Centre for Quantum Technologies

NUS National University of Singapore

annual report 2013

Content

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Letter from the Director

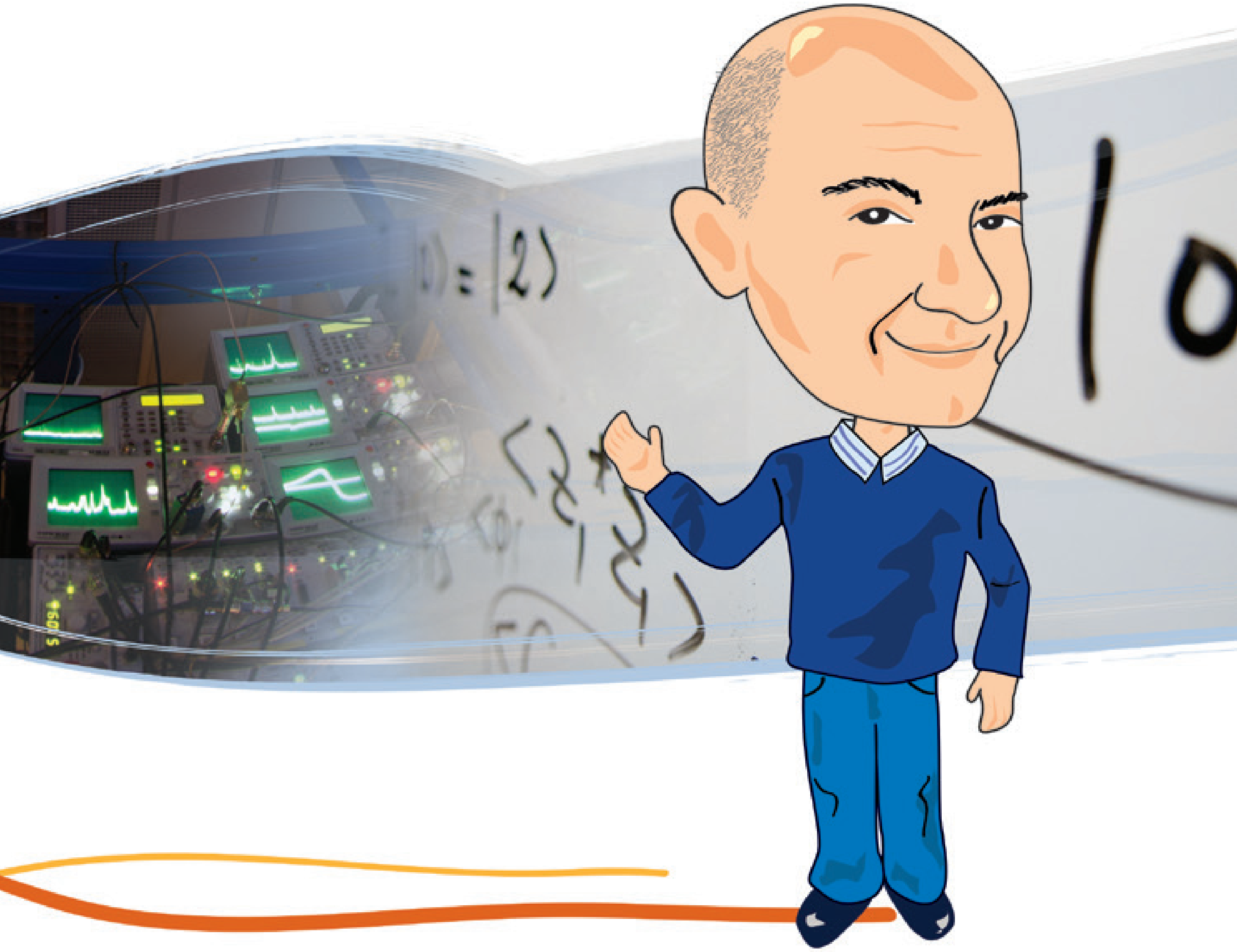
Six years and counting. Publications, citations, invitations and the like will tell you part of the CQT story, but to really appreciate what our Centre has achieved you need to hear the gossip and tales from our small island of Singapore. We are proud that we have made our mark in the international scientific community; we are equally proud of our place in Singapore's research scene. Without any false modesty, we seem to be doing well on both fronts.

Needless to say, it does not mean it is all rosy. We had our share of uncertainties this year. The main issue that kept some of us busy was long-term financial planning. CQT was established in December 2007 with generous core funding from Singapore's Ministry of Education and National Research Foundation, in the form of a one-off grant. This year the two organisations have been discussing how to fund the Centre's continuing operations. I'm pleased to say they have agreed another tranche of core funding. Alongside the grants our researchers are winning, we are now set up for the years to come.

Truth be told, we should not complain about uncertainty anyway, for this is what we study for a living. Uncertainty is a defining feature of quantum theory. In the quantum realm, a single measurement may return different answers with different probabilities, and for some pairs of answers, knowing one means being uncertain about the other.

This year our researchers showed that quantum uncertainty may help prevent the possibility of a perpetual motion machine (see p 48). Moreover, our researchers secured a grant worth almost $10 million to study randomness in all its quantum incarnations. Randomness, of course, is uncertainty by another name, and it's a very valuable resource, for example for creating privacy in communication, for simulations and for gaming.

Here connections with cryptography are visible. This year saw lots of preparatory work for fascinating things to come. We will be sending sources of entangled photons way up into space to see how they perform in this alien environment (see pp. 26–27). Back on the ground, we are detecting entangled photons with near-perfect efficiency. This experimental work will take secure communication to an entirely new qualitative level and will provide the best privacy quantum technology can offer.



Even though we are mostly focused on fundamental research we do care about the applications and industrial relevance of quantum technology. This year we welcomed Serguei Beloussov to our Governing Board. As you can read on pages 20–21, Serguei, who is a self-made entrepreneur and a physicist by training, is very passionate about turning blue sky research into commercial products. Quantum technology is slowly coming of age, and we will be looking more and more often into its applied side.

Our birthday is a good time to reflect upon our main asset – our people. This year another 8 CQTians got their PhDs, and this impressive group of young researchers began the next step of their careers. If you are one of our graduates, do not worry, there is life after CQT (see pp. 36–37). This year we also said goodbye to one of our PIs – Andreas Winter took a faculty position in Barcelona. We wish him all the best in remote Catalonia and hope to see him frequently as a visitor.

Back at CQT, we congratulated Joe and Troy on their award of the NRF fellowships, Murray, Rahul and Stephanie on their promotions to Associate Professorships at NUS and Rainer on his promotion to an Associate Professorship at NTU. Some of the undergraduate students we hosted for projects yet again won prizes. We are proud of all of you!

As always, the year was filled with all kinds of activities, conferences and meetings (see pp. 38–39). And we have not forgotten about the outreach, as you can see (see pp. 40–41). Our film-maker in residence, CQT's first Outreach Fellow, Karol Jalochowski, transformed quantum conundrums into a beautiful documentary (read Karol's summary of his visit at pp. 28–29).

Let me finish this by thanking the editorial team of this report – Jenny, Evon and Tim. I hope you agree with me that they did a fantastic job and that this Annual Report is a pleasure to read.

Pictured from left to right, front row, are Umesh Vazirani, Christophe Salomon, Michele Mosca, Artur Ekert, Ignacio Cirac, Dave Wineland, Jun Ye and Kuldip Singh. Behind them are CQT's admin managers Chan Chui Theng and Evon Tan.

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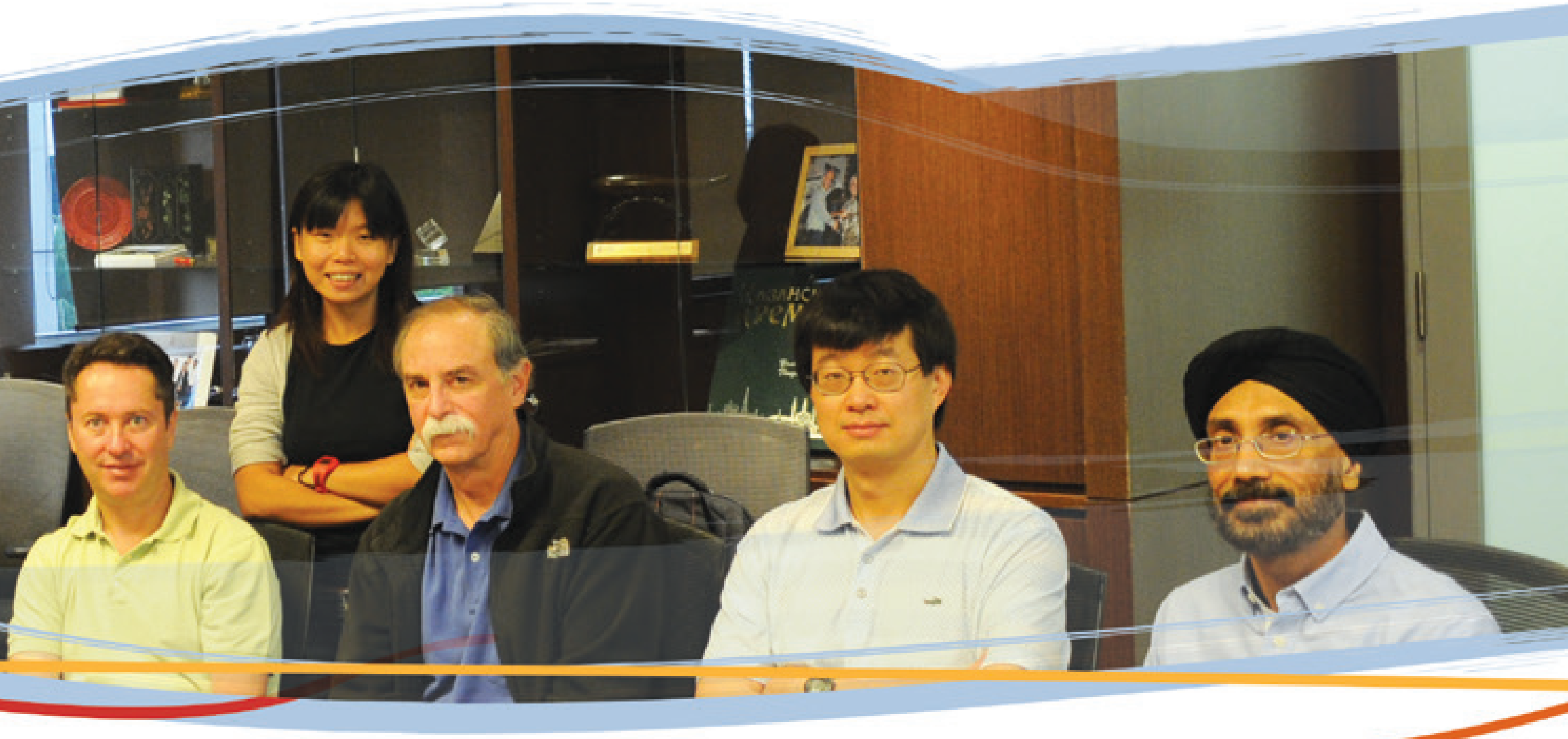
Deputy Executive Director, Science and Engineering
Research Council, A*STAR

Serguei Beloussov
Senior Founding Partner, Runa Capital
Chairman of the Board and Chief Architect,
Parellels Chairman of the Board of Trustees,
Russian Quantum Center



Scientific Advisory Board

Ignacio Cirac
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Institute of Quantum Electronics, ETH Zurich

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

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

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

Christophe Salomon
Research Director,
Laboratoire Kastler Brossel, CNRS

Principal Investigators

The fun is about to begin. After two years building my experiment to trap Yb+ and SiO+ ions, we are making our first measurements.

Dzmitry Matsukevich

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

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

In one of my group's papers this year, we constructed for the first time all the optimal quantum stabiliser codes capable of correcting single-qubit errors. This provides efficient ways to protect quantum data from small noise.

Choo Hiap Oh

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

Choo Hiap's group's main research areas are quantum phase factors and their application, decoherence, contextuality, entanglement and other measures of quantum correlations.

My group is proud that as many as seven of our PhD students have defended their theses since last August.

Berthold-Georg Englert

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

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

I was promoted to Associate Professor at NTU. I thank my group members for their support and hard work.

Rainer Dumke

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

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

It is an exciting time as our founding works on interacting photons for quantum simulations are on the brink of being experimentally implemented in more than one lab worldwide.

Dimitris G. Angelakis

Appointed CQT Principal Investigator in 2009
Other appointments: Assistant Professor, School of Electronic and Computer Engineering, Technical University of Crete, Greece

Dimitris' group works on theoretical quantum optics and implementations of quantum information. Particular interests include quantum simulations of condensed matter and exotic physics phenomena with photons and ions.

In the year since our optics tables were installed last July, we have developed the laser systems required for laser cooling and fluorescence observation of trapped ions.

Manas Mukherjee

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

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

Principal Investigators

> This year we tested the robustness of our Small-Photon Entangling Quantum Source to the radiation it will encounter in orbit (see pp. 24–25)

Alexander Ling

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

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

> I'm the lead PI for a $10 million grant CQT won in February 2013 to study quantum randomness. My group and the groups of my 12 co-PIs will be working on this project over the next five years.

Valerio Scarani

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

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

> I was awarded a grant from the Foundational Questions Institute (FQXi) to study the operational and information theoretic meaning of contextuality (see grant listings p. 54)

Dagomir Kaszlikowski

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

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

We've worked hard to increase our efficiency of entangled photon detection for experiments on quantum randomness.

Christian Kurtsiefer

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

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

Congratulations to our group member Giovanni Vacanti and all the other students who have completed their PhDs at CQT this year!

Vlatko Vedral

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

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

Our lab reached a major milestone this year with the simultaneous cooling of three atomic species, including two fermions. This triple degeneracy is an entry ticket to competitive science at the highest level (see pp. 20–21)

Kai Dieckmann

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

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

It was another good year for my group with a number of results that use information theory to understand the foundations of quantum physics (see pp. 22–23)

Stephanie Wehner

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

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

Principal Investigators

My co-authors presented our work on the cost of creating shared quantum states at the prestigious ACM−SIAM SODA conference.

Rahul Jain

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

The computer science group hosted around 20 short-term visitors this year – these interactions are good for our research and for our students.

Miklos Santha

Appointed CQT Principal Investigator in 2008
Other appointments: Senior Researcher at CNRS in the Laboratoire d'Informatique Algorithmique: Fondements et Applications at the University Paris Diderot, France

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

Hartmut Klauck

I helped to co-organise a workshop on “Communication Complexity, Linear Optimization, and lower bounds for the nonnegative rank of matrices" held in Germany in February.

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

Now we have a well-running apparatus, we are working towards getting a Bose–Einstein condensate and making Rydberg excitations.

Wenhui Li

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

Wenhui's group explores the coherent excitation and manipulation of cold Rydberg gases, and aims at investigating quantum many-body physics and quantum optics in such systems.

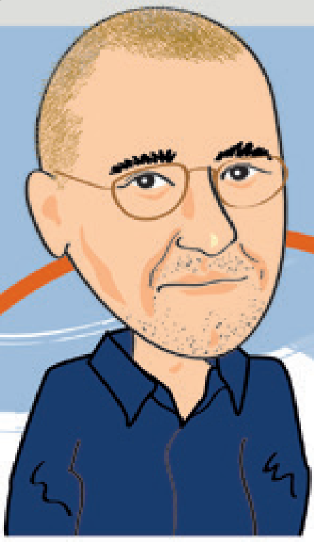
Our fiber devices are now ready for experiments with atoms. Let's see how the near-field imaging will work.

Bjorn Hessmo

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

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

We published a paper in Physical Review Letters about the threshold for self-organisation of rubidium-87 atoms in our cavity.



Murray Barrett

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

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

I've made a patent application in Italy with collaborators in Italy and Brazil for a precision measurement technology that uses the orbital angular momentum of light.

