Invited Speaker

Quantum error correction beyond the depolarizing noise paradigm

Steve Flammia, University of Sydney

Invited Speaker

Black holes and holographic encoding

Daniel Harlow, MIT

Invited Speaker and JQI Seminar

Error suppression for Hamiltonian quantum computation

Daniel Lidar, University of Southern California

We present general conditions for quantum error suppression for Hamiltonian-based quantum computation using subsystem codes. This involves encoding the Hamiltonian performing the computation using an error detecting subsystem code and the addition of a penalty term that commutes with the encoded Hamiltonian. The scheme includes the stabilizer formalism of both subspace and subsystem codes as special cases. We derive performance bounds and show that complete error suppression results in the large penalty limit. We illustrate the power of subsystem-based error suppression with several examples of two-local constructions for protection against local errors, which circumvent an earlier no-go theorem about two-local commuting Hamiltonians. We also discuss the generalization of the quantum error suppression results of Jordan, Farhi, and Shor to arbitrary Markovian dynamics. In this setting we show that it is possible to suppress the initial decay out of the encoded ground state with an energy penalty strength that grows only logarithmically in the system size, at a fixed temperature.

Joint work with Milad Marvian

PRL 118, 030504 (2017)

PRA 95, 032302 (2017)

Hardware-Efficient Bosonic Quantum Error-Correcting Codes

Murphy Niu, MIT

We propose three hardware-efficient bosonic quantum error-correcting (QEC) codes that are suitable for $\chi^{(2)}$-interaction quantum computation in multi-mode-Fock-bases: the $\chi^{(2)}$parity-check code, the $\chi^{(2)}$embedded error-correcting code, and the $\chi^{(2)}$binomial code. All of these QEC codes detect photon-loss or photon-gain errors by means of photon-number parity measurements, and then correct them via $\chi^{(2)}$Hamiltonian evolutions and linear-optics transformations. We establisha symmetry-operator framework for categorizing properties of our $\chi^{(2)}$ QEC codes. This frameworkenables convenient extension of a given encoding to higher-dimensional qudit bases. The $\chi^{(2)}$binomial code is of special interest because, with $m \leq N$ identified from environment monitoring, it can correct m-photon-loss/gain errors and $(m - 1)$th-order dephasing errors using logical qudits that are encoded in $O(N)$ photons. In comparison, other bosonic QEC codes require $O(N^2)$ photons to correct the same degree of bosonic errors. Such improved photon-efficiency underscores the additional error-correction power that can be provided by environment monitoring. We developquantum Hamming bounds for photon-loss errors in the code subspaces associated with the $\chi^{(2)}$ parity-check code and the $\chi^{(2)}$ embedded error-correcting code, and we prove that these codes saturate their respective bounds. Our $\chi^{(2)}$ QEC codes exhibit hardware efficiency in that they address the principal error mechanisms and exploit the available physical interactions of the underlying hardware, thus reducing the physical resources required for implementing their encoding, decoding, and error-correction operations, and their universal encoded-basis gate sets.

Invited Speaker

Quantum error correction for sensing

Paola Cappellaro, MIT

Quantum sensors exploit the strong sensitivity of quantum systems to external disturbances to measure various signals in their environment with high precision. However, the same strong coupling to the environment also limits their sensitivity due to its decohering effects.

Error correction strategies, including quantum error correction codes and dynamical decoupling, can help in fighting decoherence, but they incur the risk of also canceling the coupling to the signal to be measured. Here I will show various strategies that exploit ancillary qubits to achieve an advantageous compromise between noise and signal cancellation, thus improving the sensitivity of the quantum sensor.

Quantum error correction with spins in diamond

Tim Taminiau, QuTech Delft

Spins in diamond are a promising platform for quantum information processing. They combine long coherence times, good gate fidelities and an optical interface that enables coupling spins together into quantum networks [1]. Initial experiments with control of up to 6 qubits have already been realized [2,3], bringing basic quantum error correction codes within reach.

Here I will present an experiment that uses active real---time quantum error correction to improve the dephasing time of a logical qubit beyond the best qubit used in the encoding [4,5]. Furthermore I will discuss recent progress in coherence and control that will enable more sophisticated schemes – such as small surface codes – in the near future.

