The program is compiled by the organizers. However, from Dagstuhl's side, some times are fixed, especially the meals:

Breakfast	between 7.30 am – 8.45 am during this time, guests can freely choose when to partake	(Mon–Fri)	dinner hall
Coffee and Tea	between 10 am – 11 am the organizers choose concrete duration and start	(Mon–Fri)	your seminar's coffee-break areas
Lunch	12.15 pm – 1 pm	(Mon–Fri)	dinner hall
Coffee and Cake	between 3 pm – 4 pm the organizers choose concrete duration and start	(Sun–Thu)	dinner hall
Dinner	6 pm	(Mon–Thu)	dinner hall
	Self-service buffet from 6 pm (open end)	(Sun)	dinner hall

Seminar program

- *All the speakers have allocated **30 min for the presentation, plus 10 additional min** for discussions (the goal is to initiate discussions that may continue during the breakout sessions).*
- *There are seven technical sessions, each one consisting of two talks (2 x 40 min).*
- *In addition, there are five breakout sessions (which will give more time for discussions). Participants can make **suggestions for topics to be covered during these breakout sessions**, on the wiki page of the seminar ("Suggestions for Seminar Topics").*

	Tuesday, May 21	Wednesday, May 22	Thursday, May 23
8:45 am – 9:00 am	**Opening**		
9:00 am – 10:20 am	**Session 1**	**Session 4**	**Session 7**
10:20 am – 10:45 am	Coffee break	Coffee break	Coffee break
10:45 am – 12:05 am	**Session 2**	**Session 5**	**Breakout session**
12:15 am – 1:00 pm	Lunch	Lunch	Lunch
1:15 pm – 3:00 pm	**Breakout session**	**Breakout session**	
3:00 pm – 3:30 pm	Coffee break	Coffee break	
3:30 pm – 4:50 pm	**Session 3**	**Session 6**	
5:00 pm – 6:00 pm	**Breakout session**	**Breakout session**	
6:00 pm	Dinner	Dinner	

Session 1 (May 21, 9:00 am – 10:20 am)

- Kenneth R. Brown, Coherent errors and compass codes
- Eleanor Rieffel, A new family of Floquet codes: dynamical logical qubits in the Bacon-Shor code

Session 2 (May 21, 10:45 am – 12:05 am)

- Robert König, How to fault-tolerantly realize any quantum circuit with local operations
- Ashutosh Goswami, Fault-tolerant quantum input-output

Session 3 (May 21, 3:30 pm – 4:50 pm)

- Pavel Panteleev, Maximally extendable sheaf codes (remote)
- Liang Jiang, Constant-overhead fault-tolerant quantum computation with reconfigurable atom arrays (remote)

Session 4 (May 22, 9:00 am – 10:20 am)

- Emina Soljanin, On some quantum internet information rates
- Alexei Ashikhmin, Pairwise transversality of CSS codes with applications to quantum networks

Session 5 (May 22, 10:45 am – 12:05 am)

- Gilles Zémor, A study of the decoding radius of fast renormalisation decoders for the Kitaev code
- Joseph M. Renes, Tensor network decoding beyond 2D

Session 6 (May 22, 3:30 pm – 4:50 pm)

- Pradeep Sarvepalli, Color codes with twists: construction and universal-gate-set implementation
- Shayan Srinivasa Garani, Entanglement-assisted quantum error correction with qudits

Session 7 (May 23, 9:00 am – 10:20 am)

- Mac Hooper Shaw, Lowering connectivity requirements for quantum LDPC codes using middle-out circuits (remote)
- Ching-Yi Lai, Correcting phenomenological quantum noise via belief propagation.

Session 1 (May 21, 9:00 am – 10:20 am)

Kenneth R. Brown, Duke University

Coherent Errors and Compass Codes

Abstract: Quantum error correction often considers Pauli noise channels where the errors can be described as the random application of Pauli operators. Here we consider a coherent noise channel where all the qubits experience a common rotation around the Z axis of an unknown error. This error model can be studied numerically for the surface code using a transformation from qubits to Majorana fermions. We extend this transformation to compass codes, gauge fixings of the Bacon-Shor code, and develop a family of compass codes where we can analytically determine a threshold rotation angle. We discuss the possibility for extending this result to improve the analytic bound on the coherent error threshold for the surface code.