Leong Chuan Kwek

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

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

Our staff

Researchers

Research Assistants

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Chia Zhong Yi
Chuah Boon Leng
Do Thi Xuan Hung
Elnur Hajiyev
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Guo Ruixiang
Han Rui
Herbert Crepaz
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James Oliver Vicary
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Jimmy Sebastian
Jiri Minar
Johannes Tomas Gambari
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Kanhaiya Pandey
Krzysztof Gawryluk
Kyle Joseph Arnold
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Lee Kean Loon
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Lu Xiaoming
Marco Tomamichel
Mark Simon Williamson
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Martin Aulbach
Martin Rudolf Kiffner
Mile Gu
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Stephen Richard James Franz -Clark
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Troy Jeffrey Lee

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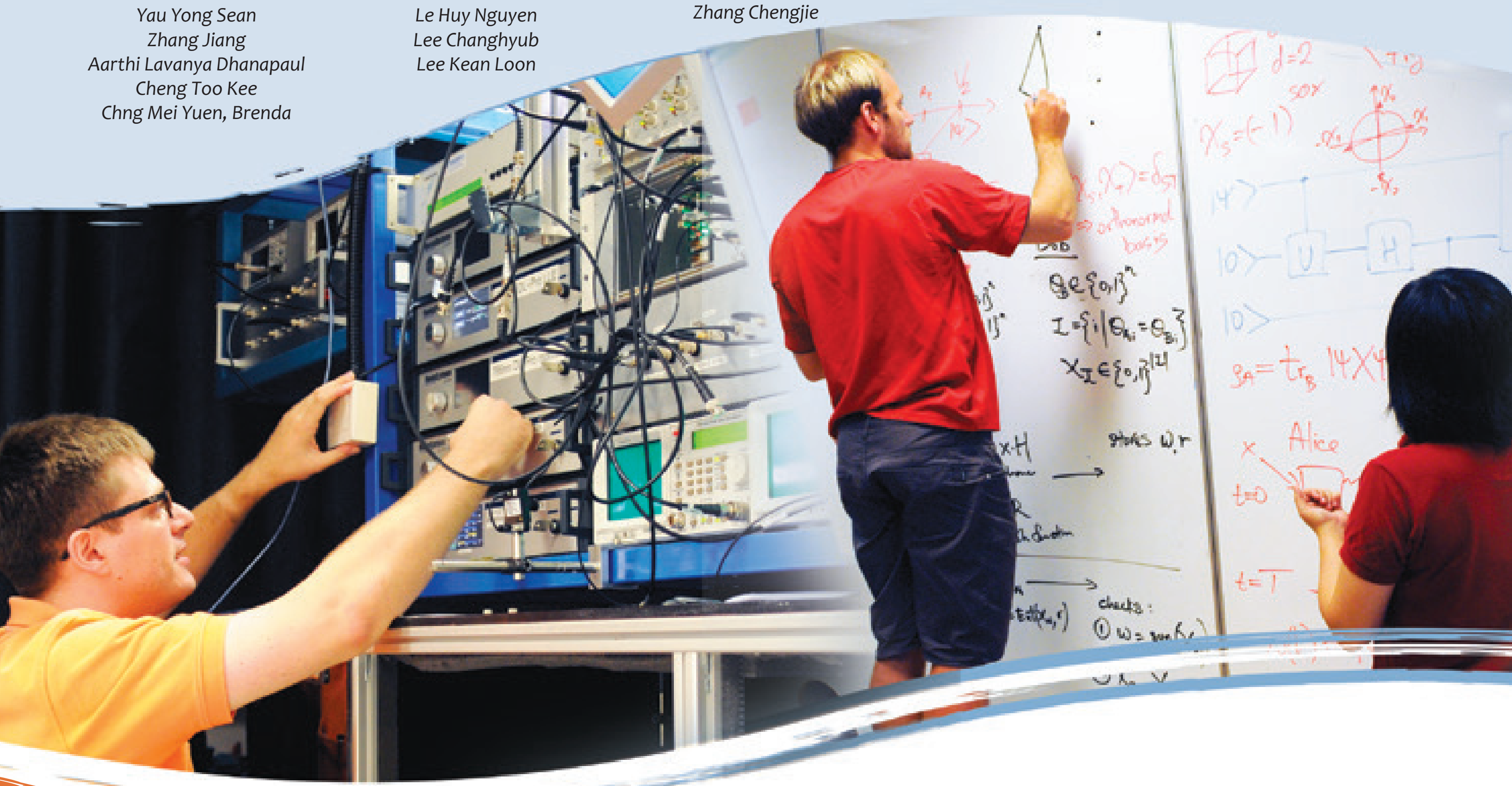
Masahito Hayashi
Miklos Santha
Miniatura Christian Pierre-Marie
Paolo Zanardi
Rosario Fazio
Thomas Francis Gallagher



Administrative staff

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Frederic Leroux
Wei Nie
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Tarun Dutta
Swarup Das
Han Jingshan
Aarthi Meenakshi Sundaram
Ewan Franek Munro
Anurag Anshu
Priyanka Mukhopadhyay
Sanjib Ghosh
Nguyen Chi Huan
Ye Luyao
Gan Huat Chai Jaren
Jungjun Park
Marek Wajs

Our annual review

What did the Centre's Scientific Advisory Board have to say about us in 2013?

The eminent scientists on CQT's Scientific Advisory Board visit Singapore every year to review the Centre's activities. Their visit in August 2013 included a celebration for SAB member David Wineland, who shared the 2012 Nobel Prize in Physics "for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems". The audience overflowed the 200 seat auditorium at the Asian Civilizations Museum, where he gave a public talk that was followed by a reception.

Celebrations aside, the SAB put the Centre under scrutiny. SAB members met with each Principal Investigator individually and with groups of postdocs and students. They not only considered the details of CQT research and management, but also assessed the Centre's status in a global context.
The 2013 SAB report comments that CQT "is recognized and respected worldwide as one of the reference research centers in quantum information science."

The report continues "We view this current state of CQT as the successful completion of a start-up phase. It is now time to move into the next stage in order to take advantage of this hard-fought position on the world stage and reap the fruits of the substantial investments already made and the hard work of many stakeholders. The key to this next stage will be the setting and attaining of new and more ambitious research goals that leverage the broad and deep range of expertise at CQT. CQT can thus strengthen its leadership position in quantum information science and technology globally".

About people

In December 2013, CQT completes its sixth year of operation. The number of researchers at CQT is now fairly steady at around 200, including an evolving family of postdocs and students. "CQT is now a stronger magnet for talented students, postdocs and faculty, and should take advantage of this not just to preserve, but to enhance its research potential and reputation, especially in the face of growing competition world-wide. It can and should compete more directly with other leading institutions for international stars," says the SAB report.

CQT researchers and students enjoy certain benefits, which the SAB highlights as valuable. "In its future evolution, the privileges of membership in CQT (including teaching reductions, stipends, and financial support from CQT funds) will continue to play a central role in attracting and retaining the best talent, and in facilitating research at the highest level."

"We reiterate the importance of investing effort into recruiting the best graduate students," writes the SAB "…the quality of the PhD students is crucial to achieving the highest level of excellence pursued by CQT." So far, so good, according to the report. "CQT continued to attract good students overall. In general, they seem to be doing well both in their coursework and in their research."

The SAB has also recommended that CQT maintain ties with its alumni.

Research advantages

In the 2013 report, the SAB looks back at suggestions made last year to increase integration. "One of the unique features of CQT is the juxtaposition of expertise across several aspects of quantum information science. We emphasized the importance of continuing to explore and implement practical ways of enabling researchers to be aware of the work going on in other groups and the expertise residing across CQT. This is an important area where CQT has a competitive

advantage over most other quantum information groups in the world."

Some activities have started: a Journal Club by students, a lunch-time 'pizza session' for PIs to discuss scientific ideas and tutorials organised by Stephanie Wehner's group. "We are pleased to see these initiatives, and encourage CQT to continue (and where appropriate, expand) the initiatives that are working, and to explore ways of improving or replacing initiatives that are not as successful," the SAB writes.

On the experiments at CQT, many of which have been in build-up phase, the report comments: "The visibility of the experimental groups has been increasing as more groups have established themselves and move towards producing publishable results. It remains important for the newer groups to produce publications even in these early stages of set-up".

Collaborations

CQT has collaborations with researchers around the world. The SAB emphasises the importance of this: "The benefits are clear: better access to cutting-edge knowledge worldwide, better visibility and impact for CQT research and researchers, supporting recruitment, and enhancing career success for trainees who leave CQT." The SAB makes the further recommendation "that students/postdocs/research assistant travelling abroad for conferences or workshops attempt to take advantage of these opportunities to incorporate one or more additional visits to research groups."

One particularly strong collaboration is between CQT and the French public research organisation the Centre National de la Recherche Scientifique (CNRS), backed by the formal creation of an International Associated Laboratory (LIA) in 2011. "The CQT-CNRS collaboration has continued to be very productive," comments the SAB.

Through some of its research projects, CQT has also begun to forge connections with industry. "Last year we were pleased to see the first steps in the development of links to applications and industry," the SAB writes. "Since then, Dr Serguei Beloussov, Senior Founding Partner, Runa Capital, has become a new CQT Governing Board member, and is expected to provide further links with industry. We encourage CQT to continue to find meaningful and appropriate ways to expose CQT researchers to industry, and vice versa."

Future plans

CQT is entering a new phase in its funding, with core support from Singapore's National Research Foundation (NRF) and Ministry of Education (MOE) increasingly supplemented by competitive grants. "We are very pleased to see that PIs at CQT have been successful at attracting large competitive funding awards, and we encourage the PIs to continue seeking such opportunities when possible and appropriate. It would be appropriate to explore the possibility of awarding part of CQT funding in the form of matching grants, or more strategically to the most competitive or novel proposals," says the SAB.

The SAB also lent its support to CQT's semi-autonomous structure. The Centre is hosted at NUS with additional laboratories at NTU and, in many procedures, follows the university practices. In other areas CQT has license to set its own policies, with the oversight of a Governing Board that includes representatives of NUS, NRF and MOE.

"CQT's current level of autonomy has been crucial in attaining its current level of excellence. Its continued autonomy will be even more critical to carrying out a bold vision for the future of CQT, working in collaboration with NUS and NTU (and perhaps SUTD in the future). For example, CQT must continue to drive strategic recruitment of faculty, fund top-ups, support its communications and outreach activities, strategically fund research projects, and so on."

News in brief

$10 million for randomness research

In February, a team of 13 Principal Investigators led by Valerio Scarani won a large grant from Singapore's Ministry of Education (MOE) to study randomness in all its quantum forms. The project will explore where quantum randomness will be useful, how to characterize it and what technologies to use to produce it. Outcomes of the project could include devices with commercial potential - some companies are already marketing quantum random number generators - and fundamental advances opening new lines of research. The grant is worth approximately S$10 million over five years.

Film and fiction competitions achieve international reach

CQT has run a series of Quantum Shorts competitions calling for people around the world to take inspiration from quantum physics. The 2012 competition sought films no longer than three minutes and the 2013 competition is seeking ‘flash fiction’ – stories no longer than 1000 words. Organised as part of CQT’s outreach effort, the competitions encourage creative learning about quantum physics and raise the profile of research in Singapore internationally. In 2012, the winning film was “Quantum Daughter” (pictured) from a team in Australia, featuring a multiverse-hopping girl with a banana-shaped quantum computer phone.

Major conference coming to Singapore

In June, it was announced that CQT had won its bid to bring a prestigious biannual physics conference, the International Conference on Laser Spectroscopy (ICOLS), to Singapore in 2015. Strong overlaps with the research carried out in CQT's experimental labs make ICOLS an exciting meeting for CQTians to bring to their neighbourhood. The conference will draw between 200 and 300 scientific experts, who will have opportunities to sample Singapore’s attractions as well as the conference's scientific updates. ICOLS will build on CQT’s success in organising other conferences in Singapore (see pp. 28–29).

For more news

Keep up to date with CQT news and events throughout the year by signing up to our email newsletter at http://quantumlah.org/mailing-list

Fellows win awards

Two CQT Senior Research Fellows were awarded prestigious fellowships by Singapore's National Research Foundation in 2013. Troy Lee and Joseph Fitzsimons each received a grant of up to S$3 million to establish their own research groups. Troy is exploring the power of quantum algorithms and calculating the resources needed to solve particular problems. Joe is developing techniques for verifying the correctness of quantum computations. Both researchers remain affiliated with CQT after being awarded tenure-track positions at local universities: Troy is an Associate Professor at Nanyang Technological University and Joe is an Assistant Professor at the Singapore University of Technology and Design.

Congratulations to our graduates

Seven students from the PhD@CQT programme collected their degrees in 2013, following in the footsteps of the first student to graduate from CQT's programme in 2012. We congratulate them and look forward to following their careers. For more information about PhDs at CQT and a full listing of our graduates and their theses, see pp.32–33.

Singapore universities rank highly

CQT is hosted at the National University of Singapore (NUS), which awards graduate degrees to CQT PhD students and co-appoints Principal Investigators. NUS performed strongly in this year's world university rankings. It was 24th in the Quacquarelli Symonds (QS) World University Ranking 2013 and 26th in the Times Higher Education (THE) World University Rankings 2013-14. Phil Baty, Editor, Times Higher Education Rankings, said "NUS has established itself as a true global force – a magnet for global talent with particularly outstanding scores for its international outlook. NUS is not just rising in status in the Asia-Pacific region, but also proving its excellence against the best that the US, UK, Canada and the rest of Asia has to offer."

CQT has additional staff and laboratory space at the Nanyang Technological University. NTU was ranked 76th in the THE World University Rankings and 41st in the QS World University Ranking, where it is the fastest-rising university in the top 50 universities.

Small, fast and precise:

the promise of quantum technology

Technology entrepreneur and research advocate Serguei Beloussov joined CQT's Governing Board in 2012. He sees a bright future for quantum devices

I founded the Russian Quantum Center in 2010 with the goal of helping researchers and institutions connect with one another to build understanding and advance innovation at the quantum scale. The RQC shares a common mission with the Centre for Quantum Technologies, and we are fortunate to be able to collaborate.

I am also a managing partner of a venture capital fund focused on materials sciences and quantum physics, QWave Capital. My colleagues and I believe very strongly in the potential of quantum physics-based technology to revolutionise nearly every industry in the coming decades.

QWave Capital isn't the only investment fund to notice the potential. Mike Laziridis, inventor of the BlackBerry phone, has long funded basic physics research through the Perimeter Institute for Theoretical Physics and, more recently, the Institute for Quantum Computing in Waterloo, Canada. He started Quantum Valley Investments in 2013.

As a board member at CQT, I want to encourage the Centre's researchers to review all opportunities – patents, tech licensing and spin-outs – to promote commercialisation efforts in the scientific community. I sometimes feel there is skepticism in academia about the viability of quantum technologies outside of the labs. What I see in industry is evidence that quantum technologies can succeed, delivering fast, precise and energy-efficient devices.

There are already a handful of very impressive companies bringing quantum innovations to market. These companies manufacture real devices that ship to paying customers. My hope is that these examples will encourage and inspire further connections between scientists and entrepreneurs and catalyse partnerships that will speed up the quantum revolution.

Real devices, real customers

My favorite quantum technology company, one that QWave Capital has invested in, is ID Quantique (www.idquantique.com). Founded in 2001 by scientists from the University of Geneva, it was the first company to ship quantum-based secure communication solutions to customers in 2004. ID Quantique provides financial institutions and several governments with point-to-point data encryption solutions that are impossible to breach now and will remain impossible to breach tens of years from now. The security stems from quantum theory's no-cloning theorem – the underlying physics guarantees protection from eavesdropping even if somebody is listening and has massive computing power. If you follow the news, you'll know about the 'listening' on today's communication channels. It was not a revelation for security practitioners.

QWave Capital is also an investor in Centice (www.centice.com), a company with expertise in drug detection and identification. Centice improved one of the oldest practical quantum technologies, Raman spectroscopy, to enable detection of single molecules. The solution makes non-invasive testing quick and easy with a device that fits into a standard briefcase. This allows law enforcement agencies, for example, to rapidly identify drugs in the field. There are also huge pharmaceutical implications for this technology in the future.

Precision measurement, or metrology, is another field where quantum technologies could have huge implications. An interesting company here is Symmetricom (www.symmetricom.com). Symmetricom has developed extremely low power, chip-sized atomic clocks using a quantum technology known as coherent population trapping (CPT).

the man means business

Serguei has a 20-year track record in building, growing and leading high-performing multi-national technology companies. He has founded and led three technology companies that became market leaders in their respective industries and attained annual revenues in excess of US$100 million. He has coauthored close to 100 patents and received over 50 awards for products and technology. Serguei is also the founder of the Russian Quantum Centre and a managing partner of a venture capital fund focused on materials sciences and quantum physics, QWave Capital. A Russian-born Singaporean, he joined the Governing Board of CQT in 2012 as a representative of industry. He has a BS in Physics, an MS in Physics and Electrical Engineering and a PhD in Computer Science from the Moscow Institute of Physics and Technology.

The chips bring reliable autonomous timekeeping to applications and fields where an atomic clock would not have previously been considered due to space and/or power constraints. For example, a network of cheap self-powered sensors could be deployed over large territory for undersea oil and gas exploration. With time and further development, similar chips might find their way into every smartphone as a basis for ultra-precise sensors of all kinds – physical, chemical or biological.

As of October 2013, Symmetricom had reached an agreement with Microsemi Corporation to be acquired for approximately US$230 million.

