

Institute for Quantum Information

Activities – 2000-2006

The Institute for Quantum Information at Caltech (IQI) was launched in September 2000, supported by a \$5M five-year ITR award from the NSF (later extended to $5\frac{1}{2}$ years). With this NSF support, helpfully leveraged by Caltech, the IQI has become one of the world's strongest theoretical efforts in Quantum Information Science (QIS), with high international visibility. Through our own scientific contributions and our highly successful visitor program, we have exerted a broad influence on the development of the field.

Personnel

The IQI is an NSF-supported collaboration of Caltech's Divisions of Engineering and Applied Science and of Physics, Mathematics, and Astronomy. It is led by five Caltech faculty members: John Preskill (Director and PI, MacArthur Professor of Theoretical Physics), Alexei Kitaev (co-PI, Professor of Physics and Computer Science), Jeff Kimble (Valentine Professor of Physics), Hideo Mabuchi (Associate Professor of Physics and Control and Dynamical Systems), and Leonard Schulman (Professor of Computer Science). Administration of the IQI is supervised by Ann Harvey (IQI Administrative Assistant).

The IQI has attracted and trained some of the world's top postdoctoral scholars, many of whom have moved on to faculty positions elsewhere and are emerging leaders among the scientists working on quantum computing. During our first $5\frac{1}{2}$ years, there have been 23 IQI postdoctoral scholars appointed for terms of one, two, or three years; of these, 13 now occupy faculty positions (or the equivalent): Dave Bacon (Washington), Sougato Bose (University College London), Andrew Doherty (Queensland), Luming Duan (Michigan), JM Geremia (New Mexico), Sean Hallgren (NEC), Patrick Hayden (McGill), Debbie Leung (Waterloo), Ashwin Nayak (Waterloo), Yaoyun Shi (Michigan), Kirill Shtengel (Riverside), Barbara Terhal (IBM), and Guifre Vidal (Queensland). Three former IQI postdocs (Sergey Bravyi, Stefano Pironio, and Robert Raussendorf) have moved on to postdocs elsewhere. Seven IQI postdocs (Robin Blume-Kohout, Luc Bouten, Andrew Childs, Jennifer Sokol, Frank Verstraete, Jon Yard, and Pawel Wocjan) are currently in residence, and two of these (Verstraete and Wocjan) are expected to depart Caltech in the fall of 2006 to begin faculty appointments elsewhere. Also, Dominic Mayers served for several years as an IQI Senior Scientist.

This high level of activity has been possible for several reasons. First, IQI has received strong support from Caltech, particularly in the form of prize postdoctoral scholarships; although the number of these fellowships is limited, IQI has attracted such outstanding candidates that we have competed for the prize postdocs very successfully with research groups working in other fields. (Childs, Hayden, and Verstraete were hired as prize postdocs; Geremia, Leung, and Vidal were brought to Caltech with IQI funding and later became prize postdocs.) Second, we have attracted postdocs who were funded primarily by outside sources (Hallgren, Pironio). Third, IQI has sometimes been able to share the cost of a postdoc with other funding sources (Bouten, Doherty, Duan, Raussendorf, Shtengel, Sokol, Wocjan). In any case, the large roster of postdocs has fueled excitement and contributed heavily to the career development of our young people (both postdocs and students). About 35 Caltech students (both graduate and undergraduate) have contributed to IQI research projects

Visiting Scholars and Students

Another central component of the IQI is a vibrant visitor program. In our first $5\frac{1}{2}$ years we have had 13 long-term senior visitors (Dorit Aharonov, Michael Ben-Or, David DiVincenzo, Steven van Enk, Jeffrey Goldstone, Salman Habib, Gerard Milburn, Michael Nielsen, Scott Parkins, Eric Rains, Ben Schumacher, Mikhail Vyalyi, Umesh Vazirani), typically staying for at least several months, and 90 additional senior and postdoctoral visitors whose stays have lasted at least one week. Furthermore, 54 graduate students from other institutions have visited for at least one week. The IQI pays the full travel and local expenses for most of our visitors; some longer-term visitors receive salary. Caltech has also contributed to the visitor program.

