QI 7: Quantum Error Correction

Time: Monday 15:00–18:00 Location: HFT-TA 441

QI 7.1 Mon 15:00 HFT-TA 441

Outperforming Gottesman-Kitaev-Preskill quantum error correction via feedback with memory — •Matteo Puviani[1], Sangkha Borah[1,2], Remmy Zen[1], Jan Olle[1], and Florian Marquardt[1,2] — [1]Max Planck Institute for the Science of Light, 91058 Erlangen, Germany — [2]Friedrich-Alexander Universität Erlangen-Nürnberg, 91058 Erlangen, Germany

Bosonic codes allow the encoding of a logical qubit in a single component device, utilizing the infinitely large Hilbert space of an harmonic oscillator. In particular, the Gottesman-Kitaev-Preskill code has recently been demonstrated to be correctable well beyond the break-even point of the best passive encoding in the same system. However, the current approaches to quantum error correction (QEC) are based on protocols that only implement immediate measurement-based feedback. In our work, we train a recurrent neural network using the recently proposed Feedback GRAPE (Gradient Ascent Pulse Engineering with Feedback) method to develop a time-dependent QEC scheme based on feedback memory that outperforms current strategies and paves the way for novel measurement-based QEC.

QI 7.2 Mon 15:15 HFT-TA 441

Discovering Compact Quantum Circuits for Fault-Tolerant Logical State Preparation with Reinforcement Learning — •Remmy Zen[1], Jan Olle[1], Luis Colmenarez[2,3], Matteo Puviani[1], Markus Müller[2,3], and Florian Marquardt[1,4] — [1]Max Planck Institute for the Science of Light, Staudtstrasse 2, 91058 Erlangen, Germany — [2]Institute for Quantum Information, RWTH Aachen University, 52056 Aachen, Germany — [3]Peter Grünberg Institute, Theoretical Nanoelectronics, Forschungszentrum Jülich, 52425 Jülich, Germany — [4]Department of Physics, Friedrich-Alexander Universität Erlangen-Nürnberg, Staudtstrasse 5, 91058 Erlangen, Germany

One of the key aspects in realizing large-scale fault-tolerant quantum computers is quantum error correction (QEC). The first essential step of QEC is to encode the logical state into physical qubits. However, there is no unique recipe for finding a compact quantum circuit that encodes or prepares the logical state in a fault-tolerant way, especially under hardware constraints such as qubit connectivity and gate set. In this work, we use reinforcement learning (RL) to automatically discover compact quantum circuits that prepare the logical state of a QEC code fault-tolerantly with the flag-based protocol for a given qubit connectivity and gate set. We first demonstrate that an RL agent can fault-tolerantly prepare logical states of a code with up to 15 physical qubits without any hardware constraints. We then show RL-discovered compact circuits for fault-tolerant logical state preparation on a 2D grid.

QI 7.3 Mon 15:30 HFT-TA 441

Coherent errors and readout errors in the surface code — •Aron Marton[1] and Janos Asboth[1,2] — [1]Institute of Physics, Budapest University of Technology and Economics, Budapest, Hungary — [2]Wigner Research Centre for Physics, Budapest, Hungary

We consider the combined effect of readout errors and coherent errors, i.e., deterministic phase rotations, on the surface code. We use a recently developed numerical approach, via a mapping of the physical qubits to Majorana fermions. We show how to use this approach in the presence of readout errors, treated on the phenomenological level: perfect projective measurements with potentially incorrectly recorded outcomes, and multiple repeated measurement rounds. We find a threshold for this combination of errors, with an error rate close to the threshold of the corresponding incoherent error channel (random Pauli-Z and readout errors). The value of the threshold error rate, using the worst case fidelity as the measure of logical errors, is 2.6%. Below the threshold, scaling up the code leads to the rapid loss of coherence in the logical-level errors, but error rates that are greater than those of the corresponding incoherent error channel. We also vary the coherent and readout error rates independently, and find that the surface code is more sensitive to coherent errors than to readout errors. Our work extends the recent results on coherent errors with perfect readout to the experimentally more realistic situation where readout errors also occur.

QI 7.4 Mon 15:45 HFT-TA 441

Coherent error threshold for surface codes from Majorana delocalization — Florian Venn[1], •Jan Behrends[2], and Benjamin Béri[1,2] — [1]DAMTP, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, UK — [2]T.C.M. Group, Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge, CB3 0HE, UK

Statistical mechanics mappings provide key insights on quantum error correction. However, existing mappings assume incoherent noise, thus ignoring coherent errors due to, e.g., spurious gate rotations. We map the surface code with coherent errors, taken as X- or Z-rotations (replacing bit or phase flips), to a two-dimensional (2D) Ising model with complex couplings, and further to a 2D Majorana scattering network. Our mappings reveal both commonalities and qualitative differences in correcting coherent and incoherent errors. For both, the error-correcting phase maps, as we explicitly show by linking 2D networks to 1D fermions, to a $\mathbb{Z}_2$-nontrivial 2D insulator. However, beyond a rotation angle ϕ_{th}, instead of a $\mathbb{Z}_2$-trivial insulator as for incoherent errors, coherent errors map to a Majorana metal. This ϕ_{th} is the theoretically achievable storage threshold. We numerically find $\phi_{\mathrm{th}} \approx 0.14\pi$. The corresponding bit-flip rate $\sin^2(\phi_{\mathrm{th}}) \approx 0.18$ exceeds the known incoherent threshold $p_{\mathrm{th}} \approx 0.11$.

