Book of abstracts QEC meets OA

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Invited talks

Stabilizer Formalism for Operator Algebra Quantum Error Correction and Entanglement-Assisted Codes

David Kribs

In this talk, I'll start with a brief review of the general quantum error correction framework introduced a number of years ago called operator algebra quantum error correction (OAQEC). I'll then discuss recent work that introduces a stabilizer formalism for OAQEC, which generalizes Gottesman's formulation for traditional quantum error correcting codes and Poulin's for operator quantum error correction and subsystem codes, and also allows for the construction of hybrid classical-quantum stabilizer codes. I'll discuss some of the error correction theory we've developed and some examples. Additionally, and time dependent, I'll discuss a new framework, which we have discovered as an application of this stabilizer formalism, for entanglement-assisted quantum error correction that both unifies and generalizes the main frameworks for such codes.

Throughout the talk I'll also try to mix in some of my personal perspectives on QEC history over the last couple of decades. This talk is based on joint works with many collaborators over the years, but primarily on recent works with Serge Adonsou, Guillaume Dauphinais, Priya Nadkarni, and Michael Vasmer.

Dynamical Decoupling of Unbounded Operators

Daniel Burgarth

Dynamical Decoupling is a practical and generic method to reduce errors in quantum devices via a sequence of fast pulsed rotations. This is before error correction- the errors are (partially) prevented in the first place. The motivation is to get the physical error rate sufficiently low to be able to then use quantum error correction on top. While this is experimentally well established, relatively little is known theoretically on how efficient the method is when the environment Hamiltonian or the coupling to the environment is unbounded. I will report some work in progress which provides us with bounds on the convergence speed of dynamical decoupling of unbounded operators.

Sufficient condition for quantum advantage in continuous-variable quantum computing architectures

Giulia Ferrini

In this talk I will show how tools borrowed from quantum error correction can be used to derive results on the simulatability of a restricted class of continuous-variable quantum computing architectures, as well as a sufficient condition for quantum states to restore quantum advantage in such architectures. The restricted class of circuits that we consider is composed of stabiliser Gottesman-Kitaev-Preskill (GKP) states [1], together with Gaussian operations and quadrature measurements. Using the stabilizer formalism, we show that this class of architectures is classically efficiently simulatable [2,3,4]. Hence we refer to these circuits as to SGKP circuits, for "simulatable" GKP circuits. Such architectures also include the circuit gadget used for performing quantum error correction with GKP states. Combining this with the result that GKP error-correction of the vacuum yields magic states [5], we point out that our result on the simulatability of SGKP circuits implies that vacuum provides quantum advantage in such circuits. Finally, we address the question: which other states provide quantum advantage for computation in such architectures? We answer this question by introducing a sufficient condition, based on mapping the CV states to the qubit space defined by the GKP code-space. This sufficient condition also provides an operational interpretation to some of the sub-system decompositions that were previously introduced in the litterature, such as the stabilizer subsystem decomposition [7]. [1] D. Gottesman et al, Phys.Rev.A 64, 01231 (2001) [2] L. García-Álvarez et al, Physical Review Research 2 (4), 043322 [3] C. Calcluth et al, Quantum 6, 867 (2022) [4] C. Calcluth et al, Physical Review A 107, 062414 (2023) [5] B. Baragiola et al, Phys. Rev. Lett. 123, 200502 (2019) [6] C. Calcluth et al, arXiv preprint arXiv:2309.07820 (accepted on PRX Quantum) [7] M. H. Shaw et al, PRX Quantum 5, 010331 (2024)

Quantum Error Correction with Erasure Qubits

Katie Chang

Simulation of error models

Marius Junge

Abstract: We will discuss continuous error models and how to simulate them with accessible sets of unitaries. Using ideas from noncommutative geometry, we can cook up norms on spaces for channels which allow for lower bounds on the convexified simulation cost. In some cases the lower and upper bounds can both be expressed as polynomial in number of qubits.

