Quantum Information and Computation, Vol. 5, No. 4&5 (2005) 273–274

EDITORIAL: QUANTUM INFORMATION AND QUANTUM CONTROL

This special issue grew out of a workshop held by the Centre for Quantum Information and Quantum Control (http://qubit.chem.utoronto.ca/CQIQC/index.html) at the Fields Institute at the University of Toronto in July 2004 (see http://www.fields.utoronto.ca/programs/scientific/04-05/quantumIC/). The idea of the workshop, as of the Centre and of this issue, is to bring together researchers, ideas, and methods from these two communities, which we believe are intimately related.

In recent decades, techniques to measure and control physical systems have progressed to the extent that it is now possible to exert remarkable control over the evolution of a variety of quantum-mechanical systems, in contexts ranging from trapped ions to molecular collisions, from entangled photons to nuclear magnetic resonance, from optical lattices to spin currents in semiconductors. The field of quantum control has long focused on the task of using interference to "steer" a system towards one or another of its potential final states, and has seen remarkable successes, generally by using lasers to transfer optical coherence to the intermediate states of molecular or solid-state systems. Quantum information, meanwhile, has grown up largely independently, as a field that builds upon a truly novel theoretical perspective about quantum mechanics, on the one hand; and upon a few laboratory systems that already allow single- and/or multiple-qubit operations. The promise of quantum computation is, in fact, the ultimate example of quantum control wherein a large quantum system is to be driven through a set of states in a fully coherent way, arriving with high probability in the appropriate final state. Noise and environmental decoherence along the way will tend to interfere with this desired evolution, and the control will have to be designed to minimize the effect of these "errors" on the final outcome of the "calculation."

It is not difficult to find numerous examples of the overlap of quantum information and quantum control. A few follow below.

The problem of quantum error correction is widely viewed as one of the principal challenges if quantum information processing is to become a reality. As a consequence, the field of quantum information has produced a variety of error-correction methods, as well as striking theorems about error thresholds for scalable computation. However, achieving these thresholds is a difficult task which will require us to learn how to control the evolution of real systems with an accuracy which may need to be on the order of 10^{-5}.

"Feedback control" has been found useful in quantum control studies as means of driving a complex system through a long series of steps. This method requires measuring the state of the system and then adjusting the control parameters in response to the measurement. However, since quantum measurements are necessarily incomplete and inevitably alter the state of the system, any such technique will be limited. Nonetheless, the theory of quantum error correction surprised many by showing, for specific error models, that (a) it would be possible to maintain the coherence of a logical qubit over the course of such measurements and feedback, and (b) that so long as errors were kept below a finite threshold, a system could, in principle, be controlled for an arbitrary period of time and maintained arbitrarily close to its ideal quantum evolution without any information loss during this time. Much more work remains to be done to implement and optimize these protocols in real-world settings, to determine the best methods for extracting information about quantum systems, and to assess limits on quantum feedback control in general.

Questions of this kind create a connection with the theory of quantum communication, where the "environment" often plays the role of an eavesdropper, Eve, who potentially has arbitrarily sophisticated technological abilities. In the case of cryptography, the challenge is to develop the best strategies for preparing and measuring systems, so that Eve obtains as little information as possible, and legitimate partners as much as possible. Quantum communications includes many other protocols, ranging from coin- tossing to digital signatures to 'pseudo-telepathy.' In all, as in quantum error correction, the crucial task is to identify what information can be extracted, disturbed, or controlled by the use of particular measurements and interactions, and to design a system which makes optimal use of these constraints. Often, as in the case of stabilizer codes, the same formalism which illuminates the error-correction problem proves enlightening in this context as well.

Much of the work of developing practical quantum information processing aims at building a complete and reliable set of one- and two-qubit logic gates. In many candidate systems for quantum information processing, there are logic gates, e.g., single-qubit operations in ion traps, which can naturally be manipulated using resonant laser pulses. There are others which are less natural, including single-qubit operations in many solid-state systems, and two-qubit operations in most atomic, molecular, and optical systems. While in some settings, experimentalists already have the capability to perform many of these operations with 99% fidelity, there are settings in which new proposals were needed in order to carry out the operations at all. Even in the best cases, however, the question of how to achieve a high enough fidelity to meet the thresholds for scalable computation (which in some cases are likely to be as high as 99.999%) is far from trivial. This is a fundamentally new problem in quantum control, and one which may be expected to call upon all of the resources of these two communities, ranging from dynamical decoupling and decoherence-free subspaces to two-pathway interference control to adaptive algorithms for optimal control.

This special issue consists of 9 papers selected from the workshop contributions. It includes articles on entanglement in quantum communications protocols; on the extent of errors caused by quantum measurements; on universal features of decoherence, control, and quantum feedback; on specific proposals for controlling qubits in particular systems; and on new results in quantum cryptography. We believe that it gives a sense of the convergence of quantum information and quantum control, and the exciting developments underway in this field today.

We would like to acknowledge the Fields Institute and the Canadian Institute for Advanced Research for their support of this workshop.

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