Eleanor Rieffel, NASA Ames Research Center

A new family of Floquet codes: Dynamical Logical Qubits in the Bacon-Shor Code

Abstract: I will discuss work, joint with Sohaib Alam, on dynamical logical qubits in the Bacon-Shor code. We choose measurement schedules on a d x d square lattice that at each round is a subset of the Bacon-Shor code checks. These measurement schedule results in a Floquet code with several dynamical logical qubits. In this talk, I will briefly review Bacon-Shor subsystem codes, and then discuss the new family of Floquet codes. This work is part of a larger program trying to understand when one can define Floquet codes, when it is useful to do so, and subtleties with regard to defining their distance. The talk will conclude with the statement of some specific open problems.

https://arxiv.org/abs/2403.03291

Session 2 (May 21, 10:45 am – 12:05 am)

Robert König, Technical University of Munich

How to Fault-Tolerantly Realize any Quantum Circuit with Local Operations

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 $O\left(n^{3/2}\log^3 n\right)$ 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.

https://arxiv.org/abs/2402.13863

Ashutosh Goswami, University of Copenhagen

Fault-Tolerant Quantum Input-Output

Ongoing work with Matthias Christandl (University of Copenhagen) and Omar Fawzi (Ecole Normale Supérieure de Lyon).

Abstract: Standard models of computation and communication concern the design of algorithms and protocols that make use of black boxes, i.e. fixed input-output relations, such as oracles or communication channels. The design of such algorithms and protocols focuses typically on aspects of efficiency, both in terms of complexity and capacity. Whereas this focus is justified in the classical realm, the noise in quantum encoding and decoding devices may put the entire model in doubt; at the least, it will require the quantum designer to come up with noise-robust procedures. In the context of quantum Shannon theory, such procedures have recently been proposed (Christandl and Müller-Hermes, IEEE Trans. Inf. Th. 70, 282 (2024)). Working in Kitaev's framework for fault-tolerant computation, we present general criteria and tools for the fault-tolerant design of algorithms and protocols, which make use of fixed quantum black boxes. Applications of our work can be found in the design of quantum networks or the solution of quantum learning tasks.

Session 3 (May 21, 3:30 pm – 4:50 pm)

Pavel Panteleev, Moscow State University (remote)

Maximally Extendable Sheaf Codes

Abstract: Sheaf codes are linear codes with a fixed hierarchical collection of local codes, viewed as a sheaf of vector spaces on a finite topological space. Many existing codes, such as tensor product codes, Sipser-Spielman codes, and their more recent high-dimensional analogs, can be naturally represented as sheaf codes defined on simplicial and cubical complexes. I am going to introduce a new property called maximal extendibility, which ensures that within a class of codes on the same space, we encounter as few obstructions as possible when extending local sections globally. It is possible to show that in every class of sheaf codes defined on the same space and parameterized by parity-check matrices with polynomial entries, there always exists a maximally extendable sheaf code. As it turns out, maximally extendable tensor product codes are good coboundary expanders, which allows one to generalize the recent constructions of good qLDPC codes to more than two dimensions, and potentially could be used to attack the qLTC conjecture.

https://arxiv.org/abs/2403.03651

Liang Jiang, University of Chicago (remote)

Constant-Overhead Fault-Tolerant Quantum Computation with Reconfigurable Atom Arrays

Abstract: Quantum low-density parity-check (qLDPC) codes can achieve high encoding rates and good code distance scaling, providing a promising route to low-overhead fault-tolerant quantum computing. However, the long-range connectivity required to implement such codes makes their physical realization challenging. Here, we propose a hardware-efficient scheme to perform fault-tolerant quantum computation with high-rate qLDPC codes on reconfigurable atom arrays, directly compatible with recently demonstrated experimental capabilities. Our approach utilizes the product structure inherent in many qLDPC codes to implement the non-local syndrome extraction circuit via atom rearrangement, resulting in effectively constant overhead in practically relevant regimes. We prove the fault tolerance of these protocols, perform circuit-level simulations of memory and logical operations with these codes, and find that our qLDPC-based architecture starts to outperform the surface code with as few as several hundred physical qubits at a realistic physical error rate of 10^{-3}. We further find that less than 3000 physical qubits are sufficient to obtain over an order of magnitude qubit savings compared to the surface code, and quantum algorithms involving thousands of logical qubits can be performed using less than 10^5 physical qubits. Our work paves the way for explorations of low-overhead quantum computing with qLDPC codes at a practical scale, based on current experimental technologies.