How to fault-tolerantly realize any quantum circuit with local operations

Robert Koenig

We show how to realize a general quantum circuit involving gates between arbitrary pairs of qubits by means of geometrically local quantum operations and efficient classical computation. We prove that circuit-level local stochastic noise modeling an imperfect implementation of our derived schemes is equivalent to local stochastic noise in the original circuit. Our constructions incur a constant-factor increase in the quantum circuit depth and a polynomial overhead in the number of qubits: To execute an arbitrary quantum circuit on n qubits, we give a 3D quantum fault-tolerance architecture involving $O(n^{(3/2)} log^3 n)$ qubits, and a quasi-2D architecture using $O(n^2 log^3 n)$ qubits. Applied to recent fault-tolerance constructions, this gives a fault-tolerance threshold theorem for universal quantum computations with local operations, a polynomial qubit overhead and a quasi-polylogarithmic depth overhead. More generally, our transformation dispenses with the need for considering the locality of operations when designing schemes for fault-tolerant quantum information processing.

This is joint work with Shin Ho Choe, arXiv:2402.13863 .

Evidence for the utility of quantum computing before fault tolerance

Kristan Temme

Quantum computers can offer dramatic speed-ups over their classical counterparts for certain problems. However, noise remains the biggest impediment to realizing the full potential of quantum computing. While the theory of quantum error correction offers a solution to this challenge, a large-scale realization of fault tolerance is still pending. What can one hope to do then, with existing noisy processors? In this talk I will discuss noise - learning and error-mitigation protocols used in experiments, that produce reliable expectation values from a noisy 127 qubit processor. These experiments demonstrate the implementation of quantum circuits at a scale that in general is only accessible with classical approximation methods. We argue that these experiments represent the first evidence that useful information can be obtained from current devices in a pre-fault-tolerant era.

Homological Quantum Rotor Codes

Christophe Vuillot

We formally define homological quantum rotor codes which use multiple quantum rotors to encode logical information. These codes generalize homological or CSS quantum codes for qubits or qudits, as well as linear oscillator codes which encode logical oscillators. Unlike for qubits or oscillators, homological quantum rotor codes allow one to encode both logical rotors and logical qudits in the same block of code, depending on the homology of the underlying chain complex. In particular, a code based on the chain complex obtained from tessellating the real projective plane or a Möbius strip encodes a qubit. We discuss the distance scaling for such codes which can be more subtle than in the qubit case due to the concept of logical operator spreading by continuous stabilizer phase-shifts. We give constructions of homological quantum rotor codes based on 2D and 3D manifolds as well as products of chain complexes. Superconducting devices being composed of islands with integer Cooper pair charges could form a natural hardware platform for realizing these codes: we show that the 0-π-qubit as well as Kitaev's current-mirror qubit – also known as the Möbius strip qubit – are indeed small examples of such codes and propose a systematic way of designing superconducting circuits implementing any given quantum rotor code.

Information capacities of quantum dynamical systems

Omar Fawzi

I will discuss the information transmission capabilities (both classical and quantum) of quantum dynamical systems. I will present different setups, but will mostly focus on the zero-error setting and its algebraic characterization. Based on joint work with Mostafa Taheri and Mizanur Rahaman.

Universal quantum computing in two dimensions without getting tied in knots

Ben Brown

Large-scale quantum computing requires a universal set of fault-tolerant logical operations. Here we show that we can complete a universal set of logic gates with an Abelian topological phase by transforming its ground state onto that of a non-Abelian phase, and subsequently reversing the operation. We show concretely that this process maps the ground-space of an Abelian phase onto a useful magic state. We show how this process can be made fault-tolerant using a just-in-time decoder. In addition, we show how known proposals for non-Clifford operations for two-dimensional codes can be interpreted as a transition between different topological phases, thereby unifying the theory of non-Clifford gates with Abelian codes. Conversely, we argue that this equivalence gives us a path to robustly prepare non-Abelian phases with apparatus that is available with near-term experiments.

