Institute for Quantum Information
Findings – 2006-07

Quantum information science is an exciting emerging field that addresses how fundamental physical laws can be harnessed to dramatically improve the acquisition, transmission, and processing of information. The primary goal of the Institute for Quantum Information (IQI) is to carry out and facilitate research in quantum information science. Our research covers six broad areas: (1) Quantum algorithms that achieve speedups relative to classical algorithms, and limits on such algorithms. (2) Quantum cryptographic protocols, and other types of communication using quantum states. (3) Quantum entanglement and the theory of transformations among quantum states. (4) Protection of quantum information using quantum error correcting codes, fault tolerant protocols for quantum information processing, and control of quantum systems. (5) Theory and practice regarding physical implementations of quantum information processing. (6) Connections between quantum information science and other aspects of fundamental physics.

Since our last annual report in May 2006, IQI participants have produced 46 publications, which we summarize here.

Quantum algorithms and quantum complexity

Quantum algorithms for hidden nonlinear structures. Andrew Childs and Leonard Schulman, with Vazirani, studied the quantum complexity of finding hidden nonlinear structures [1]. They found two black-box problems involving spheres over finite fields for which a classical computer requires exponentially many queries, but a quantum computer can solve the problem in polynomial time. These results show that abelian Fourier sampling is applicable to algebraic structures other than groups, suggesting a new way to generalize the abelian hidden subgroup problem solved by Shor's algorithm.

Discrete-query quantum algorithm for NAND trees. Childs, with Cleve, Jordan, and Yeung, pointed out that a recent algorithm of Farhi, Goldstone, and Gutmann for evaluating balanced binary AND-OR trees, which operates in an unconventional model of quantum query complexity, can be simulated in the conventional model with only small overhead [2]. Their result is an algorithm for evaluating such trees using only $O(N^{\frac{1}{2}+\epsilon})$ queries, for arbitrarily small $\epsilon > 0$.

Quantum speedup for arbitrary Boolean formulas. Childs, Ben Reichardt, and Shengyu

Zhang, with Spalek, generalized the algorithm of Farhi, Goldstone, and Gutmann to arbitrary Boolean formulas written in terms of NAND gates [3]. In general, such formulas can be evaluated using only $O(N^{\frac{1}{2}+\epsilon})$ queries, nearly matching the $O(N^{\frac{1}{2}})$ lower bound of Barnum and Saks.

The power of weak Fourier-Schur sampling. Childs and Wocjan, with Harrow, investigated the Schur transform as a tool for distinguishing quantum states when many copies are available [4]. They showed that a technique called "weak Schur sampling" is not useful for solving the hidden subgroup problem, even when combined with weak Fourier sampling. They also established precise bounds on how many copies are required to distinguish maximally mixed states of two different dimensions, and they related this problem to a quantum version of the collision problem.

Improved quantum algorithms for ordered search. Childs, with Landahl and Parrilo, used numerical semidefinite programming to find an improved quantum algorithm for the problem of searching an ordered list of size N [5]. While the best classical algorithm for this problem uses $\log_2 N$ queries to the list, a quantum computer can solve the problem using a constant factor fewer queries; however, the precise value of this constant is unknown. The running time of the new algorithm of Childs *et al.* has running time approximately $0.433 \log_2 N$, which is the best known result for exact algorithms.

Natural BQP-Complete problems. The hardest problems that can be solved efficiently by a quantum computer are said to be BQP-complete. By characterizing the problems in this class, we deepen our understanding of the power and limitations of quantum computers. Wocjan and Zhang formulated several BQP-complete problems, including Local Hamiltonian Eigenvalue Sampling and Phase Estimation Sampling [6]. In contrast to previously known BQP-complete problems, these problems have a natural formulation in terms of basis notions of linear algebra.