Where Do We Go From Here?

These are just three examples of ways that fundamental science is being developed and applied today. Connections between research centers, scientists and industry are vital to keep this up. We must continue to practice fundamental science and to study materials in depth to gain more knowledge about our world. And we must not shy away from the practical implications of what we discover. As scientists and researchers, we need to encourage and support commercialisation in order to bring the most good to the most people.

Keeping CQT

the coolest place on the equator

Cold fermions created in Kai Dieckmann's lab make the team internationally competitive on a hot topic

Back in 2009, CQT claimed the title of coolest place on the Equator after one of its experimental groups created Singapore's first ultra-cold quantum matter. Atoms cooled to near absolute zero – the coldest temperature possible – are now found routinely in CQT's labs. But what Kai Dieckmann and his team have done is out of this extraordinary ordinary: they have cooled three species of atoms simultaneously. It's a goal the group has been working towards since 2010. "This milestone is an entry ticket to competitive science at the highest level," says Kai.

Since June 2013, the team have been reliably achieving a 'triple degeneracy' in their experimental setup: that is, cold rubidium (^{87}Rb) atoms trapped simultaneously with cold potassium (^{40}K) atoms and cold lithium (^{6}Li) atoms. The experimental goal is to study the physics of dipolar molecules formed when ^{40}K pairs with ^{6}Li. The team plan to build a 'quantum simulator' using these dipolar molecules as building blocks. Once the researchers have mastered precise control over the molecules' interactions, they can fine-tune the interactions to mimic real materials and study their properties.

"It is a hot topic right now. Initial work was done at Boulder and Innsbruck. Now groups at MIT, Munich, Paris, and elsewhere have joined the race to demonstrate successful approaches in their second generation of enhanced setups like ours," says Kai.

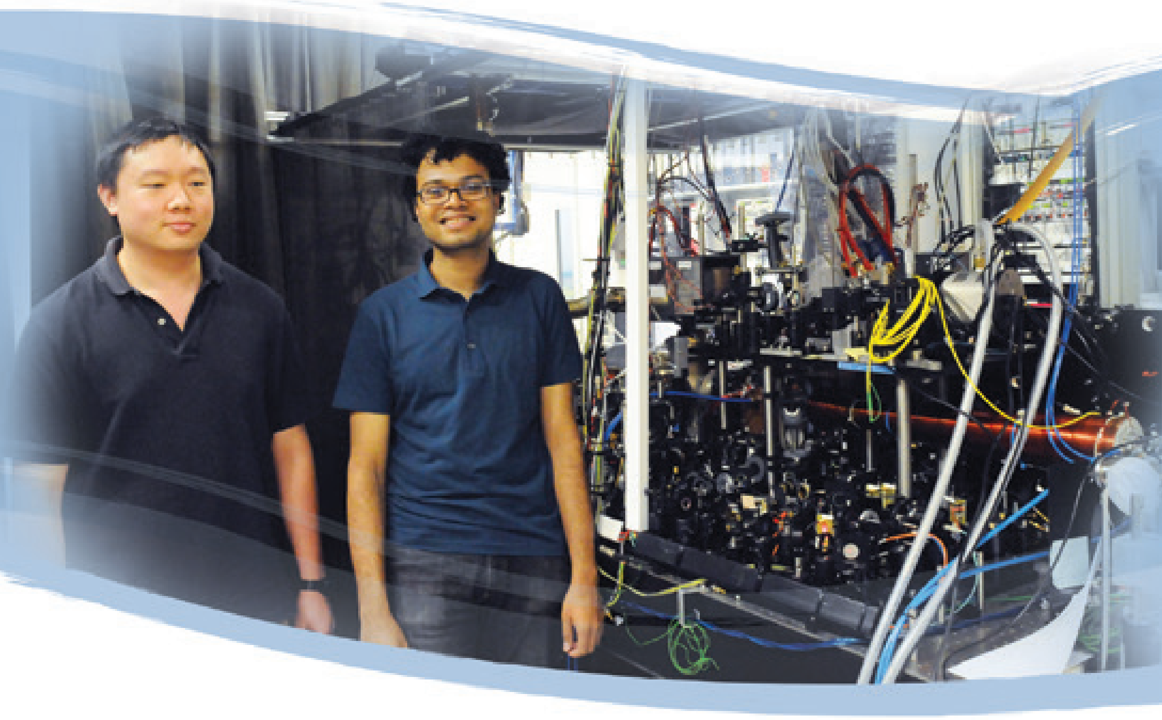
In it together

Lithium and potassium are types of atom known as fermions, and rubidium is a boson. This difference in classification, arising from the quantum 'spin' of the atom, means that lithium and potassium are much harder to cool than rubidium. In the Fermi–Fermi mixture experiment, the ^{87}Rb is cooled first and then helps to cool the two fermions. All are cooled to a temperature of around 500nK when they are described as degenerate, meaning they are in their lowest possible energy state.

In practice, this means that the atoms' motion has been brought almost to a standstill. Absolute zero temperature represents the

Steady does it

An optical frequency comb installed as a shared facility in 2011 stabilises lasers around CQT, keeping their frequency steady. This steadiness is necessary in the precision experiments carried out by the Centre's researchers. Johannes Gambari, the Research Fellow who manages the comb, says the past year has seen improvement in the comb's short-term stability thanks to a slow lock. You can see for yourself how steady the laser is by following it on Twitter @FermiMixture. The laser tweets every three minutes to help Johannes track fluctuations in the frequency to mHz. "Essentially from one number, I can know if I can be somewhere else or I have to run down to the lab," he says. (To the general reader, the comb's tweets every three minutes are likely less than thrilling. A typical example is "$Repetion rate at 2013-06-12 05:47:24.692857 is 250004164.359 Hz".)



CQT PhD students Mark Lam (left) and Sambit Pal (right) have mastered a complex experimental setup to produce a 'triple degeneracy' of cold atoms.

temperature at which all motion would have ceased. Atoms at room temperature move at hundreds of metres per second. At the nano-Kelvin temperatures achieved in the experiment, the atoms are moving only at millimeters per second. These cold, slow atoms form a small cloud about 0.2mm in diameter, which floats inside a vacuum in a steel chamber. The atoms are held in place by electromagnetic fields in a magneto-optical trap (MOT), where they can be imaged (pictured below). The team can currently trap more than 100,000 atoms each of rubidium and potassium and approaching 100,000 lithium atoms.

The next step for the team is to increase the atom numbers to reach the team's science goal of studying dipolar molecules and using them as a quantum simulator. They will also need to put the molecules into their vibrational and rotational ground state by implementing a technique known as 'Stimulated Raman Adiabatic Passage' using CQT's optical frequency comb (see box “Steady does it”).

LiK molecules in their absolute ground state can be polarised by an external electric field to have a large electric dipole moment, leading to long range dipole-dipole interactions. When the molecules are confined in an optical trap of suitable geometry, external DC and microwave fields can be used to tune the long-range interactions to mimic the behaviour of other materials. For example, molecules arranged in a hexagonal lattice might simulate the carbon material graphene. The ability to change parameters in this simulated system should make it possible to test the relevant 'spin-lattice' models in ways not possible by other techniques. Having control over the interactions would also pave the way for modelling and designing novel artificial materials that do not exist in nature.

Student powered

Kai gives credit for reaching the triple degeneracy to his PhD students Sambit Pal and Mark Lam. "It is too early for celebration," says Sambit, "but we've got it and we've got it reliably".

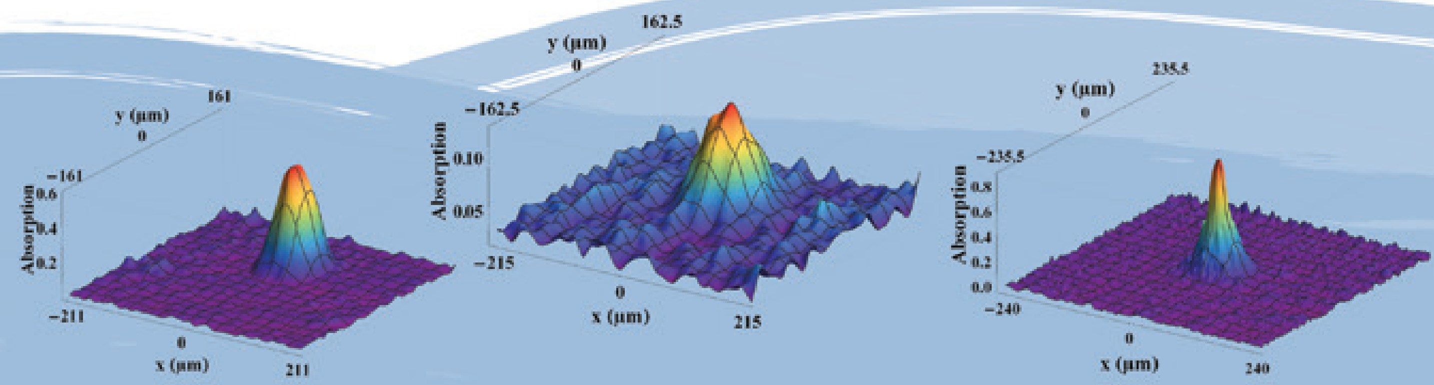
The 'reliably' is crucial. The team first achieved triple degeneracy last year but it proved to be short-lived. After a few successful runs, most of the cold Li atoms went missing. The graduate students spent months tweaking the setup: they adjusted lasers (the optics for the setup cover two large tables), timings and temperatures. This was very helpful for learning the ins and outs of the setup, but it didn't reveal the source of the problem. "We were a bit frustrated," recalls Sambit. Eventually, having ruled out everything else, they opened up the vacuum chamber to see what was happening inside. This is the last thing to check because once the chamber is opened, the whole system will have to be cleaned by 'baking' it for three weeks before the air is pumped out and experiments can begin again. But it was the right decision, recalls Sambit, "We had found the culprit. The lithium oven was in a completely messed up state." Now, with the parts replaced and the problem fixed, the experiment is back on track.

"The graduate students have mastered an advanced experimental setup that was running in a competitive field before" says Kai. He moved parts of the experiment to Singapore from his former laboratory at the Ludwig-Maximilians-University of Munich, Germany. "The circumstances were difficult because nobody moved along from Germany. Special credit should go to Sambit and Mark who are on a steep learning curve and are hardworking. Now this first generation of students is on top of things, the usual passing on of information between the generations of graduate students on a working setup should make work much easier in the future."

The student perspective

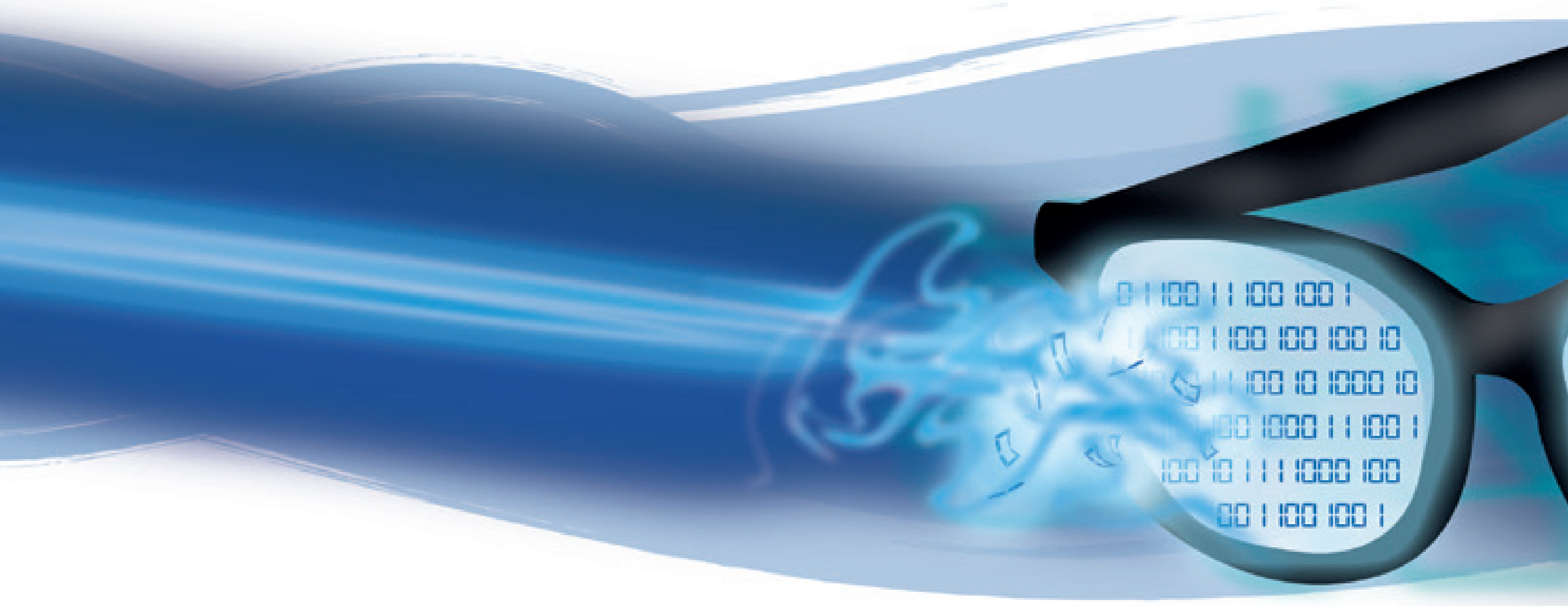
By Sambit Pal

I visited Kai's lab for a week during the last semester of my Master’s degree and was fascinated by the Fermi-Fermi project. This led me to join CQT's PhD program in 2011. Kai had moved his project to Singapore in 2010, and I have felt pressure to re-assemble the experiment as fast as possible so that we can redo and then build on his previous work. There have been several ups and downs in the lab. Although it is frustrating at times, I accept that this is part and parcel of experimental science. We have also had our moments of excitement, in particular when we got back the ultracold mixture of Li, K and Rb. It’s these signs of progress that spur us forward and keep our spirits up. The feeling that you get when you find a solution to a problem after days of tweaking is indescribable. It will be rewarding to make even a small contribution to the project's long term goals through my PhD work.



These plots show early experimental data mapping the trapped fermions. The atom clouds are detected by 'absorption imaging': a laser beam is shone through the cloud towards a camera. Because the atoms scatter light, the atom cloud creates a shadow that is darkest where the atoms are densest. The plots are three-dimensional representations of the darkness of the shadow for ^{40}K (left), ^{6}Li (centre) and ^{87}Rb (right).

Through the



We put some questions to PI Stephanie Wehner, whose group specialises in applying information theory to quantum systems

What's new?

Looking at physical questions through the glasses of information theory has generated quite a number of exciting results lately.

What do you mean by the 'glasses of information theory'?

The term glasses of information theory means that we like to view problems from the perspective of information theory – that is, we like to think of physical processes as a computation that is processing information.

Personally, I think we are at a very exciting point in time. Maybe for the first time in history, tools developed for quantum information theory allow us to really understand how information behaves in very tiny physical systems where entanglement and other quantum mechanical effects are relevant. We find that information there behaves in rather different and surprising ways, and we are slowly starting to see what this means for our understanding of physics.

Can you give some examples of this approach?

A good example is given by uncertainty relations. Instead of the traditional way of thinking about them involving measurements of physical properties such as position or momentum, we think of measurements as retrieving information from an encoding. An uncertainty relation can then be understood as a limit on how well such information can be retrieved. This is a purely conceptual step, but it has been very effective in understanding the relation between uncertainty and non-locality, for example.

We use a large variety of mathematical tools drawing from statistics, abstract algebra, representation theory and harmonic analysis.

How, historically, has information theory come together with quantum physics?

I don't think these events, or I, have been around for long enough to take a historical point of view!

There has always been a strong relationship between physics and information theory, mostly in the area of thermodynamics. For example, information theory plays a role in Maxwell's demon, a thought-experiment conceived over a hundred years ago. The demon is imagined to break the second law of thermodynamics – that systems tend to equilibrium – by creating a temperature difference between two connected compartments of gas. The demon uses information about the speed of the molecules in the gas to choose whether or not to allow them to pass from one side to the other.

What are some of the exciting results?

I very much enjoyed a result by the group of Renato Renner at ETH Zurich with some of my CQT colleagues that shows that in the quantum regime, one can gain work by erasing a quantum memory as long as one is entangled with it ("The thermodynamic meaning of negative entropy", *Nature* 474, 61 (2011)). This is in sharp contrast to the classical regime where erasure always costs work. Of course, it's a consequence of entanglement, which we already knew could cause certain informational quantities to be negative. I like the result because

glasses of information theory

it attaches a very physical consequence to this information-theoretic phenomenon.

... and from your group?

