Quantum Information

February 25th – March 1st, 2024

Les Diablerets
(Hotel Les Sources)

Matthias CHRISTANDL

Title: Fault-tolerant Coding for Quantum Communication

Abstract: *Designing encoding and decoding circuits to reliably send messages over many uses of a noisy channel is a central problem in communication theory. When studying the optimal transmission rates achievable with asymptotically vanishing error it is usually assumed that these circuits can be implemented using noise-free gates. While this assumption is satisfied for classical machines in many scenarios, it is not expected to be satisfied in the near term future for quantum machines where decoherence leads to faults in the quantum gates. As a result, fundamental questions regarding the practical relevance of quantum channel coding remain open. By combining techniques from fault-tolerant quantum computation with techniques from quantum communication, we initiate the study of these questions. We introduce fault-tolerant versions of quantum capacities quantifying the optimal communication rates achievable with asymptotically vanishing total error when the encoding and decoding circuits are affected by gate errors with small probability. Our main results are threshold theorems for the classical and quantum capacity: For every quantum channel* T *and every* $\epsilon > 0$, *there exists a threshold* $p(\epsilon, T)$ *for the gate error probability below which rates larger than* $C - \epsilon$ *are fault-tolerantly achievable with vanishing overall communication error, where* C *denotes the usual capacity. Our results are not only relevant in communication over large distances, but also on-chip, where distant parts of a quantum computer might need to communicate under higher levels of noise than affecting the local gates.*

Giacomo DE PALMA

Title: Quantum neural networks as Gaussian processes

Abstract: *We study quantum neural networks trained on supervised learning problems in the limit of infinite width. First, we prove that the probability distribution of the function generated by the untrained network with randomly initialized parameters converges to a Gaussian process whenever each output qubit is correlated only with few other output qubits. Then, we analytically characterize the training of the network via gradient descent. We prove that, whenever the network is not affected by barren plateaus, the trained network can perfectly fit the training set and that the probability distribution of the function generated after training is still a Gaussian process. These results generalize to the quantum setting a recent breakthrough in classical machine learning. Finally, we consider the statistical noise of the measurement at the output of the network and prove that a polynomial number of measurements is sufficient for all the previous results to hold and that the network can always be trained in polynomial time.*

Jens EISERT

Title: Are there practical applications of near-term quantum computers?

Abstract: *Quantum computers promise the efficient solution of some computational problems that are classically intractable. For many years, they have been primarily objects of theoretical study, as only in recent years, protagonists have set out to actually build intermediate-scale quantum computers. This creates an interesting state of affairs, but also begs for an answer to the question what such devices are possibly good for. In this talk, we discuss what practically minded applications in quantum computing and simulation could be conceivable. This talk will be dedicated to a number of results offering substantial progress along these lines. We will discuss rigorous quantum advantages in paradigmatic problems [1,2], and will explore the use of quantum computers in machine learning [3,4,5] and optimization [6]. We will also discuss limitations, by providing efficient classical algorithms for instances of quantum algorithms, hence "de-quantizing" them, and by identifying limitations to quantum error mitigation [9]. The talk will end on the note that quantum simulation remains one of the core applications of near-term quantum devices [10,11].*

Omar FAWZI

Title: Certified algorithms for equilibrium states of local quantum Hamiltonians

Abstract: *We design algorithms for computing expectation values of observables in the equilibrium states of local quantum Hamiltonians, both at zero and positive temperature. The algorithms are based on hierarchies of convex relaxations over the positive semidefinite cone and the matrix relative entropy cone, and give certified and converging upper and lower bounds on the desired expectation value. In the thermodynamic limit of infinite lattices, this shows that expectation values of local observables can be approximated in finite time, which contrasts with recent undecidability results about properties of infinite quantum lattice systems. In addition, when the Hamiltonian is commuting on a 2-dimensional lattice, we prove fast convergence of the hierarchy at high temperature leading to a runtime guarantee for the algorithm that is polynomial in the desired error.*

Nicolas GISIN

Title: Towards a measurement theory in QFT: "Impossible" quantum measurements are possible but not ideal

Abstract: *Naive attempts to put together relativity and quantum measurements lead to signaling between space-like separated regions. In QFT, these are known as impossible measurements. We show that the same problem arises in non-relativistic quantum physics, where joint nonlocal measurements (i.e., between systems kept spatially separated) in general lead to signaling, while one would expect no-signaling (based for instance on the principle of no-nonphysical communication). This raises the question: Which nonlocal quantum measurements are physically possible? We review and develop further a non-relativistic quantum information approach developed independently of the impossible measurements in QFT, and show that these two have been addressing virtually the same problem. The non-relativistic solution shows that all nonlocal measurements are localizable (i.e., they can be carried out at a distance without violating no-signaling) but they (i) may require arbitrarily large entangled resources and (ii) cannot in general be ideal, i.e., are not immediately reproducible. We find all joint quantum measurements on 2 qubits that are localizable with 1 and 3 e-bits. Interestingly, the Elegant Joint Measurement appears naturally in such a structuring of all joint measurements.*
Nicolas Gisin, Flavio Del Santo, Jef Pauwels and Alejandro Pozas Kerstjens. Group of Applied Physics, University of Geneva, 1211 Geneva, Switzerland and Constructor University, Geneva, Switzerland