[1] B. Hensen, et al., Nature 526, 682, 2015
[2] A. Reiserer, et al., Phys. Rev. X 6, 021040, 2016
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[4] J. Cramer, et al., Nature Commun. 7:11526, 2016
[5] N. Kalb, et al., Nature Commun. 7:13111, 2016

Invited Speaker

Universal fault-tolerant computing with Bacon-Shor codes

Theodore Yoder, MIT

We present a fault-tolerant universal gate set consisting of Hadamard and controlled-controlled-Z (CCZ) on Bacon-Shor subsystem codes. Transversal non-Clifford gates on these codes are intriguing in that higher levels of the Clifford hierarchy become accessible as the code becomes more asymmetric. For instance, in an appropriate gauge, Bacon-Shor codes on an m-by-mk lattice have transversal k-qubit-controlled Z. We also describe how, for any stabilizer code, logical operator asymmetry is a necessary condition for transversal gates in high levels of the Clifford hierarchy. For Bacon-Shor CCZ, through a variety of tricks, including intermediate error-correction and non-Pauli recovery, we reduce the overhead required for fault-tolerant implementation. We calculate pseudothresholds for our universal gate set on the smallest 3-by-3 Bacon-Shor code and also compare our gates with magic-states within the framework of a proposed ion trap architecture.

Invited Speaker

The Definition(s) of Fault Tolerance

Daniel Gottesman, Perimeter Institute

There are many different fault-tolerant quantum protocols known. However, it is surprisingly difficult to come up with a rigorous definition of exactly what it means for a protocol to be fault tolerant. This is important in part because a number of groups are attempting to demonstrate fault tolerance experimentally, and we need an agreed-upon definition to evaluate if they are successful. It is also important as we try to come up with new fault-tolerant protocols, perhaps based on different principles than existing protocols, or perhaps to apply to particular error models instead of the fairly generic ones typically used. I will discuss different possible definitions that one might use and conclude that there is no single correct answer, but rather a set of related fault-tolerant properties that protocols may have.

Invited Speaker

Gauge color codes in two dimensions

Cody Jones, HRL

I describe recent results for constructing subsystem color codes that are capable of universal encoded logic, using only finite-range operations in two dimensions. The codes can be constructed by "gluing together" conventional 2D color codes using low-weight measurements of gauge operators, up to a maximum weight of 8. In addition to the construction, I briefly discuss the connection to recent results that jointly constrain dimensionality of a code (where two-qubit physical operations are finite range) and the allowable encoded operations (which level of the Clifford hierarchy). By having transversal T gates in two dimensions, these codes necessarily do not have a threshold for error correction in the strict sense, but I describe how the codes come interestingly close to having a threshold.

The results are published at Jones, et al. Phys. Rev. A 93, 052332 (2016).

Majoranas and Color Codes -- A Topological Love Story

Daniel Litinski, Free University of Berlin

We present a scalable architecture for fault-tolerant quantum computation in topological superconductor networks using color codes for error correction. Color codes have a set of transversal gates which coincides with the set of topologically protected gates of Majorana-based qubits, namely the Clifford gates. In this way, we establish color codes as a perfect match to Majorana-based qubits, as color codes allow the direct use of braiding of Majoranas for logical gates. For Majorana-based qubits with ancilla-free syndrome readout, color codes not only minimize the overhead for Clifford gates, but also offer a higher error threshold compared to surface codes. We provide a complete description of our architecture, from the underlying physical ingredients to the arrangement of logical qubits for universal quantum computation.

Based on arXiv:1704.01589

Invited Speaker

Logical state preparation subject to coherent errors

Sergey Bravyi, IBM

We investigate the effect of coherent errors on the performance of 2D surface codes in the regime of large code distances. To this end we consider the standard fault-tolerant protocol for preparation of logical X or Z states by performing syndrome measurements starting from a tensor product of physical X or Z states. The initial product state may deviate from the ideal one due to unitary over-rotation or misaligned axis errors. We propose an exactly solvable Majorana fermion model describing the above protocol. The model enables efficient numerical simulation of the syndrome measurements and calculation of the logical Bloch vector conditioned on the observed syndrome. The runtime of the simulation algorithm scales as n^2, where n is the number of physical qubits. Numerical results are reported for systems with n=O(1000) qubits.