A BQP-complete matrix problem. Wocjan, with Janzing, showed that estimating the diagonal entries of powers of a sparse symmetric matrix A is a BQP-complete problem [7]. The problem can be solved efficiently on a quantum computer by repeatedly measuring A and raising the outcome to a power. Conversely, every quantum circuit that solves a problem in BQP can be encoded into a sparse matrix such that a basis vector corresponding to the input induces one of two different spectral measures, depending on whether the input is accepted or not. These measures can be distinguished by estimating the mth statistical moment for some appropriately chosen m, polylogarithmic in the size of the matrix.

BQP-complete problems concerning mixing properties of classical random walks. Pawel Wocjan, with Janzing, showed that quantum algorithms outperform classical one in analyzing mixing properties of *classical* random walks (provided that BQP $\neq$ BPP) [8]. They described two BQP-complete problems concerning properties of sparse graphs having certain symmetries. These problems could be solved by sampling classical random walks on the graph, but an exponential number of trials would be needed; on the other hand a quantum computer can solve the problems efficiently using the phase estimation algorithm. Furthermore, these problems can be shown to be as hard as any problems in BQP, and so provide interesting examples of BQP-complete problems that have a natural graph-theoretic formulation.

Quantum communication and quantum cryptography

Quantum source coding with side information. Jon Yard, with Devetak, introduced and solved a general two-terminal quantum source coding problem where the sender and receiver each have quantum side information [9]. They determined the asymptotic cost, in terms of entanglement and transmitted qubits, for Alice to redistribute part of a global state to Bob with vanishing error, in the limit where many copies of the state are transmitted. The qubit cost provides the first known operational interpretation of quantum conditional mutual information. The corresponding 'quantum state redistribution' protocol unifies and generalizes several known quantum Shannon-theoretic protocols, including the fully quantum Slepian-Wolf, fully quantum reverse Shannon, state merging, and Schumacher compression protocols.

A decoupling approach to the quantum capacity. Yard, with Hayden, Horodecki and Winter, provided a new proof of the Lloyd-Shor-Devetak coding theorem which proves the existence of quantum codes achieving the coherent information over i.i.d. quantum channels [10]. Their proof uses simple representation-theoretic arguments techniques — in particular, quadratic averages over the unitary group — to provide unitarily invariant ensembles of codes which decouple quantum information from the environment of the channel.

Unification of quantum information theory. Anura Abeyesinghe, with Devetak, Hayden, and Winter, found a simple, direct proof of the "mother" protocol of quantum information theory [11]. In their new formulation, it is easy to see that the mother protocol simultaneously accomplishes two goals: quantum-communication-assisted entanglement distillation, and state transfer from the sender to the receiver. As a result, in addition to her other "children," the mother protocol generates a state merging primitive, a fully quantum reverse Shannon theorem, and a new class of distributed compression protocols. Furthermore, they showed that the mother protocol can be easily transformed into a "father" protocol, whose consequences include the quantum capacity and the entanglement-assisted classical capacity of a quantum channel. Thus the mother protocol provides a unifying theme whose consequences include many of the fundamental results of quantum Shannon theory.

The quantum capacity with symmetric side channels. Graeme Smith, with Smolin and Winter, studied the quantum capacity of a quantum channel when assisted by an arbitrary channel that maps symmetrically to its output and to the environment [12]. This capacity provides an upper bound that is both additive and convex for the (unassisted) quantum channel capacity. The bound seems to be quite tight, and for degradable quantum channels it coincides with the unassisted channel capacity. Using this symmetric side channel capacity, they found new upper bounds on the quantum capacity of the depolarizing channel.

Dynamics of a quantum reference frame. David Poulin and Yard studied how a quantum reference frame is degraded as it is used repeatedly [13]. In their analysis, the reference frame is an object with large angular momentum, and the angular momenta of many spin-$\frac{1}{2}$ objects are measured sequentially relative to this object. They showed that, generically, the reference frame thermalizes in a time linear in its size. They also found that, if the source of spin-$\frac{1}{2}$ particles is polarized, then the reference object rotates to align with the source. Their results shed light on the quantum-to-classical transition in measurement devices.