Session 4 (May 22, 9:00 am – 10:20 am)

Emina Soljanin, Rutgers University

On Some Quantum Internet Information Rates

This talk discusses information rates in two quantum internet building blocks concerning quantum (conference) key distribution (QKD). We first focus on QKD based on time-entangled photon pairs. These systems extract key bits from photon arrival times and thus promise to deliver more than one bit per photon instead of polarization-entanglement QKD, where each entangled photon pair contributes at most one bit to the secret key. However, realistic photon detectors exhibit time jitter and require non-zero time to recover upon registering a photon arrival. We model and evaluate the effect of these impairments on information rates generated based on photon arrival times and ask whether time-entanglement-based QKD can live up to its promise. We next ask whether quantum network multicast can make conference key agreements more efficient. Since there is no quantum information without physical representation (e.g., by photons), the problem of quantum multicast initially seems nothing more than the multi-commodity flow problem of shipping a collection of different commodities through a shared network. However, we show that besides the apparent similarity to the multi-commodity flow problems, quantum networks, to a certain extent, behave as classical information networks. In particular, we show that lossless compression of multicast quantum states is possible and significantly reduces the link capacity requirements of the multicast.

https://www.ece.rutgers.edu/emina-soljanin

Alexei Ashikhmin, Bell Labs, Alcatel-Lucent Inc.

Pairwise Transversality of CSS Codes with Applications to Quantum Networks

Joint work with Mahdi Bayanifar, Dawei Jiao, Olav Tirkkonen (Aalto University)

Abstract: In this work, we study the transversality of pairs of CSS codes and their application in quantum networks employing second- generation quantum repeaters. Motivated by the observation that different stations within a quantum link may encounter different types of errors, we propose utilizing CSS codes tailored to the error models specific to each station. Additionally, we suggest using $[\![n,k]\!]$ codes with $k>1$ due to their higher efficiency compared to codes with $k=1$. Quantum networks require that quantum codes used at neighboring stations possess pair-wise transversality. In this work, we establish sufficient and necessary conditions for a pair of CSS codes to be non-local CNOT-transversal. We demonstrate that, unlike the stringent constraints imposed by single CSS code CNOT-transversality, our case requires less restrictive constraints. Further, we establish sufficient and necessary conditions for a code pair to be CZ-transversal. Finally, we demonstrate that our proposed approach yields significant performance gain compared to the conventional approach of employing the same CSS code across all network stations.

Session 5 (May 22, 10:45 am – 12:05 am)

Gilles Zémor, Université de Bordeaux

A Study of the Decoding Radius of Fast Renormalisation Decoders for the Kitaev Code

Abstract: The renormalisation decoders for Kitaev's toric code introduced by Duclos-Cianci and Poulin exhibit one of the best trade-offs between accuracy and efficiency, with a time complexity in $n \log n$. One question that was left open is how they handle worst-case or adversarial errors, i.e. what is the order of magnitude of the smallest weight of an error pattern that will be wrongly

decoded. We initiate such a study involving a simple hard-decision and deterministic version of the Duclos-Cianci and Poulin decoder.

https://arxiv.org/abs/2309.12165

Joseph M. Renes, Insitute for Theoretical Physics, ETH Zurich

Tensor Network Decoding Beyond 2D

Abstract: Decoding algorithms based on approximate tensor network contraction have proven tremendously successful in decoding 2D local quantum codes such as surface/toric codes and color codes, effectively achieving optimal decoding accuracy. In this work, we introduce several techniques to generalize tensor network decoding to higher dimensions so that it can be applied to 3D codes as well as 2D codes with noisy syndrome measurements (phenomenological noise or circuit-level noise). The three-dimensional case is significantly more challenging than 2D, as the involved approximate tensor contraction is dramatically less well-behaved than its 2D counterpart. Nonetheless, we numerically demonstrate that the decoding accuracy of our approach outperforms state-of-the-art decoders on the 3D surface code, both in the point and loop sectors, as well as for depolarizing noise. Our techniques could prove useful in near-term experimental demonstrations of quantum error correction, when decoding is to be performed offline and accuracy is of utmost importance. To this end, we show how tensor network decoding can be applied to circuit-level noise and demonstrate that it outperforms the matching decoder on the rotated surface code.

https://arxiv.org/abs/2310.10722

Session 6 (May 22, 3:30 pm – 4:50 pm)