QI 7.5 Mon 16:00 HFT-TA 441

Accurate optimal quantum error correction thresholds from coherent information — •Luis Colmenarez[1,2], Ze-min Huang[3], Sebastian Diehl[4], and Markus Mueller[1,2] — [1]Institute for Quantum Information, RWTH Aachen University, Aachen, Germany — [2]Institute for Theoretical Nanoelectronics (PGI-2), Forschungszentrum Juelich, Juelich, Germany — [3]Department of Physics and Institute for Condensed Matter Theory, University of Illinois at Urbana-Champaign, Illinois, USA — [4]Institute for Theoretical Physics, University of Cologne, Cologne, Germany

In general, obtaining optimal thresholds of quantum error correcting codes (QEC) implies simulating QEC using complicated and, often, sub-optimal decoding strategies. In a few cases, optimal decoding can be framed as a phase transition in disordered classical spin models. In both situations, accurate estimation of thresholds demands intensive computational resources. In this work we use the coherent information of noisy mixed states, to accurately estimate optimal QEC thresholds already from small-distance codes at moderate computational cost. We show the effectiveness and versatility of our method by applying it first to the topological surface and color code under bit-flip and depolarizing noise, and then extend the coherent information based methodology for phenomenological and circuit level noise. For all examples we obtain optimal error thresholds from small instances of the codes with 1% difference compared to known values. We establish the coherent information as a reliable competitive practical tool for the calculation of optimal thresholds under realistic noise models.

15 min. break

QI 7.6 Mon 16:30 HFT-TA 441

Coherent errors in stabilizer codes caused by quasi-static phase damping — •David Pataki[1], Aron Marton[1], Janos Asboth[1,2], and Andras Palyi[1,3] — [1]Department of Theoretical Physics, Institute of Physics, Budapest University of Technology and Economics, Muegyetem rkp. 3., H-1111 Budapest, Hungary — [2]Wigner Research Centre for Physics, H-1525 Budapest, P.O. Box 49., Hungary — [3]HUN-REN–BME Quantum Dynamics and Correlations Research Group, Muegyetem rkp. 3., H-1111 Budapest, Hungary

Quantum error correction is a key challenge for the development of practical quantum computers, a direction in which significant experimental progress has been made in recent years. In solid-state qubits, one of the leading information loss mechanisms is dephasing, usually modelled by phase flip errors.

In this talk, I will introduce quasi-static phase damping, a more subtle error model which describes the effect of Larmor frequency fluctuations due to $1/f$ noise. I will show how this model is different from a simple phase flip error model, in terms of repeated syndrome measurements.

Considering the surface code, I will provide numerical evidence for an error threshold, in the presence of quasi-static phase damping and readout errors. I will also discuss the implications of our results for spin qubits and superconducting qubits.

QI 7.7 Mon 16:45 HFT-TA 441

Simultaneous Discovery of Quantum Error Correction Codes and Encoders with a Noise-Aware Reinforcement Learning Agent — •Jan Olle[1], Remmy Zen[1], Matteo Puviani[1], and Florian Marquardt[1,2] — [1]Max Planck Institute for the Science of Light, Staudtstraße 2, 91058 Erlangen, Germany — [2]Department of Physics, Friedrich-Alexander Universität Erlangen-Nürnberg, Staudtstraße 5, 91058 Erlangen, Germany

Finding optimal ways to protect quantum states from noise remains an outstanding challenge across all quantum technologies, and quantum error correction (QEC) is the most promising strategy to address this issue. In the context of real-world scenarios there are two challenges: codes have typically been categorized only for their performance under an idealized noise model and the implementation-specific optimal encoding circuit is not known. In this work, we train a Reinforcement Learning agent that automatically discovers both QEC codes and their encoding circuits for a given gate set, qubit connectivity, and error model. The agent is noise-aware, meaning that it learns to produce encoding strategies simultaneously for a range of noise models, thus leveraging transfer of insights between different situations. Moreover, by developing a vectorized Clifford simulator, our RL implementation is extremely efficient, allowing us to produce many codes and their encoders from scratch within seconds, with code distances varying from 3 to 5 and with up to 20 physical qubits. Our approach opens the door towards hardware-adapted accelerated discovery of QEC approaches across the full spectrum of quantum hardware platforms of interest.