Security of quantum key distribution using weak coherent states with nonrandom phases. John Preskill, with Lo, proved the security of the Bennett-Brassard (BB84) quantum key distribution protocol in the case where the key information is encoded in the relative phase of a coherent-state reference pulse and a weak coherent-state signal pulse, as in some practical implementations of the protocol [14]. In contrast to previous work, their proof applies even if the eavesdropper knows the phase of the reference pulse, provided that this phase is not modulated by the source, and even if the reference pulse is bright.

Better codes for BB84 with one-way post-processing. Smith, with Renes and Smolin, studied the achievable secret key rate for the BB84 quantum key distribution protocol with one-way classical post-processing [15]. Specifically, they characterized the performance of a family of error-correcting codes when used in the information reconciliation phase of BB84. When combined with noisy postprocessing, these codes allow secure key to be established for quantum bit error rates up to 12.9%. This improvement over the previous best noise threshold of 12.4% illustrates (in contrast to the classical scenario) a marked advantage of structured codes over random codes when used for quantum key distribution.

Quantum entanglement and quantum information theory

Immunizing proof systems against entanglement. Toner, with Kempe, Kobayashi, Matsumoto, and Vidick, described two generic ways to make multi-prover classical games resistant against entangled provers [16]. The first uses quantum communication and a quantum verifier, the second adds an additional prover. Their results establish that computing the quantum value of a Bell inequality with polynomial precision is NP-hard, which implies that the values of entangled prover games cannot be computed by semidefinite programs that are polynomial in the size of the verifier's system, a method that has been successful for more restricted quantum games.

Monogamy of Bell correlations and Tsirelson's bound. Toner and Frank Verstraete studied Bell inequality violation in a tripartite system ABC, characterizing the trade-off between the nonlocality of the Bell correlations observed by AB and of those observed by AC [17]. This generalizes Tsirelson's bound on the quantum value of the CHSH inequality; the latter emerges when C is completely uncorrelated with AB.

Local models for noisy entangled quantum states. Toner, with Acin and Gisin, related the nonlocal properties of noisy entangled states to Grothendieck's constant, a mathematical constant appearing in Banach space theory [18]. For a two-qubit Werner state $\rho_p^W = p|\psi^-\rangle\langle\psi^-| + (1-p)I/4$, they showed that there is a local model for projective measurements if and only if $p \leq 1/K_G(3)$, where $K_G(3)$ is Grothendieck's constant of order 3. Known bounds on $K_G(3)$ prove the existence of this model at least for $p < 0.66$, quite close to the currently known region of Bell violation, $p \sim 0.71$.

Purification of large bi-colorable graph states. Kovid Goyal, Alex McCauley, and Robert Raussendorf described novel protocols for purifying a large class of noisy many-particle entangled states [19]. The protocols work for bicolorable graph states, and scale efficiently for large graph states. They derived simple recursion relations characterizing the behavior of the protocols, and found analytical expressions for the thresholds and the fixed point behavior.

Optimal, reliable estimation of quantum states. Robin Blume-Kohout proposed a new scheme for quantum state estimation, called "Bayesian mean estimation" (BME), which has advantages over the more commonly used method, maximum likelihood estimation (MLE) [20]. BME, unlike MLE, never yields the conclusion that the density operator has zero eigenvalues, and furthermore its eigenvalues provide a bound on their own uncertainties. He showed how to implement BME numerically, and how to determine the error bars of the estimate.

Quantum Darwinism in quantum Brownian motion. Blume-Kohout, with Zurek, studied "quantum Darwinism" — the redundant recording of information about a decohering system by its environment — in zero-temperature quantum Brownian motion [21]. They observed that an initially nonlocal quantum state leaves a record whose redundancy increases rapidly with its spatial extent. Significant delocalization (e.g., a Schroedinger's cat state) causes high redundancy: many observers can measure the system's position without perturbing it. This redundancy, then, can explain the objective existence of decoherence-resistant pointer states of macroscopic objects, giving rise to classical behavior.