Dmitry GRINKO

Title: Efficient quantum circuits for port-based teleportation via mixed Schur-Weyl duality

Abstract: *Port-based teleportation (PBT) is a variant of quantum teleportation that, unlike the canonical protocol by Bennett et al., does not require a correction operation on the teleported state. Since its introduction by Ishizaka and Hiroshima in 2008, no efficient implementation of PBT was known. We close this long-standing gap by building on our recent results on representations of partially transposed permutation matrix algebras and mixed quantum Schur transform, which appear in the so-called mixed Schur-Weyl duality. We describe efficient quantum circuits for probabilistic and deterministic PBT protocols on* n *ports of arbitrary local dimension, both for EPR and optimized resource states. We present two constructions based on different encodings of the Gelfand–Tsetlin basis for* n *qudits: a standard encoding that achieves* $O(n)$ *time and* $O(n\log(n))$ *space complexity, and a Yamanouchi encoding that achieves* $O(n^2)$ *time and* $O(\log(n))$ *space complexity, both for constant local dimension and target error. Our results in representation theoretic aspects of mixed Schur-Weyl duality are of independent interest and can be utilized more broadly in the context of unitary-equivariant quantum channels.*

David GROSS

Title: Network correlations and polynomial optimization over states

Abstract: *The problem of deciding whether bi-partite correlations are compatible with a quantum model has been extensively studied and is now well-understood (there are algorithms in the "commuting operator model" and an undecidability result for the "tensor product model"). In contrast, much less is known about the problem of algorithmically recognizing correlations in quantum models that have a non-trival "network" or "causal" structure. From a mathematical point of view, the problem is related to the question whether the "non-commutative polynomial optimization SDP hierarchy" can be generalized from linear constraints and objective functions, to polynomial ones. I will explain the problem and report on a number of results: A general method (based on de Finetti Theorems) for the polynomial optimization problem just mentioned; a complete solution for the membership problem in the simplest network model, the "bi-local scenario", and partial results for general structures. I will also mention recent unpublished results, including a method for recognizing tensor product correlations under entanglement bounds.*
Joint work with Laurens Ligthart and Mariami Gachechiladze. [2110.14659 (CMP), 2212.11299 (JMP)]

Robert KOENIG

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

Abstract: *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* $O(n^{3/2} log^3 n)$ *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 and available at arXiv:2402.13863

Barbara KRAUS

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

Abstract: *I will discuss here several protocols designed for the verification and the characterization of quantum devices. They range from protocols which were designed to verify the output of a quantum cloud computer using only classical means to practical testing and verification protocols of quantum devices utilized for quantum computation and simulation.*

Ludovico LAMI

Title: Entanglement dilution with PPT operations

Abstract: *Calculating the ultimate rates of entanglement manipulation is well known to be exceedingly difficult, for at least three different reasons: first, the set of transformations implementable with local operations assisted by classical communication (LOCC) is hard to characterise mathematically; secondly, the usual paradigm allows for a vanishing transformation error, which adds a further complication; and last but not least, looking at ultimate limitations brings with it the omnipresent curse of regularisations. Regularised formulas are well known to be analytically intractable and very difficult to evaluate numerically. Here we look at a problem that is designed to eliminate the first two hurdles, isolating the latter one. The problem is zero-error entanglement dilution with positive partial transpose (PPT) operations, which was studied in [Wang/Wilde, PRL 125:040502, 2020]. We argue that the single-letter solution presented there is not correct, as the corresponding quantity fails to be additive and therefore needs to be regularised. Instead, we show how to construct an algorithm that computes the regularisation up to an additive error epsilon in time poly(d, log(1/epsilon)) through a hierarchy of semi-definite programs. Some open problems related to this approach are discussed.*
Joint work with Francesco Anna Mele and Bartosz Regula.