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Hardware-Tailored Logical Gates for Quantum Error-Correcting Codes — •Eric Kuehnke[1], Kyano Levi[2,1], Jens Eisert[1], and Daniel Miller[1] — [1]Freie Universität Berlin — [2]Technische Universität Berlin

Quantum error-correcting codes play a key role in fault-tolerant quantum computing. Due to the encoding of logical information into higher-dimensional and abstract Hilbert spaces of quantum error-correcting codes, however, the transformation of said logical information poses a difficult challenge. We use the representation of Clifford gates as symplectic binary matrices to construct hardware-tailored logical circuits for quantum error-correcting codes. We achieve this by translating the problem of circuit compilation into a binary optimization problem, which we solve with the help of Gurobi, a professional tool for mathematical optimization.

We apply our newly developed method to construct hardware-tailored logical gates for specific quantum error-correcting codes. One of these is the twisted toric-24 code, a quantum error-correcting code that encodes two logical qubits into twelve physical qubits.

QI 7.9 Mon 17:15 HFT-TA 441

Scaling Hardware-Based Quantum Error Correction via a Multi-Context Approach — •Jan-Erik Reinhard Wichmann, Maximilian Jakob Heer, and Kentaro Sano — RIKEN Center for Computational Science, Kobe, Japan

The theory of quantum error correction is generally well understood, though its practical implementation remains challenging. This is due to the low-latency requirements for the classical computations that are required to carry out the quantum error correction. Recent advancements have shown that it is possible to meet these latency requirements for surface codes using algorithms implemented in FPGA hardware, but the issue of growing hardware resource consumption persists.

A commonly suggested approach is to distribute the error correction algorithm across multiple FPGA chips. However, the incurred communication overhead runs counter to the latency requirements and will cause the so-called exponential backlog problem.

Here we thus present a different way to reduce hardware resource consumption by using a multi-context approach, trading hardware resources for execution time. By repeatedly saving and loading parts of the error decoder in memory, we can overcome the size limits of a single FPGA. This allows for the simultaneous treatment of larger qubit numbers for higher code distances and even lattice surgery operations, which has remained a difficult challenge so far. The technique we are presenting is developed with our own variant of the Union-Find algorithm in mind but is sufficiently general to be used with all algorithms which work on decoder graphs with limited connectivity.

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Fermionic Tetrahedron: Test-Bed for Error Analysis on NISQ — •Daniel F. Urban[1,2], Jannis Ehrlich[1], and Christian Elsässer[1,2] — [1]Fraunhofer-Institut für Werkstoffmechanik IWM, Freiburg, Germany — [2]Freiburger Materialforschungszentrum, Universität Freiburg, Germany

Current noisy intermediate-scale quantum computers (NISQ) are error-prone, such that the results are not reliable. We employ small Fermionic clusters as test models to investigate the influence of different kinds of hardware errors on the calculation of the electronic energy spectrum. For the Fermionic tetrahedron, four pair-wise coupled electronic orbitals, we analyze the measured expectation values and the quality of states obtained by variational optimization algorithms. We identify the challenges of ad-hoc QC calculations starting from a basis of atomic orbitals opposed to those that make use of a better preconditioned basis, e.g. orbitals of a self-consistent Hartree-Fock solution. We observe significant errors in the computed expectation values on real hardware, while the optimization itself gives states that have high fidelities when compared to the exact solution. We trace back the origin of the high errors in energies to the way the expectation value is calculated on the QC hardware, and we demonstrate to which extent Zero Noise Extrapolation (ZNE) can improve the results.

QI 7.11 Mon 17:45 HFT-TA 441

Distributed quantum codes as the sensor for chip-level catastrophic errors — •Song Zhang[1,2], Xiuhao Deng[1,3], Guixu Xie[1,2], and Jinghan Lu[1,2] — [1]International Quantum Academy (SIQA), Shenzhen, P. R. China — [2]Shenzhen Institute for Quantum Science and Engineering (SIQSE), Southern University of Science and Technology, Shenzhen, P. R. China — [3]Shenzhen Institute for Quantum Science and Engineering (SIQSE), and Department of Physics, Southern University of Science and Technology, Shenzhen, P. R. China

Superconducting qubits are a key platform for quantum computing, but recent studies have revealed a critical challenge: ionizing radiation like cosmic rays can trigger correlated errors across all qubits on a chip, leading to catastrophic errors. This issue presents a significant obstacle for fault-tolerant quantum computing, as it defies the conventional assumption of short-range or uncorrelated errors in error correction strategies. To overcome this issue, we propose novel cross-chip schemes that function as a distributed quantum sensor, specifically designed to detect these chip-level correlated errors. Our sensor is particularly practical for real-world applications due to its reliance on quantum non-demolition measurements, which reduces unnecessary resets, and its ability to detect and differentiate errors with various types and correlation ranges. This approach is a crucial step towards enabling large-scale, fault-tolerant quantum architectures by tackling the problem of chip-level catastrophic errors.