The visitor program has been a great success, sparking and facilitating many collaborations of Caltech personnel with researchers from all over the world. Program participation is quite diverse, including all NSF-specified underrepresented groups that are working in the field.

Research Activities

IQI researchers are among the world leaders on both the theoretical and experimental sides of QIS. Preskill's group studies quantum information theory, quantum cryptography, and the theory of fault-tolerant control of quantum systems. Schulman's group develops new quantum algorithms that could outperform classical algorithms, and derives limits on the power of quantum computers. Kimble's group works on both the theory and practice of manipulating quantum information encoded in single atoms and in photons. Mabuchi's group is involved in both theoretical and experimental aspects of quantum control, quantum measurement, and quantum coding. Kitaev's group works on quantum complexity, quantum coding, and the interface of quantum information

with quantum many-body theory. Our postdoctoral scholars and students are also very active in all of these areas of QIS. In addition affiliated faculty are active in adjacent areas: John Doyle in control theory, Kip Thorne in the theory of quantum nondemolition measurement, Axel Scherer in nanostructures and photonic crystals, and Michael Roukes in quantum-limited nanomechanical devices.

IQI participants produced 208 publications from 1 September 2000 to 28 February 2006. These research accomplishments are summarized in the Findings section of this Final Report.

The broad scope of the IQI encourages interactions that often spark unusual collaborations among researchers with varying backgrounds. Physicists collaborate with computer scientists in studies of the security of quantum cryptography and quantum algorithms. Control theorists work with physicists on illuminating the structure of entanglement. Experts on quantum optics and on quantum error correction team up to conceive schemes for error control using continuous measurements. Particle theorists notice connections between quantum error correction and lattice gauge theory. Questions about the tradeoffs between quantum and classical communication resources are addressed that might not have been asked by a computer scientist, information theorist, or physicist working alone. Many more examples can be found in the discussion of our findings. Furthermore, interactions between theory and experiment are strong, with experiments inspiring new theoretical investigations and theorists proposing new experiments.

Education and Training

In addition to the student visitors already mentioned above, 35 Caltech graduate students have been involved in IQI research projects; We have sponsored 21 undergraduate research projects involving both Caltech students and students from elsewhere. All of our students benefit from the interdisciplinary spirit of the IQI.

IQI faculty have developed three innovative courses relating to quantum information science: A course on quantum computing (Ph/CS 219) taught by Alexei Kitaev and John Preskill, and Hideo Mabuchi's intermediate (Ph 125) and advanced (Ph 195) courses on quantum mechanics (which place strong emphasis on the information-theoretic underpinnings of the subject). These courses have frequently visited websites on which lecture notes and problem sets are posted. Links to these sites can be found at the IQI site: <http://www.iqi.caltech.edu/>.

IQI participated in the Computing Beyond Silicon Summer School (CBSSS) in 2002 and 2004. The school brought undergraduates to Caltech for four weeks of training in computing with unusual substrates, including quantum computing. We also support the Southwest Quantum Information and Technology (SQuInT) Network, and have sponsored or co-sponsored SQuInT workshops attended by many students. We have co-sponsored other workshops devoted to specialized topics: information physics (2000), quantum electromechanics (2001), control of nanoscale systems (2002),

quantum control (2004,2005), numerical renormalization group (2005), and quantum information security (2005).

We note that Kitaev was brought to Caltech as an IQI-funded Senior Research Associate, and was later invited to join the professorial faculty. This highly unusual interdivisional appointment in Physics and Computer Science never would have happened had there been no IQI. More such joint appointments will surely speed up the development of QIS, and we hope that other universities will follow this example set by Caltech and facilitated by NSF.

Finally, we remark that the IQI visitor program and well attended weekly seminar have had a broadly felt impact on the Caltech campus. The success of IQI has helped to spur the recent launch of other Caltech research centers devoted to aspects of the interface of science with information technology.