Tsinghua University
Hyunseok Jeong	Seoul National University, Korea
Marcus Johansson	Uppsala University
Jaewoo Joo	University of Calgary

Dmitris Angelakis (left) and Simon Benjamin (right) deep in discussion on the rift between experiment and theory.

Alastair Kay	University of Cambridge, United Kingdom
Achim Kempf	University of Waterloo
Pieter Kok	University of Sheffield
Paul Kwait	University of Illinois
Rallan Laukesh	University of Oxford
Changhyoup Lee	Hanyang Unversity
Tony Leggett	University of Illinois at Urbana-Champaign
Li Fuli	School of Science, Xi'an Jiaotong University, China
Ke Li	University of Science and Technology of China
Yeong-Cherng Liang	University of Sydney, Australia
Alexandra M. Liguori	Universita' Degli Studi Di Trieste, Italy
Qiu Lin	Norwegian University of Science and Technology
Seth Lloyd	Massachusetts Institute of Technology
Looi Shiang Yong	Carnegie Mellon University
Brendon Lovett	University of Oxford
Norbert Lutkenhaus	University of Waterloo
Chiara Macchiavello	University of Pavia
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Wang Xiangbin	Tsinghua University
Wang Xiaoting	University of Cambridge
Wei Lian-Fu	Southwest Jiaotong University, China
Karoline Wiesner	University of Bristol
Wolfgang Wiltschko	University of Frankfurt
Zhang Shengyu	Chinese University of Hongkong

Dieter Jaksch (left) and Ignacio Cirac (right) interacting at the Quantum Cafe

Money Matters

We spent some money

CQT Expenditure

	Dec'07 to Nov'08	Dec'08 to Aug'09	Cumulative Total
Expenditure on Manpower (EOM)	3,856,347	4,523,547	8,379,894
Equipment	1,770,957	1,707,661	3,478,618
Other Operating Expenditure (OOE)	5,146,706	5049990	10,196,696
Total SGD$	**10,774,010**	**11,281,198**	**22,055,208**

The Centre for Quantum Technologies is funded by

NATIONAL RESEARCH FOUNDATION

Ministry of Education
SINGAPORE

We are hosted by

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National University of Singapore

Some of our projects are also supported by

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Defence Science & Technology Agency

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