The structure of preserved information in quantum processes. Blume-Kohout, Poulin, and Hui Khoon Ng, with Viola, introduced a general characterization of information-preserving structures — including noiseless subsystems, decoherence-free subspaces, pointer bases, and error-correcting codes — in terms of the fixed points of quantum processes [22] . They proved that the fixed states and observables of an arbitrary process are linearly isomorphic to a matrix algebra, which unifies the Schrodinger and Heisenberg pictures and rules out unphysical kinds of information. They also constructed a simple algorithm for efficiently finding all noiseless as well as unitarily noiseless subsystems.

Quantum error correction, fault tolerance, and control

Accuracy threshold for postselected quantum computation. Preskill and Panos Aliferis, with Gottesman, proved an accuracy threshold theorem for fault-tolerant quantum computation based on error detection and postselection [23]. Their proof provides a rigorous foundation for the scheme suggested by Knill, in which preparation circuits for ancilla states are protected by a concatenated error-detecting code and the preparation is aborted if an error is detected. The proof applies to independent stochastic noise but (in contrast to proofs of the quantum accuracy threshold theorem based on concatenated error-correcting codes) not to strongly-correlated adversarial noise. Their rigorously established lower bound on the accuracy threshold, 1.04×10^{-3}, is the highest proved so far.

Fault-tolerant quantum computing using subsystem codes. Aliferis, with Cross, analyzed fault-tolerant quantum computing based on sub-system codes; that is, codes with an unfixed gauge freedom [24]. They observed that for the "Bacon-Shor code" the gauge freedom leads to a highly efficient method for fault-tolerant error correction that can be implemented using only nearest-neighbor two-qubit measurements. Using this method, they proved a lower bound on the accuracy threshold, 1.9×10^{-4} for adversarial stochastic noise, that improves previous lower bounds by almost an order of magnitude.

Effective fault-tolerant quantum computation with slow measurements. Aliferis, with DiVincenzo, showed that fault-tolerant quantum computing can work effectively if measurements are much slower than quantum gates [25]. They pointed out that if the ancilla used to extract an error syndrome is decoded before measurement, then valid syndrome information can be extracted even if the measurement is substantially delayed. They concluded that the quantum accuracy threshold is not much affected for measurement times that are 1,000 times longer than gate execution times, so that slow measurement poses no essential obstacle to scalability. This conclusion is important, since slow measurement appears to be unavoidable in many implementations of quantum computing.

Proving the quantum threshold theorem using level reduction. Aliferis observed that the proof of the quantum threshold theorem can be much simplified by employing the concept of "level reduction" [26]. He used this concept to streamline the proof in a variety of settings, including an analysis of leakage noise and of quantum computation by measurements.

Topological fault-tolerance in cluster state quantum computation. Goyal and Raussendorf, with Harrington, described a fault-tolerant version of the one-way quantum computer [27]. In their scheme, topologically protected quantum gates are realized by choosing appropriate boundary conditions on a three-dimensional cluster state. The spatial dimensionality of the scheme can be reduced to two by converting one spatial axis of the cluster into time.

Optimal and efficient decoding of concatenated quantum block codes. Poulin considered the problem of optimally decoding a quantum error correction code (finding the optimal recovery procedure given the measured values of check operators) [28]. In general, this problem is NP-hard. However, he demonstrated that for concatenated block codes, the optimal decoding can be efficiently computed using a message passing algorithm. Monte Carlo results for the five-qubit and seven-qubit codes demonstrate that the message passing algorithm has a significantly higher error threshold and a significantly better rate compared to previously used decoding methods.

Discrete models for quantum filtering and feedback control. Luc Bouten and Ramon van Handel, with James, developed quantum filters for discrete quantum stochastic models (discrete observables and discrete time) [29]. They introduced discretized models of an atom in interaction with the electromagnetic field, obtained filtering equations for photon counting and homodyne detection, and they solved a stochastic control problem using dynamic programming and Lyapunov function methods. These discrete models are extremely rich while remaining completely within the setting of finite-dimensional Hilbert spaces, thus avoiding the technical complications of the continuous theory.