Cecilia LANCIEN

Title: Quantum expanders - Random constructions and Applications

Abstract: *The goal of the talk will be to understand what quantum expanders are, what they are useful for, and how they can be constructed. We will first recall the definition of classical expander graphs, and explain how quantum analogues of these objects can be defined. We will then show that, both classically and quantumly, random constructions typically provide examples of optimal expanders. In the quantum case, such result is derived from a spectral analysis for random matrix models with a tensor product structure. Finally, we will present implications in terms of typical decay of correlations in 1D many-body quantum systems with local interactions. The talk will be based mostly on joint works with David Pérez-García (https://arxiv.org/abs/1906.11682) and Pierre Youssef (https://arxiv.org/abs/2302.07772).*

Debbie LEUNG

Title: Quantum state purification

Abstract: *Quantum state purification is the task of recovering a purer copy of an unknown pure quantum state using multiple noisy, depolarized, copies of the state. After a literature review on the qubit case, we present our results on purifying states of arbitrary dimension d. We proposed and analyzed a purification procedure based on recursive swap test, and showed for moderate noise, the process is efficient computationally, with dimensional independent upper bound on sampling complexity that is comparable to the optimal qubit case. When the states are provided one at a time in a streaming fashion, our method requires only a small quantum memory to implement. For the high noise, our tight bounds on the sampling complexity show that quantum state tomography is a better method. Joint work with Andrew M. Childs, Honghao Fu, Zhi Li, Maris Ozols, Vedang Vyas*

Graeme SMITH

Title: Additivity and Nonadditivity of Quantum Capacity

Abstract: *I will discuss examples of additivity and nonadditivity of quantum capacities. On the additivity side, I will introduce a sufficient criterion for additivity of coherent information, informational degradability, that is apparently more general than degradability. I will present a particular non-degradable channel that I believe is informationally degradable. On the non-additivity side, I will show that the platypus channel displays nonadditivity with many different qubit channels, such as erasure, amplitude damping, and depolarizing. I will also explain the spin alignment conjecture, which would imply that the platypus has additive coherent information with itself.*

David SUTTER

Title: Replica entanglement

Abstract: *We introduce a novel entropic measure called "replica entanglement" of a bipartite mixed state ρ_{AB}, which is defined by the minimal joint entropy on the $A_1, \ldots, A_n$ systems of n-copies (or replicas) of ρ_{AB} in the limit where n grows large. We show that this new quantity is an entanglement measure in the sense that it satisfies various desirable properties such as faithfulness and LOCC monotonicity. We further discuss its relation to other established entanglement measures such as entanglement of formation and entanglement cost. Based on joint work with Giulia Mazzola and Renato Renner.*

Marco Patrick TOMAMICHEL

Title: From matrix quotients and pretty-good measurements to quantum decoders and error exponents

Abstract: *We introduce a new quantum decoder based on a variant of the pretty good measurement, but defined via an alternative matrix quotient. We use this decoder to show new lower bounds on the error exponent both in the one-shot and asymptotic regimes for the classical-quantum and the entanglement-assisted channel coding problem. Our bounds are expressed in terms of measured (for the one-shot bounds) and sandwiched (for the asymptotic bounds) channel Rényi mutual information of order between 1/2 and 1. Our results are not comparable with some previously established bounds for general channels, yet they are tight (for rates close to capacity) when the underlying channel is classical. Joint work with Salman Beigi, arXiv:2310.09014*

Lauritz VAN LUIJK

Title: Embezzlement of Entanglement, Quantum Fields and the Classification of von Neumann Algebras

Abstract: *Embezzlement of entanglement refers to the counterintuitive possibility of extracting entangled quantum states from a resource state of an auxiliary system (the "embezzler") via local operations while hardly perturbing the latter. I will explain a connection between the mathematical classification of von Neumann algebras and the operational task of embezzling entanglement: We describe the bipartite system in the "commuting operator framework" by a von Neumann algebra and its commutant, and obtain the necessary and sufficient conditions for a state to be embezzling. In fact, we discover that the capability to perform approximate embezzlement gives an algebraic invariant, which implies Connes' classification of type III factors.*

Our result implies that relativistic quantum fields are universal embezzlers: Any entangled state of any dimension can be embezzled from them with arbitrary precision, which provides an operational characterisation of the infinite amount of entanglement present in the vacuum state of relativistic QFTs.

Michael WALTER

Title: Approximate QCAs and a converse to the Lieb-Robinson bounds

Abstract: *Unitary evolutions of quantum lattice systems that preserve locality are called "quantum cellular automata", or QCAs. QCAs in one dimension have been completely classified by an index theory. However, physical systems often only preserve locality approximately. For example, Hamiltonian evolutions on the lattice satisfy Lieb-Robinson bounds rather than strict locality. In this talk, we will discuss QCAs that approximately preserve locality. As we will see, the index theory of 1D QCAs is robust even when considering these more general evolutions. As a consequence, we also obtain a converse to the Lieb-Robinson bounds in one dimension. Based on joint work with Daniel Ranard and Freek Witteveen in the Annales Henri Poincaré.*