A result of my own group that I like very much is the second laws for quantum thermodynamics, which we obtained in collaboration with Jonathan Oppenheim and other researchers in Europe. This work is available as a preprint at http://arxiv.org/abs/1305.5278.

From experiment and our considerable experience in building large machines over the past 100 years, we know the laws of thermodynamics are very successful. But we find that the standard second law that we know from large systems is not enough to describe thermodynamics applied to small systems, i.e. the tiny machines that we can now build. Instead, we find that there is an entire family of second laws, that is, a whole set of equations that dictate thermodynamics behaviour at small scales.

The usual second law belongs to this family but there are many others. When applied to large systems, all such equations converge to the standard second law. This was very satisfying for us: we explain why for large machines the standard second law is all we need, and we explain it starting from first principles.

Our work discovering the relevant laws for small systems is important because we can now build machines that are very small, such as quantum computers and nano-machines.

Are there other open questions that can be tackled this way?

I think the area is presently wide open. Let me give just one concrete example related to quantum thermodynamics: we are presently examining the study of efficiency and power for extremely small machines. It turns out that even coming up with a good model is a non-trivial task.

It is a lot of fun to work in this area right now because there are so many fundamental questions to be resolved.

What hopes do you have for the field?

When it comes to science itself, I am already convinced that we will discover much more about physics on a theoretical level by using quantum information. I am also convinced that it will help us build new things, for example, that we will eventually build a quantum computer. Indeed, quantum cryptography has already reached a very feasible, practical regime.

I think there are some things to hope for when it comes to the non-scientific aspects of quantum information. Namely, I hope that traditional physics and computer science research will unite to realise the opportunity presented by quantum information.

When the Small Photon-Entangling Quantum System passes out of the protective blanket of the Earth's atmosphere, it will be exposed to radiation damage. Tests are showing how much radiation the package can tolerate. This photo was taken from a weather balloon carrying SPEQS components.

Radiation alert!

Can a quantum experiment survive in space?

The SPEQS payload will test technology for satellite-mediated quantum communication. Research Assistant Tan Yue Chuan presents results of pre-flight trials

To conduct a quantum entanglement experiment in space, we have to tackle some major challenges. Our first task was to shrink a lab-sized experiment into a 300 gram package for launch into orbit. We've got a design that does that. Now we're worrying about another problem: radiation damage.

Our Small Photon-Entangling Quantum Source (SPEQS) is a device to produce and measure entangled pairs of photons. We aim to launch it into low earth orbit (LEO) on a CubeSat – a standard small satellite – as a step towards long-distance entanglement distribution for tests of fundamental physics and for quantum communication. See the box "Countdown to lift-off" for the latest on our launch plans. Our SPEQS prototype meets the size, weight and power requirements of a CubeSat payload but we have to be sure that it is robust enough to withstand launch and the conditions in space.

To that end, we've conducted various tests of the payload. We've flown SPEQS subsystems into the upper reaches of the atmosphere on a weather balloon, twice, and we've undertaken some detailed testing of the damage the SPEQS components will suffer when exposed to radiation.

Space missions are susceptible to damage from electrons and protons trapped by Earth's magnetic field, from solar particles and from gamma-rays, which is high energy radiation from astronomical sources. The avalanche photodiodes (APDs) that we use to detect single photons, when damaged by radiation, will start to record a higher number of false detections (a dark count). Before we conducted our experiments, there was no available data on how quickly the APDs' performance would degrade under space conditions. We also tested the effect of radiation on other components of SPEQs including the microprocessor, flash memory, logic components and voltage supply. We used a piece of software called the Space Environment Information System (SPENVIS) from the European Space Agency to estimate the amount of radiation our payload would experience in different orbits, then exposed our SPEQS parts to this dosage at test facilities in Singapore and in the US.

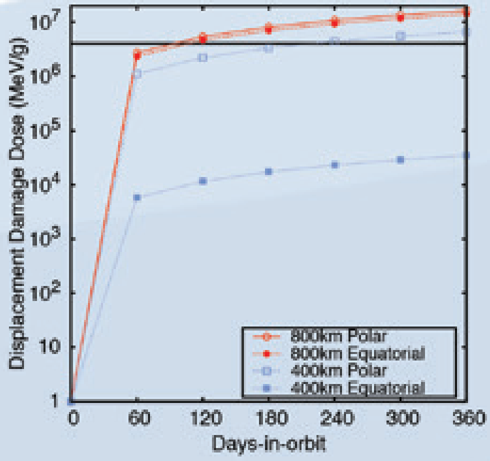
What's the damage?

There are two radiation damage mechanisms that we need to investigate, namely ionising damage and displacement damage. Ionizing radiation, such as gamma rays or charged particles, striking an electronic device may ionise atoms in the material, creating electron-hole pairs. These charges can get trapped and cause charge accumulation that changes the devices' electrical properties. We were able to test our system's susceptibility to ionising damage at NUS thanks to the Centre for Ion Beam Applications which houses a Co-60 gamma chamber. We exposed the device to up to a 5krad total dose, which is equivalent to one year of damage for our payload in an 800km polar orbit behind 1.85mm aluminium shielding. We were pleasantly surprised to find that for most of the components the radiation tolerance was very good. The APDs' dark count did increase, but we could live with the size of the change and still carry out our science mission.

Displacement damage is when atoms in a material get knocked out of place. Again, this can change the device's electrical properties. For a spacecraft orbiting in LEO, the main culprit causing displacement damage is protons. We calculated the displacement damage dose for different orbits by combining SPENVIS data with information on how

Countdown to lift-off

CQT has become an official partner in the European Union-sponsored QB50 project – an initiative to launch 50 CubeSats in 2015. Each CubeSat will consist of two or three 10cmx10cmx10cm units. CQT is collaborating with the NUS Department of Engineering to contribute a satellite from Singapore that will include the SPEQS payload.



The team's experiments point to a 'threshold' radiation exposure above which a key component of SPEQS – the single-photon sensing avalanche photodiodes (APDs) – stop being useful due to elevated 'dark count', or noise. This threshold is plotted as a dark line in the figure above. The estimated radiation exposures for different orbits show that the APDs should survive for the lifetime of the CubeSat in an equatorial orbit.

much energy protons deposit in silicon in non-ionising events. Silicon makes up the bulk of our sensitive components. Test devices were then taken to Crocker Nuclear Laboratory at the University of California at Davis (see box "Testing at a nuclear lab"), which has a cyclotron producing proton beams, to see how they stood up to these doses.

We found that the flash memory used in SPEQS for temporary storage of the experimental results was prone to radiation-induced damage. Entire sectors of data had been flipped, a problem we need to be prepared for. As in the ionizing damage test, the APDs were also affected, and the increase in dark count due to proton irradiation was much greater than that caused by gamma radiation. We identified a threshold dosage of 4×10^{6} MeV/g above which the dark count rate at room temperature becomes so high that it saturates our circuits, flushing away true events. This threshold can act as a guide to estimate the lifetime of our payload in a given orbit, as shown in the figure above.

In conclusion, our tests reveal that the high efficiency detectors on the SPEQS instrument will work for the estimated lifetime of the CubeSat. For longer duration missions, we will need to evaluate if a different detector design that trades-off efficiency with radiation cross-section will be a better choice. The alternative is to use a dedicated CubeSat that can supply cooling to the detectors (currently our CubeSats are shared with many other experiments so we are limited in electrical power). We can operate the APDs for longer if we cool them down to say -20C during operation.

The results of our radiation tests were published in July 2013 ("Silicon avalanche photodiode operation and lifetime analysis for small satellites", *Optics Express* **21**, 16946 (2013)). We are looking to perform more radiation tests on our components, especially on APDs of different designs and from more than one company. And the SPEQS package as a whole faces a battery of tests before launch. Space qualification involves thermal cycle tests, vacuum tests and vibration tests. We want to be as sure as we can that the device is going to work when it arrives in orbit.

Testing at a nuclear lab

by Cliff Cheng

On 18 November 2012, I touched down in San Francisco after a long flight across the Pacific Ocean. I had a 2.5 hour drive up to the campus of the University of California at Davis and I set off across the Bay Bridge on the Interstate Highway I-80. My destination was the Crocker Nuclear Laboratory (CNL), home to a 76-inch cyclotron built in 1965. The cyclotron is used for air quality research, the treatment of ocular melanoma and to study the effect of radiation on electronic systems used in space missions. I was going to test parts of the quantum payload we want to send into low earth orbit. TriVector, a US-based company, had helped arrange for us to use the CNL facilities.

My host at CNL was Dr Carlos Castenada, who welcomed me into the huge structure that houses the cyclotron. When we went into the dungeon where the particle experiments take place, we had to wear dosimeter badges to check how much radiation we were being exposed to. Inside the inner lab, we fixed our devices within the aperture and range of the particle rays. Before the ray was turned on, we exited the inner lab through a heavy water-filled tank on rollers, which acted as a door, and took protection behind massively thick concrete walls. We did the set of experiments that we had planned at different proton energies of 5MeV, 25MeV and 50MeV. We had to wait until the next day, after the radiation effects on our component had decayed to an acceptable level, to pick up the parts. We completed testing of the parts back in Singapore. We identified the avalanche photodiodes and flash memory as the most sensitive components (see main article). It was an exciting and enlightening experience for me to conduct experiments at a cyclotron.

Reality Lost was filmed in locations around Singapore including this boat, on which documentary host and CQT PI Dagomir Kaszlikoswki (left) asked Vlatko Vedral (right) if quantum physics needs a new revolution.

Reality Lost

CQT's first Outreach Fellow Karol Jalochowski reports on the year he spent at CQT filming a documentary about quantum physics

This wonderfully crazy year has suddenly ended: nearly fifty filming days are over, dozens of miles of location scouting covered, forty hours of footage edited through, and finally, a one hour movie rendered off.

It was quite an experiment, a challenge of a magnitude I hadn't fully appreciated when I began. But that's the way things get done, right? Staying inside your comfort zone is always safe and cosy, but it inevitably leads to a slow thermal death.

The movie was supposed to be a series of short episodes. I started off imagining that I would make one episode to deal with the existence of reality and the problem of measurement, one with the quantum multiverse, and one with quantum aspects of biology. In the making, the project transformed itself. It went through a whole Darwinian evolutionary process, and I ended up not with a collection of parts but with a single hour-long, full-blown documentary movie. Reality Lost focuses on a single question, the most fundamental question among the philosophical consequences of quantum mechanics: does reality exist? (See synopsis, right.)

Making a documentary that deals with such an elusive yet mathematically well-defined subject matter meant using two boxes of tools simultaneously – those that are designed to spark the left, dead logical half of the brain, and those that tap the right half of the brain, which likes to fiddle with emotions. And you have to be kind, very kind to the latter.

My approach was to interweave the abstract with scenes of tangible life. Eight researchers agreed to take part in the project, to talk about quantum mechanics and what they think the theory means, to describe their contributions, their passions and their hopes. I filmed them in locations ranging from dense jungle to hazy roof-tops, old boats to busy eateries. In the final cut, these interviews are stitched together with B-rolls of birds, of dancing and of pottery-making at Singapore's largest surviving dragon kiln.

At the least, I want the film to show that science equals taking risks, that scientists resist failure more often than celebrating triumphs. It should show that there are conflicts and unfulfilments, but that there also exist those almost magical moments of discovery that help make our funny *Homo sapiens* creatures truly, fully human.

A project like this one, involving many strong, fiercely intelligent and independent people, has its own internal logic and dynamics. You can't fight it. You have to find the flow, search for the beat and follow it. Zen and The Art of Shooting a Documentary Movie - something like that… The project had to negotiate its way around obstacles of changing schedules, altering plans and cancelled visits, interpersonal idiosyncrasies, shifting weather conditions, equipment

Sequences filmed at Singapore's Thow Kwang Pottery Jungle contrast the earthy reality of clay with the notion of reality that quantum theory makes us confront.

malfunctions, location availability, and, most importantly, sail through the ocean full of icebergs of my own personal limitations and assumptions. But it's ready. It's there, and it's time to set it free. Now we are busy submitting the film to festivals and exploring other distribution options.

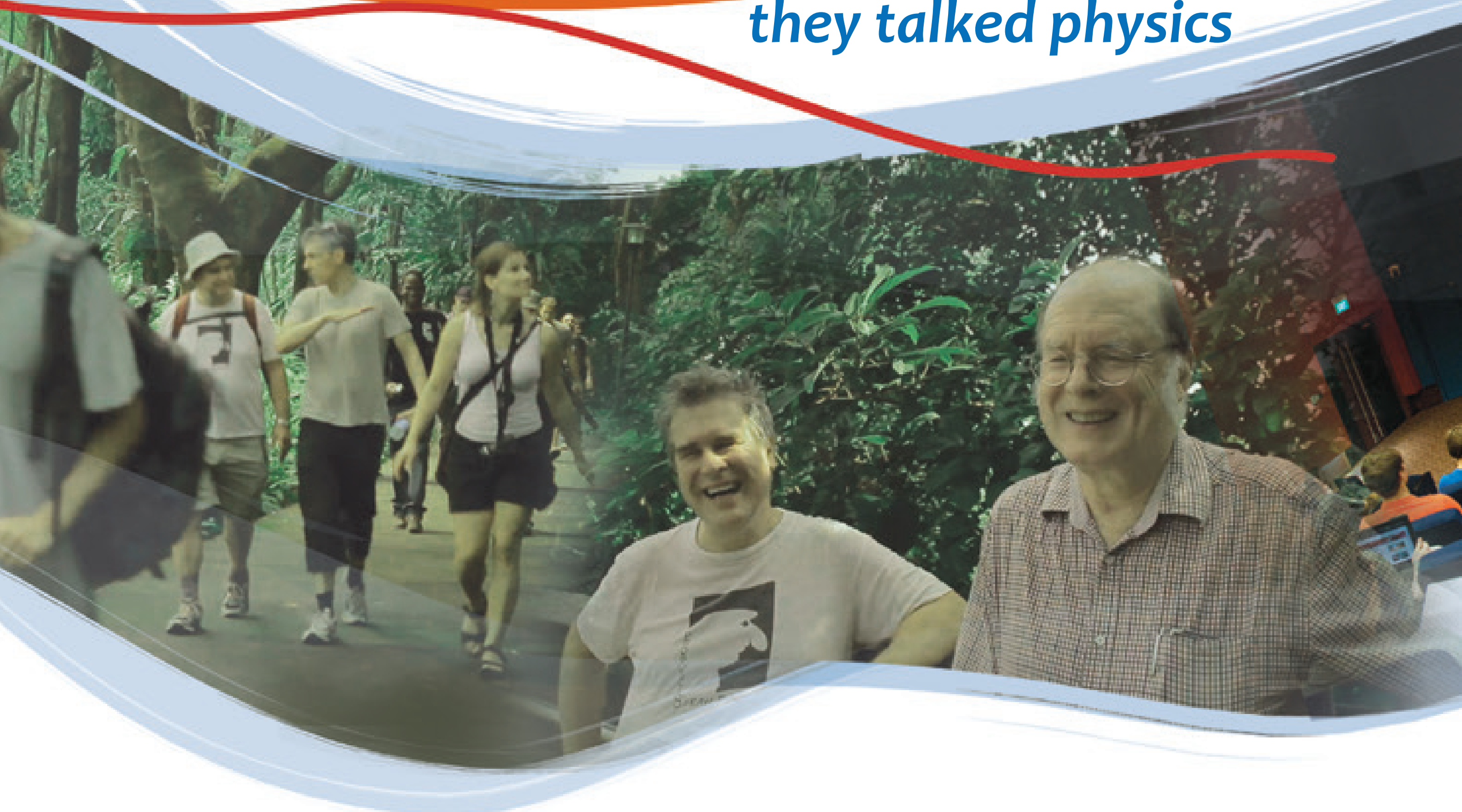
The fact that the movie is alive and hopefully kicking is thanks to the fellowship funded by CQT and NUS. The fellowship was liberating in having a loosely defined character, but there was also something deeply scientific in its core spirit. It was an experiment in the purest form. There were well defined boundary conditions, basic assumptions and all those fancy prerequisites. I hope the experiment has proven the hypothesis that one can make a non-trivial documentary movie on quantum physics to be valid.

If it doesn't work, put the blame on me. If the outcome works, it's thanks to a bunch of extraordinary people: Artur Ekert, who turned the green light knob; Jenny Hogan who made the light lit; Dag Kaszlikowski, the film's host, whose support cannot be overestimated; Charles Bennett, Gilles Brassard, Stephanie Wehner, Christian Kurtsiefer, Valerio Scarani, Vlatko Vedral – the researchers who decided to risk their reputation by participating in this project. There were also Faye Lim, Bernice Lee, Christina Chan, and Daniel Sahagun Sanchez (also a CQTian), local artists who made the movie literally dance. There were also ceramicists Steven Low Thia Kwang and Ng Yang Ce. Without them reality would have much less tangible a status. And, last but not least, there was Singapore, an amazing city state, the lab of the future, providing a multilayered visual context and the crucial subtext of the story line.