Understanding logical channels graphically: Quantum Error Correction in space-time

Julio Carlos Magdalena de la Fuente

Understanding and protecting against errors happening on a quantum device constitute one of the biggest challenges in developing a fault-tolerant quantum computing architecture. Recently, the focus of the community shifted from a static perspective, where information is encoded into a (fixed) subspace, to a dynamical perspective where one allows for the logical subspace to change over time [1], with the most famous example being Floquet codes, error-correcting protocols defined by a periodic sequence of low-weight non-commuting (Pauli) measurements [2]. Understanding and analyzing such protocols in the presence of errors is an important challenge to devise and to understand new error-correcting protocols. We argue that tensor network methods inspired by the ZX calculus are good tools to analyze the error-correction properties of dynamical protocols as they allow for a simple, graphical, yet complete understanding of the evolution of logical information through a circuit, also in the presence of errors [3]. In this talk, I want to give an introduction on how to represent circuits composed of Clifford unitaries and Pauli measurements as a tensor network. First, I introduce the elementary tensors from which one can build tensor networks resembling the circuits of the above form. To understand error-correcting properties of a circuit expressed as a tensor network, I introduce the notion of *projective Pauli flow* in terms of projective symmetries of the building blocks of the network [4]. I will show how all quantities needed to perform error-correction on a circuit can be understood graphically as different types of Pauli flow. I will conclude the talk with some examples, including a new Floquet Code which we call "XYZ Ruby Code", derived from topological subsystem codes [4].

[1] Delfosse, Paetznick; "Spacetime codes of Clifford circuits", arXiv:2304.05943
[2] Hastings, Haah; "Dynamically Generated Logical Qubits", arXiv:2107.02194
[3] Bombin et al; "Unifying flavors of fault tolerance with the ZX calculus", arXiv:2303.08829 [4] Magdalena de la Fuente, Old, et al.; in preparation

Zero-error communication, scramblings and ergodicity

Mizanur Rahaman

Motivated by Shannon's theory of zero-error communication, we study the quantum channel version of the zero-error capacity problem. The long term behaviour of a quantum channel under iterations (i.e. under repeated applications of itself) yields many interesting properties. For example, it is observed that almost all channels exhibit the property that the one-shot zero-error capacity (classical or quantum) vanishes when large iterations are applied. This motivates us to investigate the threshold point of a channel, after which no classical or quantum message can be sent through the channel without making an error. More precisely, the objective is to find the minimum number of iterations needed for a channel such that the one-shot zero-error capacity becomes trivial. In this talk, I will discuss how mathematical techniques from the theory of operator algebras can be used to provide an upper bound for this threshold point. This investigation initiates a way to understand how quantum error correction works under a dynamical system given by iterations of a quantum channel.

Localized Statistics Decoding: A Parallel Decoder for Quantum Low Density Parity Check Codes

Timo Hillmann

For fault-tolerant quantum computing, real-time decoding of measured syndromes is a strong requirement. With the looming demands of full-scale quantum computers, decoding algorithms must be highly efficient and parallelizable, processing terabytes of syndrome information per second. While this challenge has been well discussed for the decoding of surface codes that relies on the minimum-weight perfect matching algorithm, its applicability to general quantum codes is limited due to requirements for defect pairs. The current gold standard for quantum LDPC codes, belief propagation plus ordered statistics decoding (BP+OSD), exhibits notable error suppression but suffers from inefficient runtime scaling with larger decoding graphs. Here, we propose belief propagation plus localized statistics decoding (BP+LSD) as a parallel and efficient decoder for quantum LDPC codes. BP+LSD leverages the locality of errors in the Tanner graph, addressing individual decoding regions concurrently without needing full inversion of the check matrix. By employing a union-find cluster growth strategy and high-order OSD within local decoding regions, BP+LSD-0 matches the performance of BP+OSD-0 while significantly improving average runtime complexities.

Hybrid optomechanical superconducting qubit system

Juuso Manninen

We propose an integrated nonlinear superconducting device based on a nanoelectromechanical shuttle. The system can be described as a qubit coupled to a bosonic mode. The topology of the circuit gives rise to an adjustable qubit/mechanical coupling, allowing the experimenter to tune between linear and quadratic coupling in the mechanical degrees of freedom. Owing to its flexibility and potential scalability, the proposed setup represents an important step towards the implementation of bosonic error correction with mechanical elements in large-scale superconducting circuits. We give preliminary evidence of this possibility by discussing a simple state-swapping protocol that uses this device as a quantum memory element.