Joint work with Matthias Englbrecht, Robert Koenig, and Nolan Peard

Invited Speaker

Magic state distillation protocols

Jeongwan Haah, Microsoft

We present an infinite family of protocols to distill magic states for T-gates that has a low space overhead and uses an asymptotic number of input magic states to achieve a given target error that is conjectured to be optimal. The space overhead, defined as the ratio between the physical qubits to the number of output magic states, is asymptotically constant, while both the number of input magic states used per output state and the T-gate depth of the circuit scale linearly in the logarithm of the target error δ (up to log log$1/\delta$). Unlike other distillation protocols, this protocol achieves this performance without concatenation and the input magic states are injected at various steps in the circuit rather than all at the start of the circuit. The protocol can be modified to distill magic states for other gates at the third level of the Clifford hierarchy, with the same asymptotic performance. The protocol relies on the classification of weakly self-dual CSS codes and canonical choice of logical operators, allowing us to implement controlled Hadamard or controlled Swap fault-tolerantly. We present several specific small examples of this protocol.

Joint work with M. B. Hastings, D. Poulin, and D. Wecker.

Invited Speaker

The 3D surface code - the ugly duckling of topological codes?

Dan Browne, University College London

Invited Speaker

Measuring logical error scaling with the surface code

John Martinis, Google and UCSB

The practical goal of quantum error correction is logical error rates in the range of 10^{-12} to 10^{-15}. Since the error rate scales approximately as Λ^{-n}, this can only be achieved by both making accurate qubits with errors significantly below the threshold, so that Λ >~10, and scaled to large order n. I will present our project at Google to measure Lambda for both bit and phase flip error correction for the surface code, measured from first and second order error correction, which will require a square array of qubits of physical size about 50. I also will show how system fidelity can be measured with large depth and breadth quantum circuits using a quantum supremacy experiment, which is an important tool for comparing the measured and predicted Λ.

Invited Speaker

IBM Quantum Experience

Hanhee Paik, IBM

In 2016 IBM established the first cloud-based quantum processor. This superconducting quantum computing system, the IBM Quantum Experience, was designed specifically for research and education, and provides a practical environment to develop and run small quantum algorithms. I overview this Quantum Experience's hardware, focusing on details of the latest 16-qubit version. I present some of IBM's ongoing experimental efforts to reduce errors and crosstalk in the hardware, and demonstrate our new QISKIT software platform that enables quantum code developers to easily engage with the quantum processor.

Invited Speaker

TBD

Rob Schoelkopf, Yale

Invited Speaker

Renormalization group decoder for a four-dimensional toric code

Barbara Terhal, Aachen

We describe a computationally-efficient heuristic algorithm based on a renormalization-group procedure which aims at solving the problem of finding minimal surface given its boundary (curve) in any hypercubic lattice of dimension D>2. We use this algorithm to correct errors occurring in a four-dimensional variant of the toric code, having open as opposed to periodic boundaries. For a phenomenological error model which includes measurement errors we use a five-dimensional version of our algorithm, achieving a threshold of 4.35%. For this error model, this is the highest known threshold of any topological code. Without measurement errors, a four-dimensional version of our algorithm can be used and we find a threshold of 7.3%. For the gate-based depolarizing error model we find a threshold of 0.31% which is below the threshold found for the two-dimensional toric code.

Joint work with Kasper Duivenvoorden and Nikolas Breuckmann.

Invited Speaker

Towards sufficiently fast quantum error correction

Austin Fowler, Google

Superconducting qubits can implement gates in tens of nanoseconds. This is good, since we want a quantum computer to be fast, however it makes it challenging for a classical computer to keep up when performing the interactive classical computation associated with fault-tolerant quantum computation. In this talk, I discuss a failed attempt to write single-core software capable of keeping pace with approximately 100 qubits. I then discuss shortcuts that, despite hurting the logical error rate, currently appear necessary to achieve the minimum classical processing speed.