Reality Lost, the synopsis

At the beginning of the 20th Century, a major shift took place in science. Scientists started doing experiments with unprecedented precision - fiddling with single particles, atoms, and electrons. And they got bewildered. Small objects seemed to have sort of fuzzy properties. What's more, the very act of observing them, of measuring them, seemed to bring them to life, excavate them from a vague domain. The equations of quantum mechanics were beautiful. They generated astonishingly correct answers for mind-boggling questions about the exotic micro world. But there was a price to pay. Objective reality had to go. Was it regained?

They came, they saw, they talked physics



INTERNATIONAL EVENTS

QCRYPT 2012

10–14 September 2012 at National University of Singapore
http://2012.qcrypt.net

"It is great that QCRYPT, an annual conference first held last year, has already become a meeting point for everyone in quantum cryptography whether they work in experiment or theory," says Stephanie Wehner, the CQT Principal Investigator who led the local organising committee. Stephanie is one of the founders of the QCRYPT conference series. The meetings not only bring together experimental and theoretical researchers, but also those working towards commercialisation. It is the largest meeting on the topic. The 2012 conference held in Singapore included an industry panel discussion with speakers including the CEO of a company that has commercialised quantum key distribution systems, a representative from Singapore's DSO National Laboratories and an investor looking to fund quantum technology businesses. There were also industry exhibits.

- 163 registered participants (48 of them students)
- 1 keynote presentation
- 7 invited talks
- 4 focus tutorials
- 19 contributed talks (29% acceptance ratio)
- 66 posters

Mathematical Horizons for Quantum Physics 2

12 August –11 October 2013 at the Institute for Mathematical Sciences, National University of Singapore
http://www2.ims.nus.edu.sg/Programs/013mhqp/index.php

Structured as an intensive series of workshops, this programme co-organised by CQT and the Institute for Mathematical Sciences had the objective of bringing together scientists working on different many-body open quantum systems with people working on quantum information theory, to stimulate interdisciplinary contacts and contribute to the exchange of ideas. There were four overlapping three-week sessions, each devoted to a special topic.

- Session 1 : Quantum Information Theory
- Session 2: Information-Theoretic Approaches to Thermodynamics
- Session 3: Many-Particle Systems
- Session 4: Open Quantum Systems

Each session had around 30 participants and kicked off with presentations by 'discussion leaders', which hinted at new directions the speakers felt should be explored during the workshop. The participants then had 20 days to collaborate, presenting their progress in talks at the close of the session.

CQT has been involved in organising a number of conferences and workshops in Singapore

A casual explorer of Singapore's 'Southern Ridges' trail last September might have been surprised to meet a horde of trekking physicists. They would have found among them pioneers of quantum information such as Charles Bennett and Gilles Brassard, co-inventors of quantum cryptography (pictured left) and other researchers from around the world. These top scientists had come to Singapore to attend one of the many conferences that CQT has organised. In this case, it was QCRYPT, an annual conference on quantum cryptography that featured the Southern Ridge walk as an afternoon excursion.

One of CQT's roles as a leading global research centre is to organise conferences and workshops, both with international delegates and local events that build connections in Singapore's research and education communities. Here we present highlights from some of the meetings that CQT contributed to organising in 2012–13.

LOCAL EVENTS

Institute of Physics Singapore (IPS) Meeting 2013

4–6 March 2013 at Nanyang Technological University
http://www.ipsmeeting.org

The annual IPS meeting is a forum for Singapore researchers in the physical sciences to learn about each other's work. This year's meeting featured around 80 talks, 60 posters and exhibits by vendors. There were also special events held alongside the meeting: a workshop on nanoscience in conjunction with the UK's Institute of Physics and a symposium on disruptive photonic technologies. CQT provided organisational support and sponsorship.

Physics Education Seminar (PES) 2013

3-6 June 2013 at NUS High School of Mathematics and Science
http://pes2013.quantumlah.org

CQT was a co-organiser of PES 2013, a conference for Singapore's physics teachers and school administrators that attracted more than 100 attendees. First a one-day seminar offered perspectives on careers for science graduates, discussion of teaching methods and a 'learning journey' visit to a company or NUS. Teachers who visited NUS got a peek into CQT's quantum labs.

Optional extras were two 1.5-day workshops introducing in-class resources developed by the Perimeter Institute for Theoretical Physics, a renowned research centre in Canada. The first workshop covered the "Challenge of Quantum Reality" and "Measuring Planck's Constant", the second "The Physics of Innovation" and "Revolutions in Science". Feedback from the teachers was positive: "Exciting and inspiring! Cutting edge content and pedagogy that blew my mind," said Joanne Ng Li Min from Temasek Junior College, who participated in the quantum workshop.

Atom Chip Workshop

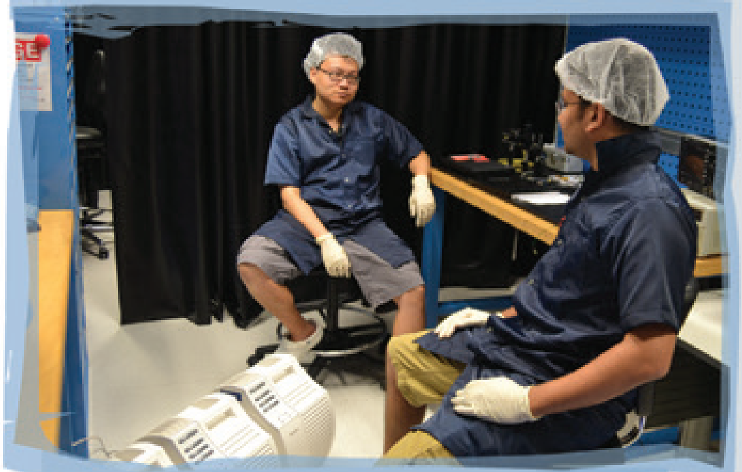
3–5 December 2012 in Pangkil Island, Indonesia

CQT has two groups working on related atom chip technologies, those of Rainer Dumke at NTU and Bjorn Hessmo at NUS. In 2011, the two PIs organised a workshop retreat on Pangkil, a little-developed island in Indonesia, to bring together their teams and invited speakers to share updates on their experiments and engage in focussed discussions. The event was so successful that it was repeated in 2012 and is scheduled to happen again in December 2013. For participants, presentations in a beach-side open-air venue and the lack of hot showers add novelty to a week that has proved productive for their science.

Student Life

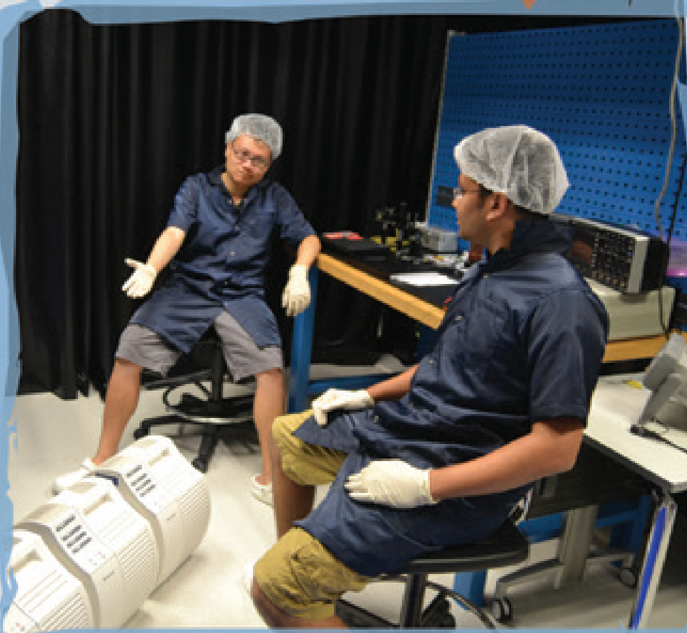
When we take refuelling breaks...

sometimes the conversations last longer than the coffee!



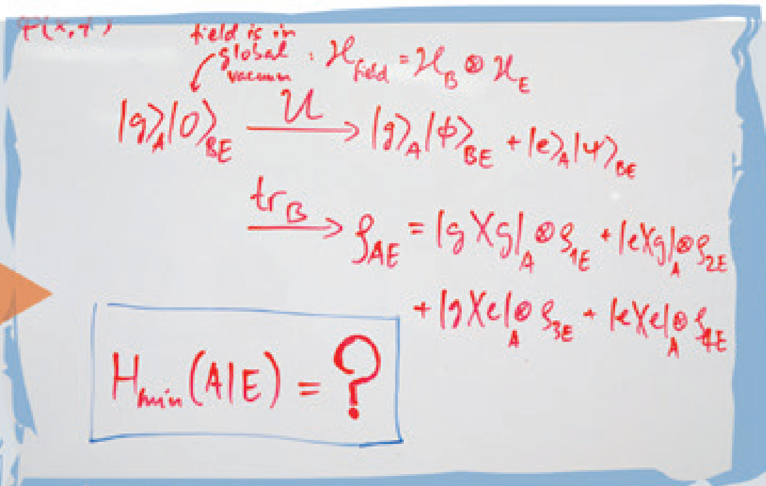
Working in the labs has lots of perks, including unexpected ones.

Because we need to keep dust out of our experiments...



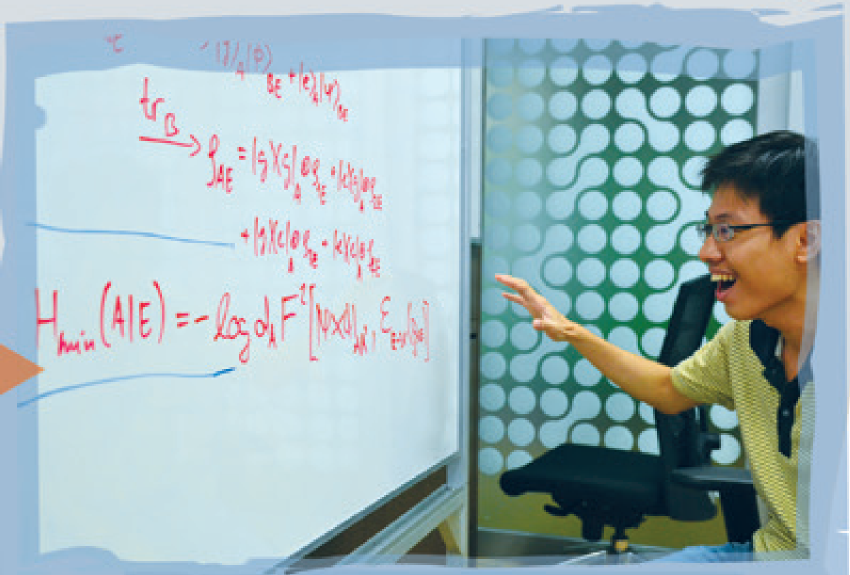
our air is clean even when the haze hits Singapore!

We try to solve problems that no-one knows the answer to.



Sometimes we get stuck...

but we help each other out



and enjoy the results of our collaboration!

We try to keep a clear head.

Photos by CQT PhD student Cai Yu (pictured) and friends

On the path to expertise

Through CQT's student programmes, we are training the next generation of scientists

Earn a PhD@CQT

CQT aims to produce high-caliber graduates in the exciting and growing interdisciplinary field of quantum technologies, which encompasses research in experimental and theoretical quantum physics and computer science. Students receive multidisciplinary training with a focus in science, engineering or computing. The PhD@CQT programme will train at least 80 PhD students over 10 years. The inaugural intake was in August 2008 after the Centre was founded at the end of 2007.

We currently have over 50 students in the PhD programme. Two of them introduce themselves in the profiles opposite.

Students under the PhD@CQT programme receive a generous scholarship, plus allowances for travel and other expenses. Principal Investigators at CQT also supervise students funded by other sources, such as the NUS Faculty of Science or NUS Graduate School for Integrative Sciences and Engineering. All doctoral degrees are awarded by the National University of Singapore, consistently ranked among the leading universities in the world.

Internships

For students contemplating a career in research, CQT offers internships. These are particularly suited to students near the end of an undergraduate degree or in the middle of an MSc. Students are invited to apply for placements to be undertaken in 2014 (dates flexible). Follow up applications by successful interns to the PhD@CQT programme will be given high priority.

More information on the student programme and a description of how to apply are available on the CQT website: www.quantumlah.org

Graduates in 2013

Congratulations to the graduates from the PhD@CQT programme who were awarded their degree in 2013.

Syed Aljunid
Interaction of a Strongly focused Light Beam with Single Atoms
Supervised by Christian Kurtsiefer

Kyle Arnold
Collective Dispersive Interaction of Atoms and Light in a High Finesse Cavity
Supervised by Murray Barrett

Han Rui
Robust Quantum Storage with Three Atoms
Supervised by Berge Englert

Ravishankar Ramanathan
Complementarity of Quantum Correlations
Supervised by Dagomir Kaszlikowski

Elisabeth Rieper
Quantum Coherence in Biological Systems
Supervised by Vlatko Vedral

Wang Guangquan
Strongly Correlated Phases in the Anisotropic Honeycomb Lattice
Supervised by Berge Englert

Wang Yimin
Quantum Information Exchange Between Photons and Atoms
Supervised by Valerio Scarani

Marta Wolak
Quantum Monte Carlo Studies of the Population Imbalanced Fermi Gas
Supervised by Berge Englert

Debashis De Munshi

Where are you from?

I'm from Calcutta in West Bengal, India – the same place where Satyendra Nath Bose, who gave his name to 'boson' particles, did his work on quantum mechanics.

What is your research about?

In classical mechanics, if a ball goes around a circle and comes back, it's still just the same ball, but in quantum mechanics if a ball goes around and comes back, it's a ball and something else. This something else is termed geometric phase. My goal is studying the behaviour of this geometric phase. There are lots of proposals for using geometric phase for quantum computation. I come at it more with the interest of seeing something that is abstract manifest itself in real life.

Being an experimentalist, you are very grounded in real life...

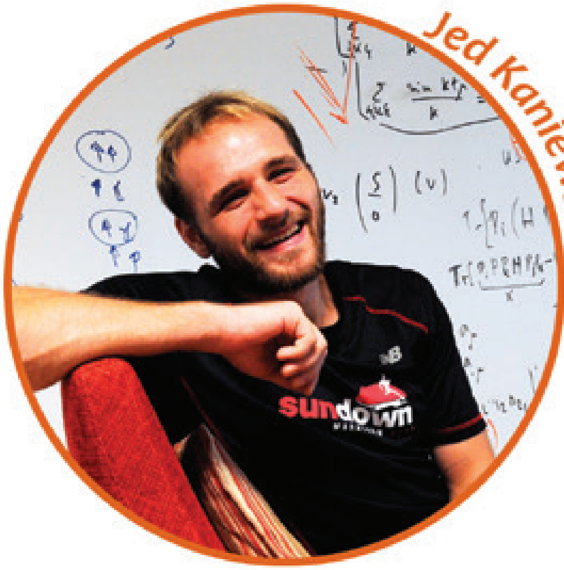
Yes, most days I'm soldering wires, making circuits, tightening bolts, aligning lasers and so on. Individually the things are really basic but when they're all combined, they can give rise to something that is very beautiful. We just have to keep reminding ourselves of our goals. We've been setting up our experiment since February 2012. Hopefully by the end of this year we will have some trapped ions.

What do you enjoy about being a researcher?

When I was a kid, I had a small lab where I did things like mix up medicines that I'd apply to plants and try to build a model ram-jet engine. I was always very curious about things, and that is what has led me here. So now research is kind of a part of my life: doing research no longer feels like doing a job, rather when I go home I feel like I'm doing a job.

Debashis is a member of Manas Mukherjee's group.

Jed Kaniewski



How did you become a quantum physicist?

My undergraduate degree is actually in chemistry, my Master's is in applied mathematics and at the moment I am working on the boundary of physics, computer science and maths so calling myself a quantum physicist would be an oversimplification. But that is exactly the reason why I am here – quantum information being an interdisciplinary and relatively new field is very appealing to young people. You do not need to read 50 years' worth of papers to get to the frontier and a lot of simple, natural problems remain relatively unexplored.

What is your research about?

I work on cryptography, which is the study of how to exchange and process information in a secure fashion, i.e. keeping it secret from an adversary. It turns out that the quantum world is strictly richer than the classical, everyday world. Certain tasks that we know are impossible classically become feasible when we start to take advantage of quantum effects.

What is something you do outside of work?