Pradeep Sarvepalli, Indian Institute of Technology, Madras

Color Codes with Twists: Construction and Universal-Gate-Set Implementation

Joint work with Manoj Gowda

Abstract: Twists are defects in a lattice that can be used to perform encoded computations. Three basic types of twists can be introduced in color codes: twists that permute color, charge of anyons, and domino twists that permute the charge label of an anyon with a color label. In this talk, we look at a subset of these twists from a coding theoretic viewpoint. Specifically, we present a systematic construction of charge permuting and color permuting twists in color codes. We show that by braiding alone, Clifford gates can be realized in color codes with charge permuting twists. We also present the implementation of a non-Clifford gate by state injection, thus completing the realization of a universal gate set. Time permitting, we also discuss implementing single-qubit Clifford gates by a Pauli frame update and CNOT gate by braiding holes around twists in color codes with color permuting twists.

https://doi.org/10.1103/PhysRevA.104.012603

Shayan Srinivasa Garani, Indian Institute of Science

Entanglement-Assisted Quantum Error Correction with Qudits

Abstract: Non-binary quantum states also called ‘qudits’ inherently have a rich quantum information content to be harnessed for applications within quantum communication and computing. Further, qudit systems allow more-complex quantum computational architectures by simplifying certain computational tasks and circuits. The use of pre-shared qudit entangled states within a quantum transceiver system can increase the error correction ability of the system. In this talk, I will discuss the ideas behind entanglement-assisted quantum error

correction over qudits along with coding-theoretic bounds and encoding circuits. Time permitting, I will also discuss some of our recent results on qudit entanglement-unassisted codes for near-threshold magic state distillation.

Session 7 (May 23, 9:00 am – 10:20 am)

Mac Hooper Shaw, Delft University of Technology (remote)

Lowering Connectivity Requirements for Quantum LDPC Codes Using Middle-Out Circuits

Authors: M. H. Shaw and B. M. Terhal (Delft University of Technology)

Abstract: Recent work by Bravyi et al. [1] proposed a set of small LDPC codes and corresponding syndrome extraction circuits that achieve a similar logical error rate to the surface code under circuit-level noise, but with a much denser encoding of logical qubits. The codes are part of a family of LDPC codes called Abelian two-block group algebra (2BGA) codes with the additional property that the stabilisers have weight six. In this work, we propose a new set of small Abelian 2BGA codes and syndrome extraction circuits with identical [[n, k, d]] parameters to those of Ref. [1] but requiring a connectivity graph with degree five instead of six. Intriguingly, each of our new codes has a depth-7 syndrome extraction circuit – the same depth as those in Ref. [1] – despite the fact that our new codes have weight-9 stabilisers. Our new codes are derived from the codes in Ref. [1] using the "middle-out circuit" construction from [2,3]: half-way through the syndrome extraction circuit, the joint code encoded between the data and ancilla qubits corresponds precisely to one of the codes in Ref. [1]. One can therefore perform logical gates by implementing half of the syndrome extraction circuit, followed by the procedures already detailed in Ref. [1]. Finally, we present preliminary numerical results comparing our new codes with those in Ref. [1] under circuit-level noise decoded using BP-OSD.

[1] Bravyi et al., "High-threshold and low-overhead fault-tolerant quantum memory", Nature 627, 778-782 (2024)

[2] C. Gidney, C. Jones, "New Circuits and an open source decoder for the color code", arXiv:2312.08813.

[3] M. McEwen, D. Bacon, C. Gidney, "Relaxing Hardware Requirements for Surface Code Circuits using Time-dynamics", Quantum 7, 1172 (2023)

Ching-Yi Lai, National Yang Ming Chiao Tung University (NYCU), Hsinchu, Taiwan

Correcting phenomenological quantum noise via belief propagation

Abstract: Quantum stabilizer codes often face the challenge of syndrome errors due to error-prone measurements. To address this issue, multiple rounds of syndrome extraction are typically employed to obtain reliable error syndromes. In this paper, we consider phenomenological decoding problems, where data qubit errors may occur between two syndrome extractions, and each syndrome measurement can be faulty. To handle these diverse error sources, we define a generalized check matrix over mixed quaternary and binary alphabets to characterize their error syndromes. This generalized check matrix leads to the creation of a Tanner graph comprising quaternary and binary variable nodes, which facilitates the development of belief propagation (BP) decoding algorithms to tackle phenomenological errors. Importantly, our BP decoders are applicable to general sparse quantum codes. Through simulations of quantum memory protected by rotated toric codes, we demonstrates an error threshold of 3.3% in the phenomenological noise model. Additionally, we propose a method to construct effective redundant stabilizer checks for single-shot error correction. Simulations show that BP decoding performs exceptionally well, even when the syndrome error rate greatly exceeds the data error rate.

https://arxiv.org/abs/2310.12682