Local efficient decoders for topological toric and color codes in any dimension

Aleksander Kubica, IBM

Invited Speaker

The cost of universality: a comparative study of the overhead of state distillation and code switching in color codes

Michael Beverland, Microsoft

Invited Speaker

Small angle rotations: exotic magic states vs gate synthesis

Earl Campbell, Sheffield

Standard error-correction techniques only provide a quantum memory and need extra gadgets to perform a computation. Central to quantum algorithms are small angle rotations, which can be fault-tolerantly implemented given a supply of an unconventional species of magic state. An important practical question is whether it is more resource efficient to distil these exotic magic state or use standard T state distillation protocols combined with gate synthesis. I will review earlier work on this problem and then introduce two new classes of magic state distillation protocols. The first class of protocols builds on the work of Duclos-Cianci and Poulin (2015 Phys. Rev. A 91 042315) by compressing their circuit. Details for this first class are published in Quantum Science and Technology 1, 015007 (2016). The second class offers a further improvement in efficiency and prepares multi-qubit magic states as an intermediate step. A paper describing this second class of protocols is in preparation. Using a popular metric counting raw magic states consumed, these approaches are found to be a significant improvement over gate synthesis. As such, these protocols hint that quantum simulation and chemistry problems may be much less resource intensive than previously thought. However, future study of a complete architecture is needed to determine the full space-time resource costs of competing approaches.

Poking holes and cutting corners to achieve Clifford gates with the surface code

Benjamin Brown, Niels Bohr International Academy

The surface code is currently the leading proposal to achieve fault-tolerant quantum computation. Among its strengths are the plethora of known ways in which fault-tolerant Clifford operations can be performed, namely, by deforming the topology of the surface, by the fusion and splitting of codes, and even by braiding engineered Majorana modes using twist defects. Here, we present a unified framework to describe these methods, which can be used to better compare different schemes and to facilitate the design of hybrid schemes. Our unification includes the identification of twist defects with the corners of the planar code. This identification enables us to perform single-qubit Clifford gates by exchanging the corners of the planar code via code deformation. We analyze ways in which different schemes can be combined and propose a new logical encoding. We also show how all of the Clifford gates can be implemented with the planar code, without loss of distance, using code deformations, thus offering an attractive alternative to ancilla-mediated schemes to complete the Clifford group with lattice surgery.

Joint work with Katharina Laubscher, Markus S. Kesselring,and James R. Wootton

Published in Phys. Rev. X **7**, 021029 (2017)

Invited Speaker

Surprises in Quantum Error Correction

David Poulin, Sherbrooke

Given a physical noise rate, how much of an overhead do I actually need to achieve a desired logical accuracy? We have devised numerical simulations platforms for the surface code and for concatenated codes that can take as input a wide range of noise models, including non-Pauli and correlated noise, and output a logical noise model after some amount of error correction. In this talk, I will briefly describe these numerical tools and present surprising results that we have obtained using them.

This work is in collaboration with Pavithran Iyer and Andrew Darmawan.

Some of the results are presented in http://arxiv.org/abs/arXiv:1607.06460

Invited Speaker

Decoding the Hawking radiation

Beni Yoshida, Perimeter Institute

We present simple decoding protocols for reconstructing a quantum state from the Hawking radiation in the Hayden-Preskill black hole thought experiment. The reconstruction fidelity can be computed from out-of-time ordered correlation functions where strong scrambling guarantees faithful reconstruction.

This is a joint work with Alexei Kitaev.

Invited Speaker

Towards holography via quantum source-channel codes

Fernando Pastawski, Free University of Berlin

While originally motivated by quantum computation, quantum error correction (QEC) is currently providing valuable insights into many-body quantum physics such as topological phases of matter. Furthermore, mounting evidence originating from holography research (AdS/CFT), indicates that QEC should also be pertinent for conformal field theories. With this motivation in mind, we introduce quantum source-channel codes, which combine features of lossy-compression and approximate quantum error correction, both of which are predicted in holography. Through a recent construction for approximate recovery maps, we derive guarantees on its erasure decoding performance from calculations of an entropic quantity called conditional mutual information. As an example, we consider Gibbs states of the transverse field Ising model at criticality and provide evidence that they exhibit non-trivial protection from local erasure. This gives rise to the first concrete interpretation of a bona fide conformal field theory as a quantum error correcting code. We argue that quantum source-channel codes are of independent interest beyond holography.