I spend most of my day sitting down in front of my computer so I occupy the rest of my time with various physical activities. It turns out that South-East Asia is a great place for rock-climbing, and that became my main hobby when I moved to Singapore.

What's good about your job?

I like the freedom and flexibility of being a PhD student – I can choose what problems I want to work on, who I collaborate with and which conference I attend. I also like the fact that if I feel like learning a new bit of maths or science, I can take my time and do it – it is part of my job.

What is hard?

Lack of progress is hard. Sometimes you find yourself working on a problem for quite some time but you get no results. You try to tackle it from different angles, using different techniques and approaches but you are still getting nowhere. That is hard and makes you think about putting the project aside. It is like attempting a climbing route that you cannot finish – it is always a tough decision and it does not feel good but at least you have given it a try. But getting out of the comfort zone is part of the job – even the greatest researchers have folders full of notes on problems they tried but did not manage to solve.

Jed is a member of Stephanie Wehner's group.

Life after CQT

We asked some of our alumni what they'd got up to after leaving CQT

Many have continued in research in Singapore and abroad

I am a post-doc at Hebrew University of Jerusalem in the School of Computing.

Loïck Magnin
CQT Research Fellow
Jan 2012 – Aug 2013

I am a Lecturer at NanJing University.

Yimin Wang
CQT PhD Student
July 2009 – March 2013

We also asked them what they remembered about working at CQT

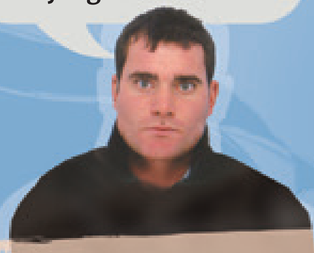
I enjoyed the excitement of the first few years, when the Centre was created and growing. It was nice to meet so many people, and that we were all pulling in the same direction to make this happen.

Andreas Winter
CQT Principal Investigator
Nov 2007 – Nov 2012

The good discussions in CQT, the liberty to pursue one's own thoughts and ideas.

Elisabeth Rieper
CQT PhD Student
Aug 2007 – Jan 2012 2013

I met great people at CQT; they became very good friends. I miss the food in Singapore and sipping cold beer sitting in buckets of ice on long balmy nights!



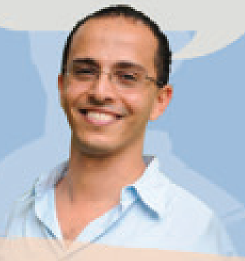
John Goold
CQT Research Fellow
Feb 2010 – Aug 2012

And what advice they have for current and future CQTians

If you have the chance to experience work at CQT... GO FOR IT!!!!!!!!!! You won't regret it.

Mussie Beian
CQT Research Assistant
Feb 2011 – Apr 2012

I'm now at the Center for Quantum Information and Control at the University of New Mexico. I have a post-doc position here.



Amir Kalev
CQT Research Fellow
Oct 2008 – Feb 2013

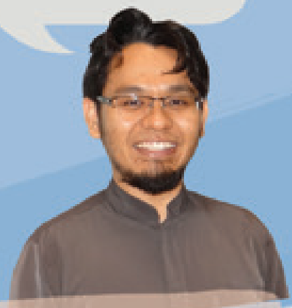
I have joined the Singapore University of Technology and Design as an Assistant Professor.

Dario Poletti
CQT Research Fellow
Apr 2009 – Aug 2010

I'm in Paris now. I'm starting the 3rd and final year of my PhD in experimental physics, in the atom optics group at Laboratoire Charles Fabry, Institut d'Optique.

Bess Fang
CQT Research Assistant
Jul 2008 – Sep 2011

I'm now in Singapore working in the Centre for Disruptive Photonic Technology in NTU as a Research Fellow.



Syed Abdullah Aljunid
CQT PhD Student
Aug 2007 – Aug 2012

Some have gone into industry

I have been in three different industries since I left CQT: Financial Risk Manager, Semiconductor Process Engineer and Geophysicist.

Arpan Roy
CQT Research Assistant
Apr 2011 – Jun 2012

I am in Frankfurt/Main, Germany. I am working for Becker Photonik GmbH doing some R&D (and almost everything else) on THz imaging system.

Andreas Keil
CQT Research Assistant
Aug 2008 – Apr 2009

Do make the most of your talents on 3Cs: "Comprehend, Communicate and Contribute".

Jing Yan Haw
CQT Research Assistant
Aug 2011 – Sep 2012

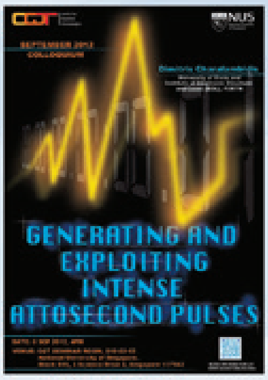
Visit CQT, enrol, attend/give a talk and stay for a while. It's a life changing experience. Follow the work from the PIs, talk with Kwek, watch Dago's short films, take Berge's lectures, read Valerio's book, play soccer with Artur. CQT may be advertised as the coldest place on the equator but it's the most warming when it comes to work camaraderie.

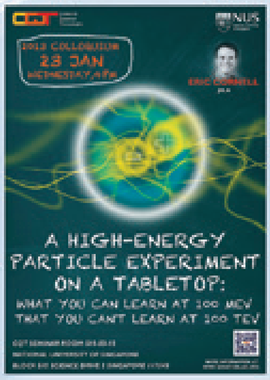
Blas Rodriguez
CQT Research Fellow
Nov 2010 – Mar 2012

Note: As of September 2013, CQT had 103 alumni. The answers here were taken from 23 replies to an email survey. Any alumni who did not hear from us but who wish to stay in touch, please contact us at secretary@quantumlah.org

Events

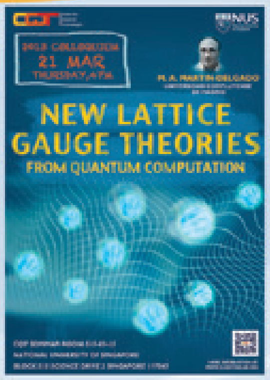
Colloquia

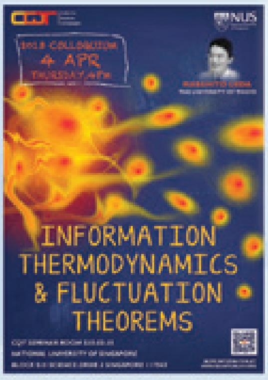


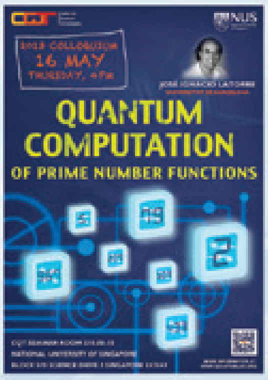


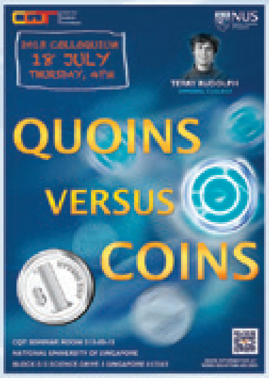
Conferences and Workshops

Date	Location	Event
10-14 Sep 2012	Shaw Foundation Alumni House, NUS	QCRYPT 2012
17-20 Sep 2012	Centre for Quantum Technologies, NUS	Japan-Singapore Workshop on Multi-user Quantum Networks
3-5 Dec 2012	Pangkil, Indonesia	Atom Chip Workshop
7 Dec 2012	University Hall Auditorium, NUS	The Famous, the Bit and the Quantum – CQT Annual Symposium 2012
4-6 Mar 2013	NTU	Institute of Physics Singapore Meeting 2013
3-6 Jun 2013	NUS High School	Physics Education Seminar 2013
12 Aug - 11 Oct 2013	IMS	Mathematical Horizons for Quantum Physics 2









Awards

CQT's Director Artur Ekert was awarded the Institute of Physics Singapore President Award 2012

Two NUS students who did research projects at CQT were awarded the university's Outstanding Undergraduate Researcher Prize in 2012-13. Physics student Jeysthur Ang (pictured) won for his work on "The Effect of Reduced Randomness on Device-Independent Certification", supervised by Valerio Scarani, and computer science student Nguyen Truong Duy won for his project on "Computing Bounds on Bell Inequalities" supervised by Stephanie Wehner.

Principal Investigator Christian Kurtsiefer was awarded the IPS-World Scientific Premier Science Research Award 2012

CQT presented two internal awards in 2012. Admin Manager Evon Tan was named "CQTian of the Year" for 2012. Senior Research Fellow Troy Lee won first prize in the CQT's Got Talent competition for a juggling performance. They are pictured at CQT's safari-themed annual event.

Outreach

The Strangeweather Movement Group choreographed dances inspired by quantum theory.

Major initiatives

Jul 2012 - Jan 2013	CQT teamed up with *New Scientist* magazine to run an online competition for short films inspired by quantum physics. The competition website received over 12,000 unique visitors and attracted nearly 50 entries. The winning films were mentioned in media including *New Scientist*, *Scientific American* and *Wired*.
Sep 2012 - Sep 2013	CQT hosted science journalist Karol Jalochowski for a year to make a documentary about quantum physics. See his article about the project on pp.26–27. He took up the newly created position of "Outreach Fellow" at CQT – an extension of the Quantum Immersion program offering residencies for writers and artists.
3-6 Jun 2013	CQT partnered with NUS High School, the Ministry of Education and the Institute of Physics (Singapore) as co-organiser of the Physics Education Seminar 2013, a four-day event for Singapore physics teachers offering professional development.
Jul 2013 - Jan 2014	With *Scientific American* and the sci-fi publisher Tor and Tor.com as media partners, CQT launched a Quantum Shorts competition for flash fiction. This followed the success of the 2012 Quantum Shorts competition for short films.

CQT researchers joined the Singapore Mini-Maker Faire to show some of the experimental kit they've built themselves.

Selected events and media mentions

Sep 2012	*Scientific American* published a feature article "Beyond the Quantum Horizon" by David Deutsch and CQT's Director Artur Ekert. The feature was later selected for the 2013 edition of The Best American Science and Nature Writing.
7 Sep 2012	An article in *Science* called "Flocking to Asia for a Shot at Greatness" that reviewed Singapore and Hong Kong as research hubs featured CQT PI Stephanie Wehner.
11 Sep 2012	Public talk: "Rise of the Quantum Age" by Gilles Brassard, Universite de Montreal, in conjunction with the QCRYPT 2012 conference at NUS.
20 Oct 2012	Dance performance by the Strangeweather Movement Group (pictured left) which "takes a look at the theory of quantum entanglement, puts it on the backburner, and creates a series of movement scores that together make a dance". The dancers include CQT Research Fellow Daniel Sahagun Sanchez. They went on to collaborate with the CQT Outreach Fellow, appearing in his documentary. Watch at http://vimeo.com/73509026.
23 Oct 2012	Public talk: "Looking through the lens" by Andrzej Dragan, a quantum physicist from the University of Warsaw who is also a successful professional photographer, at CQT.
28 Nov 2012	Public talk: "Physicist in the kitchen: exploring the gastronomic universe" by Andrey Varlamov from the Institute of Superconductivity & Innovative Materials, Italian National Research Council, at Singapore Science Centre.
17 Feb 2013	Channel NewsAsia filmed CQT Research Fellow Ng Hui Khoon for a story on young researchers returning to Singapore. This was broadcast and published online.
22 Feb 2013	NUS announces that it will launch two courses on Coursera, including one taught by CQT PI Valerio Scarani. The news was reported by many Singapore media outlets.
6 Mar 2013	Students from NUS High School visited CQT for a talk and lab visits.
13 Mar 2013	Students from University World College visited CQT for a talk and lab visits.
20-21 Apr 2013	CQT participated in Singapore's first International Space Apps Challenge – a global hackathon event organised by NASA. PI Alexander Ling contributed a local challenge involving the simulation of communication between a satellite in low-earth orbit and a ground station in Singapore. He also gave a talk.
15 May 2013	A careers feature in *Nature* "Working in Asia: The siren song of Singapore" features Research Fellow Jayne Thompson and CQT's Director.
25 May 2013	*The Economist* mentions plans by CQT PI Alexander Ling to develop quantum cryptography for satellites in a news story "The solace of quantum".
3-Jul-2013	CQT PI Vlatko Vedral authored an Instant Expert guide to quantum information that was published in the popular science magazine *New Scientist*.
19-21 Jul 2013	Participation in Xperiment! during the Singapore Science Festival with an exhibition on cryptography from ancient cyphers to quantum key distribution arranged in collaboration with NUS Science Demo Lab. Xperiment! was held at a shopping mall.
27-28 Jul 2013	CQT researchers showcased bits of experiment built in CQT's lab at Singapore's Mini Maker Faire (pictured above). They also demoed a 'dust trap' that works on the same principles as ion traps for cold atoms.
20 Aug 2013	Public talk: "Superposition, Entanglement, and Raising Schrödinger's Cat" by David Wineland, 2012 Nobel Laureate in physics and member of CQT's Scientific Advisory Board, at the Asian Civilisations Museum.

Publications

Quantum crypto resists manipulation

Quantum cryptography is the ultimate secret message service. CQT researchers and their collaborators have shown that it can counter even the ultimate paranoid scenario: when the equipment or operator is in the control of a malicious power.

Previously, quantum cryptography protocols always assumed that an adversary would not have access to information about choices made during the process of encryption. "We are challenging this assumption," says co-author Artur Ekert, co-inventor of quantum cryptography and Director of CQT. "We are asking well, what if you are controlled?".

Quantum cryptography provides a way for two parties to share a secret key – a random sequence of 1s and 0s – which can then be used to scramble a message. Security comes from quantum laws providing a built-in way to detect eavesdropping attempts. But what if the adversary controls the transmission?

The team show that some of the key can still be salvaged. They calculate for different amounts of manipulation how much genuine 'randomness' remains in the key. This offers a measure of how much of the key has been left untouched and, in turn, determines how much of the key can be guaranteed secret.

Effects of Reduced Measurement Independence on Bell-Based Randomness Expansion, D. Enshan Koh, M. J. W. Hall, Setiawan, J. E. Pope, C. Marletto, A. Kay, V. Scarani, and A. Ekert, Phys. Rev. Lett. 109, 160404 (2012); arXiv:1202.3571.

How to Counteract Systematic Errors in Quantum State Transfer
C. Marletto, A. Kay, A. Ekert
Quantum Inform. Comput. 12, (2012)

Quantum Discord of a Three-Qubit W-Class State in Noisy Environments
H. Guo, J.M. Liu, C.J. Zhang, C.H. Oh
Quantum Inform. Comput. 12, (2012)

The Device-Independent Outlook on Quantum Physics
V. Scarani
Acta Phys. Slovaca 62, (2012)

Classification of Entanglement in Symmetric States
M. Aulbach
Int. J. Quantum Inf. 10, 1230004, (2012)

Spontaneous solitons in the thermal equilibrium of a quasi-one-dimensional Bose gas.
T. Karpiuk, P. Deuar, P. Bienias, E. Witkowska, K. Pawlowski, M. Gajda, K. Rzazewski, and M. Brewczyk.
Phys. Rev. Lett. 109, 205302, (2013)

Experimental implementation of bit commitment in the noisy-storage model
N.H.Y. Ng, S.K. Joshi, C.C. Ming, C. Kurtsiefer, S. Wehner
Nat. Commun. 3, 1326, (2012)

Enhanced backscattering of a dilute Bose-Einstein condensate
G. Labeyrie, T. Karpiuk, J.F. Schaff, B. Gremaud, C. Miniatura, D. Delande
EPL 100, 66001, (2012)

A Quantum Heuristic Algorithm for the Traveling Salesman Problem
J. Bang, J. Ryu, C. Lee, S. Yoo, J. Lim, J. Lee
J. Korean Phys. Soc. 61, (2012)

Quantum non-locality based on finite-speed causal influences leads to superluminal signalling
J.D. Bancal, S. Pironio, A. Acin, Y.C. Liang, V. Scarani, N. Gisin
Nat. Phys. 8, (2012)

Nonlocal distillation based on multisetting Bell inequality
X.J. Ye, D.L. Deng, J.L. Chen
Phys. Rev. A 86, 62103, (2012)

Positivity in the presence of initial system-environment correlation
K. Modi, C.A. Rodriguez-Rosario, A. Aspuru-Guzik
Phys. Rev. A 86, 64102, (2012)

Robustness of nonadiabatic holonomic gates
M. Johansson, E. Sjoqvist, L.M. Andersson, M. Ericsson, B. Hessmo, K. Singh, D.M. Tong
Phys. Rev. A 86, 62322, (2012)

Detecting genuine multipartite correlations in terms of the rank of coefficient matrix
B. Li, L.C. Kwek, H. Fan
J. Phys. A-Math. Theor. 45, 505301, (2012)

Security of Distributed-Phase-Reference Quantum Key Distribution
T. Moroder, M. Curty, C.C.W. Lim, L.P. Thinh, H. Zbinden, N. Gisin
Phys. Rev. Lett. 109, 260501, (2012)

Qubit-qudit states with positive partial transpose
L. Chen, D.Z. Dokovic
Phys. Rev. A 86, 62332, (2012)

Collapse of the quantum correlation hierarchy links entropic uncertainty to entanglement creation
P.J. Coles
Phys. Rev. A 86, 62334, (2012)

Principle may help explain why nature is quantum

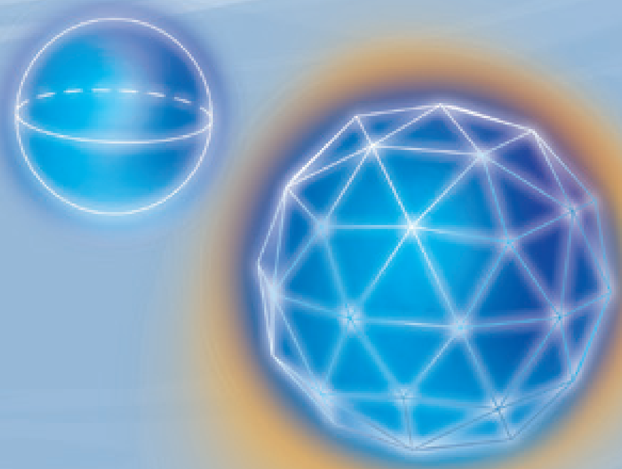
CQT researchers have shown that a principle of 'accepting the facts' implies that a quantum bit (typically pictured as a 'Bloch ball') can look like a sphere but not like a polyhedron. By ruling out alternative theories of nature, the principle may help to explain why the world is quantum.