Experiment and implementation

Protected qubit based on a superconducting current mirror. Kitaev proposed a qubit implementation based on exciton condensation in capacitively coupled Josephson junction chains [30]. In his proposal, the qubit is protected in the sense that all unwanted terms in its effective Hamiltonian are exponentially suppressed as the chain length increases. He also described an implementation of a universal set of quantum gates. Most of these gates have exponential error suppression; the only gate that is not intrinsically fault-tolerant needs to be realized with about 50% precision, provided the other gates are exact.

Criteria for experimental verification of entanglement. Jeff Kimble, with van Enk and Lütkenhaus, proposed several criteria for experimental entanglement verification procedures [31]. They provided explicit examples to demonstrate that not following these criteria will result in overestimating the amount of entanglement generated in an experiment, or in inferring that entanglement is present when it is not. They also highlighted the important distinction between refuting hidden-variable models and verifying entanglement.

Quantum stochastic model for scattering of polarized light by an atomic gas. Bouten, John Stockton, and Hideo Mabuchi, with Sarma, proposed a quantum stochastic model to describe the scattering of polarized laser light by an atomic gas in free space [32]. Within the model they derived the quantum filter equations for polarimetry measurement of the output light. They also showed that, in the strong driving/weak coupling limit, the ad-hoc filter that had already been used in experiments is actually correct.

Cavity QED with multiple hyperfine levels. Kevin Birnbaum, Scott Parkins, and Kimble calculated the weak-driving transmission of a linearly polarized cavity mode strongly coupled to the D2 transition of a single Cesium atom [33]. Their results are relevant to future experiments with microtoroid cavities, where the single-photon Rabi frequency g exceeds the excited-state hyperfine splittings, and also to photonic bandgap resonators, where g is greater than both the excited-state and ground-state splittings.

Strong coupling between one atom and the field of a toroidal microresonator. The Kimble group, in collaboration with the group of Kerry Vahala, achieved strong coupling between single Cesium atoms and the fields of a microtoroidal cavity fabricated from SiO_2 [34]. This is the first experiment to achieve strong coupling for a single atom interacting with an optical resonator other than a conventional Fabry-Perot cavity, and it opens the way for further investigations of potentially scalable optical processes with single atoms and photons in lithographically fabricated microresonators. Possible applications include implementation of quantum networks, scalable quantum logic with photons, and quantum information processing on atom chips.

Toward experimental entanglement swapping. The Kimble group presented a protocol for performing entanglement connection between pairs of atomic ensembles in the single-excitation regime [35]. They prepared two pairs of ensembles in an asynchronous fashion and then connected them via a Bell measurement. They mapped the resulting state of the two remaining ensembles to photonic modes and reconstructed the reduced density matrix. Their observations confirmed for the first time the creation of coherence between atomic systems that never interacted, a first step towards entanglement swapping, a critical requirement for quantum networking and long-distance quantum communications.

Demonstration of reversible state transfer between light and a single trapped atom. The Kimble group demonstrated the reversible mapping of a coherent state of light to and from the hyperfine states of an atom trapped within the mode of a high finesse optical cavity [36]. They verified the coherence of these processes by mapping the atomic state back onto a field state in a way that depends on the phase of the original coherent state. This experiment is an important step towards the realization of cavity QED-based quantum networks, in which coherent transfer of quantum states will enable the distribution of quantum information across the network.

Efficient retrieval of a single excitation stored in an atomic ensemble. The Kimble group reported significant improvements in the retrieval efficiency of a single excitation stored in an atomic ensemble, and in the subsequent generation of strongly correlated pairs of photons [37]. They demonstrated a 50% probability to transform the stored excitation into one photon in a well-defined spatio-temporal mode. They exploited this improvement to generate high-quality heralded single photons with a suppression of the two-photon component below 1% of the value for a coherent state.

Cooling to the ground state of axial motion for one atom strongly coupled to an optical cavity. The Kimble group demonstrated localization to the ground state of axial motion for a single trapped atom strongly coupled to the field of a high finesse optical resonator [38]. They cooled the axial atomic motion using coherent Raman transitions on the red vibrational sideband, and recorded the Raman spectrum to infer the atomic motional state. They found that the lowest vibrational level of the axial potential is occupied with probability 95%.