QEC codes: An overview of current developments

Alexander Frei

We give an overview and current developments of (fault tolerant) QEC codes in the spirit of this workshop: More precisely, we will have a look on subsystem codes improving tradeoff bounds, including Bacon–Shor codes and their dynamical variant the Floquet codes, as well as QECCs arising from anyon models, including some basic color codes and string net condensation, and just touch upon gauge color codes as their subsystem variants. We will further mention here the non-abelian stabilizer variants, the XS- and the XP-stabilizer codes (as developed by colleagues within the audience), as an interesting new direction in QEC.

This talk is meant as a recap and overview of current developments in QEC codes and to hopefully guide and serve for interesting discussions.

What algorithms should we study with 100 qubits and 1M logical gates?

Alexandru Paler

The recent neutral atom error-correction experiments have sparked the interest in the implementation and execution of larger scale protocols and computations. The near-term research question is reflected in the title of this talk, and in order to answer it, the most feasible approach is co-design. This means that QEC and FT-protocols, on the one hand, and algorithms/circuits, on the other hand, influence each other through the architecture of the hardware. Co-design is a complex process and can be both theoretically and practically, investigated by analyzing the software stack that translates an algorithm to an executable circuit. The stack includes levels which are not necessarily traversed in a top-down, sequential manner [9]: a) compilation into a fault-tolerant form [1,2], b) preparation for error-correction [3,4], and c) various types of optimization [5,6]. Computational faults are avoided and errors are corrected during the execution of the circuit [7].

In order to co-design algorithms with hundreds of qubits and millions of gates, one should start from the following research questions related to the execution of simpler protocols: a) how are injection protocols (e.g. [8]) reflected in the decoding of correlated errors?; b) do logical qubits suffer from novel/unexpected types of errors, and if so, what is the effect of these errors on the structure of the fault-tolerance compilation primitives? c) what logical cycle times are to be expected based on the underlying architecture, and how much of an improvement is necessary for lowering the resource counts?

In the first part of the talk, we will present a realistic software stack that is already available and can be used for automating the search and co-design of algorithms. In order to answer the research questions, new models, methods and (software) tools need to be researched and implemented. These aspects are discussed in the second part of the talk. The methods and results presented herein were developed partially within projects (where the speaker is a PI) funded by the DARPA Quantum Benchmarking program, QuantERA and Google.

Operational quantum reference frames and some applications

Leon Loveridge

Operational quantum physics is founded on the utilisation of the full probabilistic structure afforded by Hilbert space quantum theory, in which observables are identified with positive operator-valued measures (povms). Among other things, this allows for a general account of realistic quantum experiments, approximate joint measurements of position and momentum, and the construction of time observables 'conjugate' to some semi-bounded Hamiltonians. In this talk I'll present an application of the operational framework in the setting of quantum reference frames (qrfs). After motivating the study of qrfs, I'll describe some recent work providing a rigorous frame change procedure, followed by an illustration of the role played by qrfs in the 'type reduction' of the algebra of observables of a quantum field theory from a III_1 factor to one of type II_1, building on some recent work of Chandrasekaran, Longo, Penington and Witten [JHEP 2023, 82 (2023)].

Logical X operations for constrained problems

Ruben Pariente Bassa

In this presentation, we introduce a novel framework for constructing mixing operators that restrict quantum evolutions to subspaces defined by certain hard constraints. Our approach utilizes the stabilizer formalism, commonly used in error-correcting codes, to create projectors onto code spaces that enforce these constraints. We give examples for how this can be useful in ansatzes for QAOA and VQE. This method offers a significant advantage by avoiding the need to penalize constraint violations in the objective function. Additionally, we present strategies to reduce circuit depth and enhance computational efficiency by minimizing the number of required CNOT gates. It is based on a paper under review at the Quantum journal, https://arxiv.org/abs/2306.17083.