Research Fellow Corsin Pfister and PI Stephanie Wehner define the principle of accepting the facts in terms of the information gained in a measurement.

Quantum physicists accept that gaining information from quantum systems causes disturbance. For example, in the famous Schrodinger's cat paradox the cat is in a superposition of dead and alive only until it is measured. The measurement collapses the superposition, leaving the cat definitively dead or not.

Corsin and Stephanie suggest that in a sensible world the reverse should be true, too: if you learn nothing from measuring a system, then you can't have disturbed it. In other words, the cat stays dead or alive and if you look again, you neither learn anything nor disturb its state.

This principle rules out various theories, including the possibility that quantum particles can take up only a finite number of states rather than choose from an infinite, continuous range of possibilities. The idea of discrete 'state space' (giving rise to polyhedral bits) has been linked to quantum gravitational theories proposing similar discreteness in spacetime.



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Looking beyond space and time

Trying to explain quantum "spooky action at a distance" using any kind of signal pits Einstein's relativity against our concept of a smooth spacetime, CQT researchers and their collaborators in Switzerland, Belgium and Spain have shown.

The team came up with a ‘hidden influence’ inequality that describes the possibility of entangled particles coordinating their spooky actions through some kind of signal that stays hidden and travels at finite speed. Crucially, they find that quantum predictions violate this inequality. If experiments bear out the quantum case, that means either the signals must be ‘unhidden’ or travel at infinite speed.

"Our result gives weight to the idea that quantum correlations somehow arise from outside spacetime, in the sense that no story in space and time can describe them," says team-member Nicolas Gisin from the University of Geneva, Switzerland.

The inequality is based on the behaviour of four entangled particles. Experimental groups can already entangle four particles, so a test is feasible in the near future, though the precision of experiments will need to improve to make the effect measurable.

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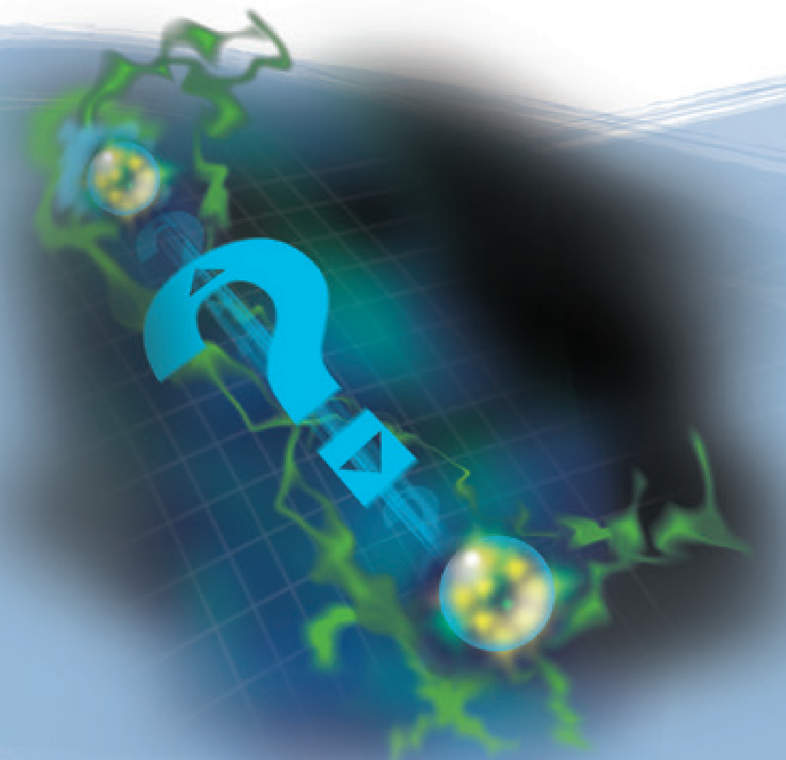

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Theorists see proposal for error-tolerant quantum gates realised

Non-adiabatic holonomic quantum computation, E. Sjöqvist, D. M. Tong, L. M. Andersson, B. Hessmo, M. Johansson and K. Singh, New J. Phys. 14 103035 (2012); arXiv:1107.5127.

Researchers sometimes have to wait decades for their theoretical ideas to bear fruit: not so the team behind the idea of 'non-adiabatic holonomic quantum computation'. Less than two years after CQT researchers and their collaborators proposed a new way to implement error-tolerant quantum gates, two experimental groups have realised the scheme.

"We showed how to do things in a much simpler way than what was known before. This simplification apparently opened the way for experiments," says Erik Sjoqvist, first author on the paper and a CQT Visiting Research Professor from Uppsala University, Sweden.

Quantum gates are the building blocks of quantum computation, equivalent to logic operations such as NOT and AND. In 1999, researchers suggested that gates could be implemented by manipulating a property of qubits known as their 'non-Abelian geometric phase' or holonomic phase. This phase should be less affected by environmental noise than a state's energy level, the target of other gate approaches.

The original schemes required 'adiabatic' implementation: the quantum states had to be influenced slowly, without injecting any energy into the system. With noise degrading the quantum state, time to do things slowly is an unaffordable luxury. The CQT team and their collaborators developed a scheme for non-adiabatic gates that could be performed quickly.

One experiment in Switzerland realised the scheme in a superconducting system and the other experiment was performed in China using nuclear magnetic resonance techniques. These experiments were described in *Nature* and *Physical Review Letters* respectively.

Quantum simulation targets particle physics

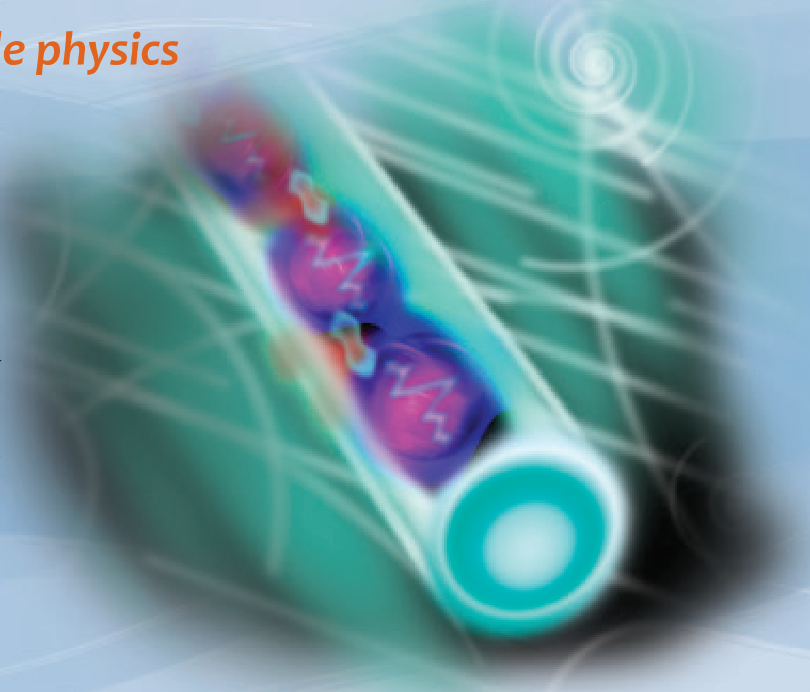
Photons could simulate the behaviour of relativistic particles predicted by the Thirring Model, a relativistic quantum field theory that has resisted full mathematical solution since the 1950s.

This is the proposal from CQT PI Dimitris Angelakis and his collaborators, who have pioneered the idea of simulating quantum systems using photons.

The Thirring Model describes the interactions of relativistic fermions. Such particles are moving at speeds close enough to the speed of light to significantly experience time slowing and length contracting, as predicted by special relativity. Weird effects occur when the particles interact, such as the 'dressing' or changing of the particle's mass.

When the model needs a mass term – for example, to describe the interactions of electrons or quarks – the mathematical solutions are cumbersome. Predictions for the behaviour of matter at these regimes are then hard or impossible to make.

This is where simulations could help. The photon-based simulator would be implementable in a table-top set-up, and Dimitris says some groups are close to having the kind of system required to test the simulation proposals. Handily, the fact that the Thirring Model has already been solved for massless particles provides a way to test the simulator's output. The unknown solutions for massive particles can then be probed by tuning optical parameters in the simulator.



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Towards scalable quantum computing

Quantum physics promises faster computations, but to realise the technology's full potential will require much larger implementations than today's 20 or so quantum bits (qubits).

There are two competing routes to scaling up: build a single bigger machine or link many small ones into a network. The former has proved hard for fragile qubits, but the latter encounters a problem with noise.

Simon Benjamin, a CQT Visiting Research Associate Professor from the University of Oxford, and his co-authors present a protocol that raises the tolerable intra-cell error rate in a noisy network from around 0.1% up to 0.825%. This approximately matches the error rate that can be tolerated in a monolithic architecture – and should be achievable experimentally.

The protocol is implemented in a network with cells of four or five qubits connected like they are arranged around a doughnut-shaped surface. This allows the use of the well-established 'toric topological code', which spreads information over the network to make it resistant to errors. The toric code is stabilised by protocols performed on sets of four neighbouring cells. The researchers' contribution is a new protocol for the toric code's stabilising steps.

Topological quantum computing with a very noisy network and local error rates approaching one percent, N. H. Nickerson, Y. Li and S. C. Benjamin, Nature Commun. 4 1756 (2013); arXiv:1211.2217.

All about quantumness

It used to be the case that researchers saw 'entanglement' – two particles being entwined in a single quantum state such that their behaviour is perfectly coordinated – as being the most important kind of quantum correlation. Entanglement was thought to be essential to gaining quantum speed-ups in computing, for example.

However, in the past decade, researchers have realised that weaker forms of correlation may have applications too. That has stirred interest in ways of measuring such quantumness: mathematical approaches to teasing out the quantum properties mixed up with classical properties. CQT researchers and a collaborator have written a review that surveys the different measures.

"The field grew very quickly and this probably made things confusing, because people were coming up with new definitions all the time," says Hugo Cable, one of the CQT authors of the review paper. For example, two measures of quantumness considered in the review, discord and deficit, come in many different variants. The review collates ideas about how the variants are related and in what situations they are relevant.

The review article is more than 50 pages long and gives over 300 references.

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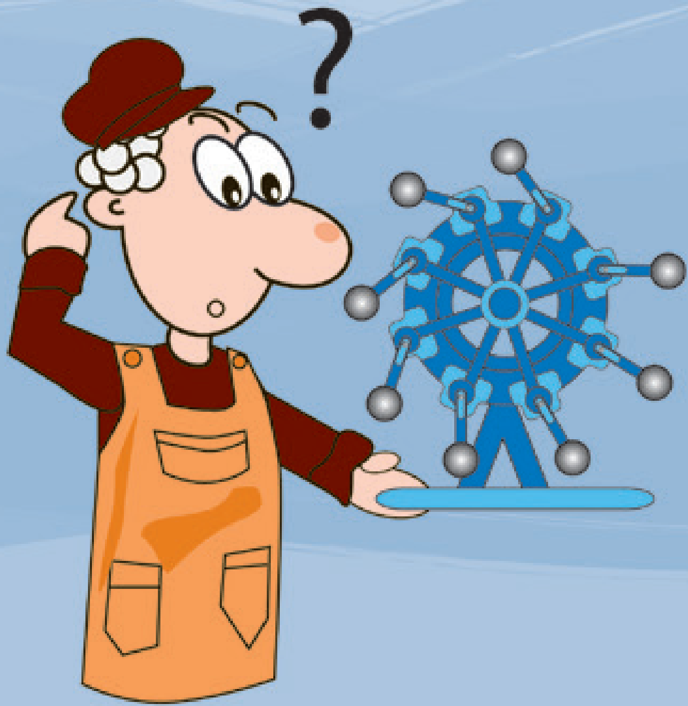
Uncertainty avoids perpetual motion machines

CQT PI Stephanie Wehner and Esther Hänggi have shown that obedience to the second law of thermodynamics could lie behind one of the most fundamental features of quantum physics: the uncertainty principle.

The second law of thermodynamics says that any system's disorder, known as entropy, will always increase. The law prohibits us from building perpetual motion machines that can do more work than they use up. The quantum uncertainty principle, meanwhile, limits how accurately two properties of a system can be known simultaneously. For example, the more precisely you pin down the momentum of a particle, the less precisely you know its position. Why should nature have this fuzziness? The new work gives us some kind of answer.

Stephanie and Esther used a technique pioneered by the scientists behind thermodynamics, which emerged from calculations in the 19th Century on the efficiency of engines. Scientists then, inspired by the steam engine, analysed the amount of work that could be extracted through various cycles of compressing and heating gases. In a similar way, Stephanie and Esther imagine an engine that is powered by quantum particles. They took an information theory approach to analysing the cycle and arrived at an equation for the work output that involves the uncertainty relations. The equations show that the uncertainty principle has to hold for the second law to stay true.



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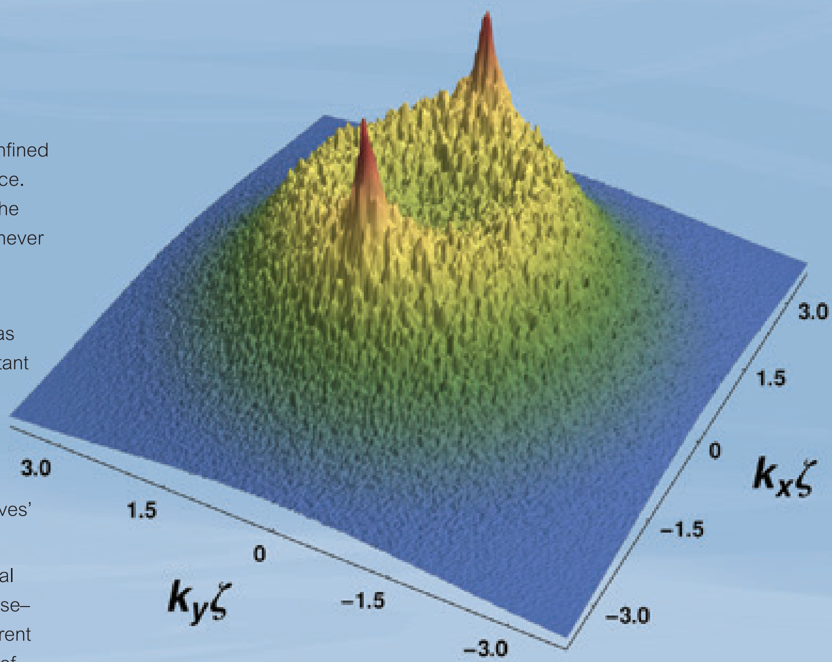
Twin peaks

Waves trying to propagate in a disordered environment can end up confined by a mechanism known as Anderson localisation, caused by interference. Calculations by CQT researchers and their collaborators suggest that the localisation should be accompanied by a twin-peak signal, something never seen before.