Joint work with Jens Eisert and Henrik Wilming

Limits on storage of quantum information in a volume of space

Michel Kastoryano, Niels Bohr Institute

Fault-tolerant quantum computation with few qubits

Rui Chao, University of Southern California

Reliable qubits are difficult to engineer, but standard fault-tolerance schemes use seven or more physical qubits to encode each logical qubit, with still more qubits required for error correction. We give space-efficient methods for fault-tolerant error correction and computation. For example, in a system with fewer than 20 qubits total, we can protect and compute fault tolerantly on seven encoded qubits. Seven qubits suffice to protect one encoded qubit. A main technique is to use gadgets to catch correlated faults. The procedures could enable testing more sophisticated protected circuits in small-scale quantum devices.

Joint work with Ben Reichardt.

Based on arXiv:1705.02329 and arXiv:1705.05365.

Invited Speaker

Fault-tolerant quantum error detection with trapped ions

Norbert Linke, University of Maryland

Fault tolerance removes the assumption of perfect encoding and decoding operations of logical qubits. Showing that all elements of error correction can be realized in a fault-tolerant way is therefore of fundamental interest.

We present the experimentalimplementation of the [[4,2,2]] code, an error detection protocol [1] which uses four physical qubits to encode two logical qubits, one of which can be made fault-tolerant by appropriate construction of the encoding and stabilizer circuits [2]. Remarkably, it works with a bare ancilla qubit.

The results demonstrate for the first time the robustness of a fault-tolerant qubit to imperfections in the very operations used to encode it, as errors are suppressed by an order of magnitude. We present data to show that this advantage over a non-fault-tolerant qubit persists even in the face of both large added error rates and coherent errors. The residual errors are also below or at break-even level compared with the error probability of a single physical qubit [3].

The experiment is performed on a programmable quantum computer comprised of five trapped 171Yb+ ions. It provides a fully connected system of atomic clock qubits with long coherence times and high gate fidelities that can be programmed to execute arbitrary quantum circuits [4].

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[2] D. Gottesman, arXiv 1610.03507 (2016).
[3] N. M. Linke, M. Gutierrez, K. A. Landsman, C. Figgatt, S. Debnath, K. R. Brown, C. Monroe, arXiv 1611.06946v2 (2016).
[4] S. Debnath, N. M. Linke, C. Figgatt, K. A. Landsman, K. Wright, and C. Monroe, Nature 536 (2016).

Repetitive stabilizer readout with conditional feedback using a mixed-species trapped ion register

Matteo Marinelli, ETH Zurich

Quantum error correction involves repeated rounds of syndrome extraction and recovery, involving multi-qubit non-demolition measurements along with conditional feedback. This requires the use of systems in which, measurement and decision times are short compared to relevant decoherence timescales, and in which the act of measurement does not destroy subspace coherence or disrupt future operations. Using a mixed-species ion chain, we demonstrate repeated parity measurement on two beryllium ion “clock” qubits by coupling these to a co-trapped calcium ion. Fluorescence readout of the calcium ancilla has no direct effect on the internal states of beryllium ions but heats up the ions’ motion, from which we re-cover by sympathetically cooling the ion chain using calcium. Using the ability to rapidly make sequence branches in our classical computer control, we perform feedback on the beryllium qubits conditioned on the ancilla readout, which we use to prepare and stabilize entangled states and parity subspaces. Our work takes place in a multi-zone segmented trap setup in which we have demonstrated full quantum control of both species and multi-well ion shuttling. The methods demonstrated here could be applied to quantum error correcting codes as well as quantum metrology and are key ingredients for realizing a hybrid universal quantum computer based on trapped ions.

Invited Speaker

Progress towards a fault tolerant color code qubit on trapped ions

Mauricio Gutierrez, University of Swansea

In this talk, I will give an overview of the current work being performed by the Encoded Qubit Alive (eQual) consortium towards the implementation of a trapped-ion based logical qubit that can outperform its physical constituent qubits. I will describe some of the experimental capabilities that are being developed by several consortium nodes in order to achieve this goal, including the operation of segmented traps, ion crystal reconfiguration, and fast on-chip feed-forward. I will also explain various trapped-ion schemes to perform fault tolerant (FT) quantum error correction (QEC) on a distance-3 color code qubit. For these, I will discuss their expected performance as obtained from numerical simulations, for current and anticipated experimental parameters, allowing us to identify the break-even point of useful QEC. Finally, I will briefly outline recent theory work of our team in Swansea aiming to address two extensibility challenges, namely the coupling of logical qubits and the implementation of a logical qubit of larger distance.