Entanglement distribution between two quantum nodes. The Kimble group demonstrated entanglement distribution between two remote quantum nodes located three meters apart [39]. They prepared two pairs of atomic memories asynchronously, and coherently mapped the stored atomic states into light fields in an effective state of near maximum polarization entanglement. They verified the entanglement by confirming the violation of Bell inequalities. Quantum nodes like these can be used as segments of a quantum repeater, an essential tool for robust long-distance quantum communication.

Connecting quantum information with the rest of physics

N-representability is QMA-complete. Verstraete, with Liu and Christandl, studied the computational complexity of N-representability, a central problem in quantum chemistry [40]. They showed that this problem is QMA-complete, the quantum generalization of NP-complete. Their proof uses a simple mapping from spin systems to fermionic systems, as well as a convex optimization technique that reduces the problem of finding ground states to N-representability. The result strongly indicates that widely used methods for quantum chemistry computations on classical computers are not scalable.

Matrix product state representations. Verstraete, with Perez-Garcia, Wolf, and Cirac, performed a detailed investigation of matrix product state (MPS) representations for multipartite pure quantum states [41]. They characterized the freedom in representations with and without translation symmetry, derived canonical forms, and provided efficient methods for obtaining them. They also extended previously known methods for constructing MPS representations of ground states of frustration-free Hamiltonians.

Simulation methods for non-Markovian master equations. Michael Zwolak developed a numerical method for simulating a particular class of non-Markovian master equations: integro-differential equations with “increasingly smooth” memory kernels [42]. This method can be used to study the real-time dynamics of a wide variety of systems that are strongly coupled to the environment. The resulting algorithm reduces the computational cost from the previously established T^2 to $T * C(T)$, where T is the total simulation time and $C(T)$ is a function that depends on the properties of the memory kernel; for example $C(T) = O(\ln T)$ for polynomially decaying memory kernels.

Probing non-Abelian statistics using shot noise in Mach-Zehnder interferometers. Kitaev, with Feldman [43] and with Feldman, Gefen, Law, and Stern [44] showed how shot noise in an electronic Mach-Zehnder interferometer in the fractional quantum Hall regime probes the charge and statistics of the quantum Hall quasiparticles. In particular, the dependence of the noise on the magnetic flux through the interferometer distinguishes Abelian from non-Abelian quasiparticle statistics. In the Abelian case, the Fano factor (in units of the electron charge) is always lower than unity. In the non-Abelian case, the maximal Fano factor as a function of the magnetic flux exceeds one. These observations, aside from their intrinsic interest, may hasten progress toward realizing robust topological quantum computers.

Decoherence of anyonic charge in interferometry measurements. Bonderson, with Shtengel and Slingerland, studied a general interferometric scheme for measuring anyonic charge [45]. In their scheme, a target anyon is placed between the arms of a Mach-Zehnder interferometer, where probe anyons travel along the arms and are detected at the output ports. They related the visibility of the interference to the topological S-matrix of the anyon model, and they derived a general criterion for decoherence of a superposition of target charges.

Critical behavior in anyon chains. Kitaev, with Feiguin, Trebst, Ludwig, Troyer, Wang, and Freedman, studied one-dimensional chains of interacting anyons, where the Hamiltonian favors neighboring anyons fusing with trivial total charge (the anyonic analogue of the quantum Heisenberg model) [46]. For a chain of Fibonacci anyons, their numerics showed that the model is critical with a dynamical critical exponent $z = 1$, and described by a two-dimensional conformal field theory with central charge $c = 7/10$. They found an exact mapping of the anyonic chain onto the two-dimensional tricritical Ising model using the restricted-solid-on-solid (RSOS) representation of the Temperley-Lieb algebra, and showed that the gaplessness of the chain has a topological origin. Thus, the theory of topological quantum computing has led to the discovery of a fascinating new class of one-dimensional critical systems.

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