The idea that disorder could stop waves dead was surprising when it was predicted in 1958 and remained largely obscure until Anderson was awarded a Nobel prize in 1977. It has since been recognised as important to understanding metal-insulator transitions and wave propagation in random media. Now there are even proposals to exploit wave localisation in applications as diverse as solar cells and quantum memories. However, the phenomenon is hard to detect in real-world experiments and is not well understood. The twin peak signal in the waves' velocity distribution could provide a distinctive signature.

The team saw the phenomenon when they performed detailed numerical and analytical calculations of the wave behaviour of cold atoms in a Bose–Einstein condensate. Earlier calculations had shown a peak from 'coherent back-scattering' (CBS), which heralds weak localisation, the precursor of Anderson localisation. The second peak appears in the strong localisation regime and is attributed to 'coherent forward-scattering'.

After the team's paper on CBS in cold atoms, experimentalists quickly observed the signal, making the researchers hopeful that their new predictions will be tested soon.



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Proposal to close loopholes in entanglement test

Researchers trying to take the assumptions out of a key test of entanglement have a new route to consider, thanks to a proposal from CQT scientists and their collaborators. Success in performing the 'loophole-free Bell test' would reinforce confidence in quantum theory and enable new technologies.

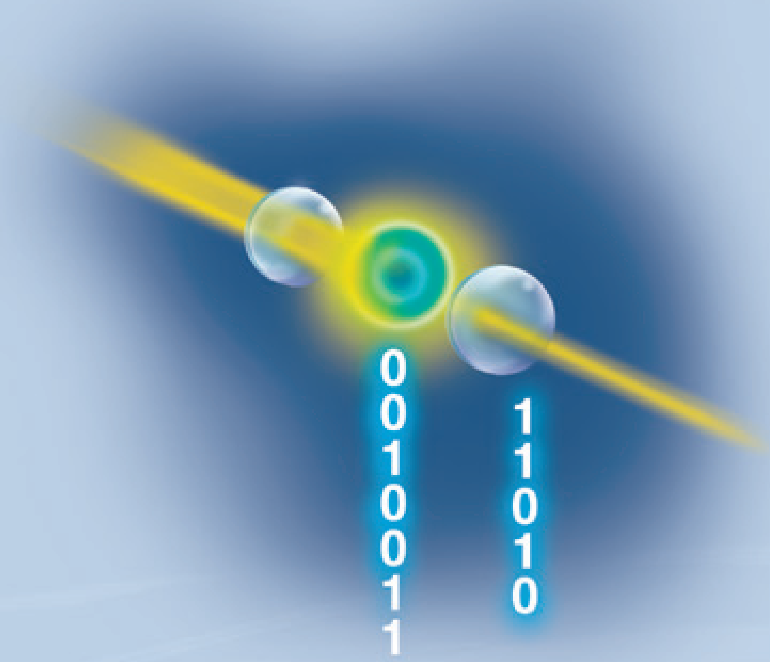
Entanglement is the property of two particles sharing a state such that their behaviours are instantly correlated whatever the distance between them. In a Bell test, researchers try to catch and measure the properties of pairs of entangled particles after the particles have been separated.

All Bell tests so far have suffered from one of two loopholes. The 'detection loophole' arises when researchers can't catch all the particles they create: they assume the ones they do catch are representative. The 'locality loophole' arises when researchers can't get the particles far enough apart, or measure them quickly enough, to rule out the possibility of communication between them.

To close both loopholes simultaneously, the team proposes to perform the Bell test on an atom in a cavity entangled with the phase and intensity of a light beam. The beam undergoes homodyne measurement, whose efficiency helps to close the detection loophole. The locality loophole can also be closed because the light signal can be routed quickly down optical fibre to cover a long distance.

Homodyne measurements had been considered previously, but researchers had not been able to come up with a state for the atom-cavity interaction that was both compatible with Bell testing and possible to make. "Our work is quite surprising because the states we propose are not very complex but are still quite useful," says Colin Teo, a CQT PhD student and the paper's first author.

A loophole-free Bell test may have applications in technologies for 'device independent' quantum cryptography and quantum random number generators.



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Extracting randomness

Random numbers are in high demand – from securing financial transactions, to running casino games, to seeding scientific simulations – but it's tough to make them. CQT PI Stephanie Wehner and her collaborators have analysed a new approach, proposing for the first time quantum analogues of widely-studied 'classical randomness extractors'.

A randomness extractor is a function that combines a small amount of initial, real randomness (r) with the outcome of a measurement on some system to generate a larger amount of real randomness (R). "They are quite central in classical theoretical computer science. They are related to concepts such as complexity and error correcting codes," says Stephanie.

In Stephanie and colleagues' proposal, measurements are performed on a closed system of quantum bits to tap the randomness inherent in quantum measurement. The researchers derive bounds on R as a function of r. The random numbers are secret as long as no observer has entangled themselves with the measurement apparatus. This makes privacy easier to guarantee than in the classical case, where information could leak from a lab at any time.

The work was accepted for the prestigious CRYPTO 2012 conference. It was also presented at the QCRYPT 2012 conference in Singapore.

Quantum to classical randomness extractors, M. Berta, O. Fawzi and S. Wehner, Advances in Cryptology — CRYPTO 2012, Lecture Notes in Computer Science 7417, 776 (2012); arXiv:1111.2026.

Double SODA showing

CQT computer scientists presented two papers at the prestigious ACM-SIAM Symposium on Discrete Algorithms (SODA) conference in New Orleans in 2013. The results set bounds on the amount of work that needs to be done to solve two different problems.

CQT Senior Research Fellow Troy Lee presented work done with CQT PI Miklos Santha and collaborator Frederic Magniez on finding triangles in a graph, a data-search problem. Troy and colleagues' new triangle-finding algorithm sets an efficiency record for this problem, having complexity $O(n^{9/7})$. Troy describes the triangle-finding problem as an algorithmic testing ground. "Each improvement in triangle finding has come with new algorithmic techniques," he says.

In the second SODA paper, Shengyu Zhang, a CQT Visiting Scholar, presented joint work with CQT PI Rahul Jain and collaborator on the cost of creating a shared quantum state between two parties. They set bounds on the 'communication complexity' and 'correlation complexity', showing that these complexities are equal and linking certain instances of them to quantities known as the PSD rank and Wyner's information. Such bounds could help experimentalists: by comparing the amount of work involved in an experimental protocol with the theoretical bound, the experimentalists would know if they were being as efficient as they could be.

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H.Y. Su, Y.C. Wu, J.L. Chen, C.F. Wu, L.C. Kwek
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Y.C. Wu, M. Zukowski, J.L. Chen, G.C. Guo
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Z.H. Wei, S.Y. Zhang
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Distinguishing Multi-Partite States by Local Measurements
C. Lancien, A. Winter
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Properties and Construction of Extreme Bipartite States Having Positive Partial Transpose
L. Chen, D.Z. Dokovic
Commun. Math. Phys. 323, (2013)

Collaborations

CQT has a global network of collaborations at both the individual and institutional level. The graphic above highlights CQT researchers' individual collaborations, showing the number of scientists in other countries who have co-authored one or more publications with CQT researchers over the past academic year. The table on the right summarises formal institutional collaborations that enable some of these scientific exchanges. All agreements are enacted with CQT's host university the National University of Singapore.

Memorandums of Understanding

... for Educational and Scientific Cooperation with the University of Waterloo (UW), host to the Institute for Quantum Computing. From March 2010.

... for Collaboration in Quantum Information Science with the University of Ulm in Germany. From June 2010.

... with the Max Planck Society for the Advancement of Science acting through the Max Planck Institute for Nuclear Physics in Heidelberg, Germany. From August 2012.

...with the University of Science, Vietnam National University in Ho Chi Minh City, Vietnam. From June 2013.

Other agreements

...CQT is a member of the International Associated Laboratory France-Singapore Quantum Physics and information Laboratory (LIA-FSQL) created with the French national research organization CNRS, the Université de Nice Sophia Antipolis, the Université Pierre et Marie Curie, the Ecole Normale Supérieure de Paris, The Université Paris-Sud 11, the Institut d'Optique Graduate School, and the Université Paris Diderot Paris. From January 2010.

...CQT is a partner organization of the ARC Centre of Excellence for Quantum Computation and Communication Technology (CQC2T) in Australia through an agreement signed with the University of New South Wales and the Australian National University. From May 2011.

Visitors

Achim Kempf
University of Waterloo

Ahsan Nazir
Imperial College

Alessandro Fedrizzi
University of Queensland

Alexander Belov
University of Latvia

Alexander Szameit
University of Jena

Alexandre Baron Tacla
University of New Mexico

Andrea Morello
University of New South Wales

Andrew Garner
Oxford University

Andrey Varlamov
INFM and Universita' di Roma Tor Vergata

Andrzej Dragan
University of Warsaw

Ansis Rosmanis
Institute for Quantum Computing

Antonio Badolato
University of Rochester

Anupam Prakash
University of Berkeley

Anurag Anshu
IIT Guwahati

Arne Løhre Grimsmo
University of Auckland

Ashwin Nayak
University of Waterloo

Avi Wigderson
Institute for Advanced Study, Princeton, USA

Bess Fang
Institut d'Optique

Brendan Fong
University of Oxford

Charles Clark
National Institute of Standards and Technology, USA

Christian Ospelkaus
University of Hannover

Christian Weedbrook
University of Toronto

Christina Kraus
University of Innsbruck

Christof Wunderlich
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Claude Fabre
Laboratoire Kastler Brossel

Cui Jian
Chinese Academy of Sciences in Beijing

Daniel Alsina
University of Barcelona

Daniel Gauthier
Duke University

Daniel Oi
University of Strathclyde

Daniel Sternheimer
Université de Bourgogne

Daniel Terno
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Dmitry Gavinsky
NEC research, USA

Eduardo Martin-Martinez
University of Waterloo

Enrique Solano
Universidad del País Vasco

Fabian Furrer
University of Tokyo

FEI Shao-Ming
Capital Normal University

Fern Watson
Imperial College

Francis Murphy
Imperial College London

Francois Arnault
University of Limoges

Frederic Chevy
LKB, ENS, Paris.

Frederik Spiegelhalder
University of Amsterdam

Gabriele de Chiara
Queen's University Belfast

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University of Queensland

Guillermo Romero
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Macquarie University

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Uniwersytet Warszawski

Ladislav Mista
Palacky University

Leif Humbert
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Li Yun
BEC Centre in Trento

Liu Ren Bao
The Chinese University of Hong Kong

Lucas Celeri
Federal University of Goias

Markus Debatin
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Martial Ducloy
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University of Heidelberg

Masahito Ueda
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Peter Ivanov
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University of Berkeley

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Shion Chaudhury
Chennai Mathematical Institute

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Chennai Mathematical Institute

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NTT

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Macquarie University

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University of British Columbia

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University of Bristol

Yuan Zhou
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Weizmann Institute of Science

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Perimeter Institute

Financial numbers

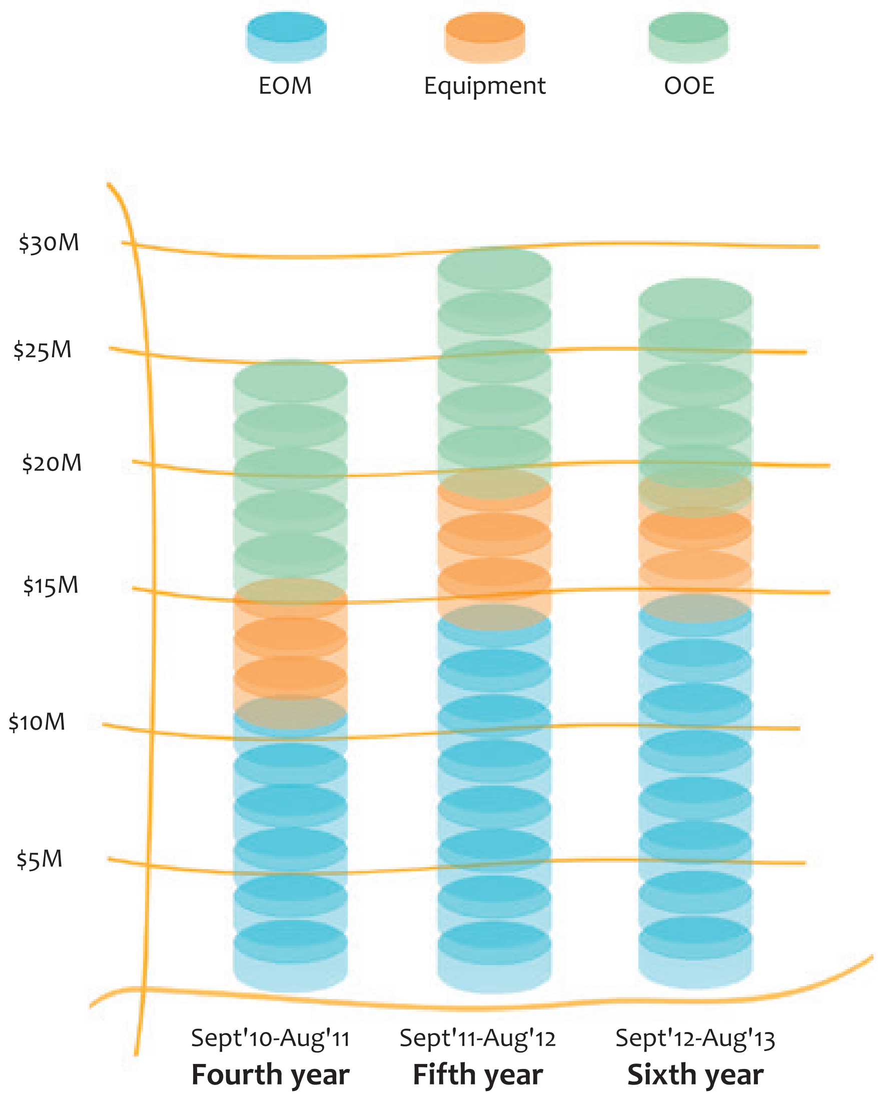
GRANTS AWARDED IN 2012-13

Amount: $9,931,731
Awarded by: Ministry of Education, Singapore
For: A five-year project on quantum randomness, to an inter-disciplinary team of 13 Principal Investigators led by Valerio Scarani.

Amount: $863,000
Awarded by: DSO National Laboratories, Singapore
For: For a collaborative effort to develop quantum technologies for sensing and metrology, involving six CQT researchers

Amount: $60,000
Awarded by: MERLION Project, Institut Francais, Singapore
For: Funding the logistical costs for two-year projects that involve French-Singaporean collaboration, awarded in two $30k grants to PIs Kwek Leong Chuan and Bjorn Hessmo.

Amount: USD 89,700 (joint with Adam Mickiewicz University, Poland)
Awarded by: Foundational Questions Institute (FQXi), United States
For: Research into the "Operational and information theoretic meaning of contextuality" by PI Dagomir Kaszlikowski and Senior Research Fellow Pawel Kurzynski, also of Adam Mickiewicz University.



	Manpower (EOM)	Equipment	Other Operating Expenditure (OOE)	Total
Fourth year Sept'10-Aug'11	$11,020,884	$3,841,551	$10,242,831	$25,105,266
Fifth year Sept'11-Aug'12	$14,080,767	$4,893,010	$11,455,527	$30,429,304
Sixth year Sept'12-Aug'13	$15,089,111	$3,212,423	$8,844,065	$27,145,599

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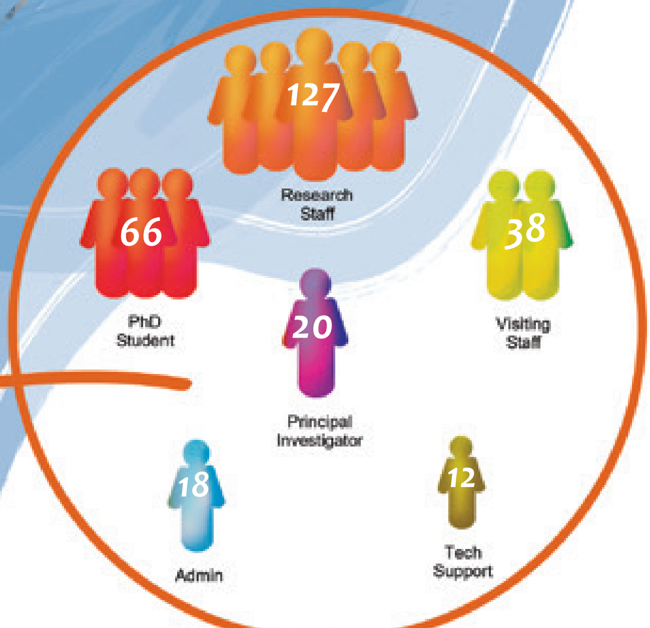
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PhD Student
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