Preparation of Grid state qubits by sequential modular position measurements of trapped ions motion

Christa Flühmann, ETH Zurich

Preparation of Grid state qubits by sequential modular position measurements of trapped ions motion
The noncommutativity of position and momentum observables is a hallmark features of quantum physics. However this incompatibility does not extend to observables which are dependent on these base variables in a periodic fashion. Thus modular position and momentum can be used as stabilizers for the quantum error correcting codes proposed by Gottesman, Kitaev and Preskill [1]. We implement sequential measurements of modular variables in the oscillatory motion of a single trapped ion, using state-dependent displacements and a heralded non-destructive readout [2]. I will describe how we analyze their commutative nature by observing non-signaling between modular position and momentum measurement on a variety of input states. Further we implement incompatible measurement settings which allow us to measure signaling in time (SIT), which we enhance using squeezed states. SIT was proposed as means to exclude macro-realistic theories and often serve as efficient quantum witness, allowing the analysis of the quantum classical divide [3, 4]. Combining the control over these sequential measurements with the ability to prepare squeezed states [5] we are able to encode an approximate Grid state qubit [1] in the continuous variable phase space of our trapped ions motion. I will present preliminary results on the preparation and readout of these states and further show how we implement single qubit operations.

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[2] D. Kienzler, C. Flühmann, V. Negnevitsky, H.-Y. Lo, M. Marinelli, D. Nadlinger, and J. P. Home, Physical Review Letters **116**, 140402 (2016).
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[5] D. Kienzler, H.-Y. Lo, B. Keitch, L. de Clercq, F. Leupold, F. Lindenfelser, M. Marinelli, V. Negnevitsky, and J. P. Home, Science **347**, 53 (2015).

Invited Speaker

Entanglement, Wormholes, and Quantum Error Correction

Brian Swingle, University of Maryland

I will discuss recent results aimed at understanding the connections between entanglement and wormholes. These results are obtained in simple topological gauge theories as well as strongly interacting gauge theories described by AdS/CFT duality. I will highlight interesting geometrical perspectives on error correcting codes obtained from these results and comment on the role of error correction in quantum gauge theories and beyond.

Performance of hyperbolic surface codes

Anirudh Krishna, Sherbrooke

Quantum Error Correction of Reference Frame Information

Sepehr Nezami, Stanford

The existence of quantum error correcting codes is one of the most counterintuitive and potentially technologically important discoveries of quantum information theory. Standard error correction refers to abstract quantum information, i.e., information that is independent of the physical incarnation of the systems used for storing the information. There are, however, other forms of information that are physical, one of the most ubiquitous being reference frame information. Here we analyze the problem of error correcting physical information. The basic question we seek to answer is whether or not such error correction is possible and, if so, the limitations to which it is subjected. The issue is highly nontrivial given the fact that the systems that need to be used for transmitting physical information must contain the physical quantity we are interested in, so that all actions applied to them (including the encoding/decoding necessary for error correction) are subject to limiting constraints. Focusing on the case of erasure noise, after demonstrating that the problem is equivalent to the study of quantum errorcorrection using group-covariant encodings, we present the following results. First, in the case of groups like U(1), SU(2) and SO(3) having an infinitesimal generator, no finite dimensional codes exist. Secondly, we show through examples that U(1), SU(2) and SO(3) nonetheless have infinite dimensional codes. Finally, we demonstrate that all finite groups have finite dimensional codes, giving both an exact construction and a randomized approximate construction with exponentially better parameters.

Joint work with Patrick Hayden, Sandu Popescu, and Grant Salton

Invited Speaker

QEC in 2017: Past, present, and future

John Preskill, Caltech

I assess some open problems in quantum error correction in light of the progress reported at QEC 2017. Topics addressed include near-term fault-tolerance experiments, quantum sensing , topological codes, self correction, quantum computing with anyons , and the interface of quantum information with condensed matter physics and quantum gravity.