Workshop on Quantum Information, 5-9 December 2022, Saarland U, Saarbrücken, Germany

List of Talks

- **Speaker**: Harry Buhrman
  Affiliation: U Amsterdam & QuSoft
  Title: Quantum fine-grained complexity
  Abstract: One of the major challenges in computer science is to establish lower bounds on the resources, usually time, that are needed to solve computational problems. This holds in particular for computational problems that appear in practise.
  One way towards dealing with this situation is the study of fine-grained complexity where we use special reductions to prove time lower bounds for many diverse problems based on the conjectured hardness of some key problems. For example, computing the edit distance between two strings, a problem that has a practical interest when determining the genetic distance between species based on their DNA, has an algorithm that takes $O(n^2)$ time. Using a fine-grained reduction it can be shown that faster algorithms for edit distance also imply a faster algorithm for the Boolean Satisfiability (SAT) problem (that is believed to not exist). This is evidence that the current edit distance algorithms are optimal. Another problem, besides SAT, that is used as a basis for these reductions is the 3SUM problem.
  The situation in the quantum regime is no better; almost all known lower bounds for quantum algorithms are defined in terms of query complexity, which doesn't help much for problems for which the best-known algorithms take super-linear time. Therefore, employing fine-grained reductions in the quantum setting seems a natural way forward. However, translating the classical fine-grained reductions directly into the quantum regime is not always possible for various reasons. In this talk, I will present some recent results in which we circumvent these challenges and prove quantum time lower bounds for some problems in BQP conditioned on the conjectured quantum hardness of for example SAT (and its variants) the 3SUM problem, and the All Pairs Shortest Path (APSP) problem.

This is based on joint work with Koen Leijnse, Bruno Loff, Subhasree Patro ,and Florian Speelman.

- **Speaker**: Felix Motzoi
  Affiliation: Forschungszentrum Jülich
  Title: Analog quantum feedback: pairing measurement with control
  Abstract: In this talk, we examine some common measurement feedback strategies. In particular we look at analog (continuous) feedback strategies, which benefit from lower latency compared to full (projective) measurement/estimation while also allowing to more directly counteract measurement noise. We focus our attention for our examples to entanglement generation in the presence of non-negligible environmental dissipation. We explore the merits of classical PID feedback control in the quantum setting, and draw conclusions about the optimal ways to maintain quantum coherence. We further consider the role of typical decay channels and discuss approaches to their mitigation, by adding appropriate operators maintaining the correct fixed point. When all the sources can be adequately compensated, either statically or dynamically, a steady-state entanglement can be stabilized.

- **Speaker**: Matteo Rizzi
  Affiliation: Forschungszentrum Jülich
  Title: Phase Diagram Detection via Number Probability Distribution
  Abstract: In recent years, methods for automatic recognition of phase diagrams of quantum systems have gained large interest in the community: Among others, machine learning analysis of the entanglement spectrum has proven to be a promising route. Here, we discuss the possibility of using an experimentally readily accessible proxy, namely the number probability distribution that characterizes sub-portions of a quantum many-body system with globally conserved number of particles. We put forward a linear fitting protocol capable of mapping out the ground-state phase diagram of the rich one-dimensional extended Bose-Hubbard model: The results are quantitatively comparable with more sophisticated traditional numerical and machine learning techniques. We argue that the studied quantity should be considered among the most informative bipartite properties [18], [17].

- **Speaker**: Jürgen Eschner
  Affiliation: UdS
  Title: Interfacing and entangling single atoms and single photons
  Abstract: We are implementing a comprehensive set of single-atom-single-photon quantum interface protocols that enable controlled generation, storage, transmission, conversion, and entanglement of photonic and atomic qubits in quantum networks. Such tools are required, for example, in quantum repeater protocols for reliable intermediate storage and

long-range transmission of quantum information.
Specifically, we operate a programmable ion-photon interface, employing controlled quantum interaction between a single trapped $^{40}Ca^{+}$ ion and single photons [6], [7]. Depending on the choice of input and output qubits, the interface protocol serves as an atom-to-photon or photon-to-atom qubit converter, or as a source of entangled atom-photon pair states. The interface lends itself also to integrating Ca^{+} ions with entangled photon pairs from a resonant, narrowband spontaneous parametric down-conversion (SPDC) source [1], [11]. As an example, we implemented atom-to-photon qubit teleportation by heralded single-photon absorption [15].
We also extend our quantum network toolbox into the telecom regime by quantum frequency conversion of ion-entangled photons [13]. The reverse conversion process from 1550-nm telecom photons to ion-resonant photons at 854 nm is also realized with high fidelity after 40 km of fiber transmission [3].

- **Speaker**: Lorenzo Piroli
  Affiliation: École Normale Supérieure
  Title: Quantum Convolutional Neural Networks
  Abstract: The concept of causality, stating that physical actions cannot propagate in space at an arbitrary speed, can be captured for qudit systems by the notion of Quantum Cellular Automata (QCA), defined as unitary maps preserving locality of observables. In this talk, I will show that QCA can be identified, in any dimension and geometry, with special tensor network operators, yielding a general connection between causality and bounds on entanglement production in the form of area laws. I will stress the importance of unitarity, by discussing generalizations of our results for different classes of non-unitary quantum channels. Finally, I will show how the set of QCA can be extended to a larger class of deterministic maps via LOCC (local operations and classical communication) and illustrate implications on state-preparation protocols and classification of phases of matter.
  Talk based on [19], [20].

- **Speaker:** Timo Felser
  Affiliation: Ulm U and Tensor AI Solutions GmbH
  Title: Tensor Networks - From Quantum Mechanics to Artificial Intelligence
  Abstract: Tensor Networks (TNs) are a numerical tool initially designed to simulate quantum many-body systems on a classical computer. Since their first success story over three decades ago, TNs have been applied to investigate various quantum systems, such as Lattice Gauge Theories modelling the fundamental particles of our universe or condensed matter systems underlying the upcoming technology of Quantum Computers.

However, in recent years it turned out that TNs can be seen as a more general tool for representing information with applications in domains, such as applied mathematics, Informatics or medical physics. In fact, we at Tensor Solutions are a start-up developing AI-Technology based on this quantum-inspired method.
In this talk, I will present the concept of Tensor Networks and their journey from addressing problems in Quantum physics up to solving Machine Learning problems in Artificial Intelligence.

- **Speaker**: Dagmar Bruß
  Affiliation: U Düsseldorf
  Title: Quantum resource theories for sets of measurements
  Abstract: Certain quantum information processing tasks, such as demonstrating the violation of a Bell inequality, require non-vanishing resources in both quantum states and measurements. While resource theories for quantum states have already been widely studied, much less is known about resource quantification for quantum measurements, in particular for sets of quantum measurements. We introduce distance-based quantifiers for resource theories of sets of measurements. This allows us to establish a hierarchy between different resource theories. Furthermore, we derive general analytical bounds on the incompatibility of sets of measurements, that take a particularly elegant form in the case of projective measurements in mutually unbiased bases. Our approach provides a general framework to quantify the resources of sets of measurements, and to evaluate their power for quantum information processing tasks.

- **Speaker**: Frank Wilhelm-Mauch
  Affiliation: UdS
  Title: Two improvements of NISQ Quantum Algorithms
  Abstract: In the NISQ era, we are looking to approach quantum advantage with shallow algorithms, which are often variational in nature. In those cases, proofs of speedup are hard to come by and a lot of research is empirical. A particularily relevant case here is the Quantum Approximate Optimization Algorithm (QAOA). I will present its semiclassical limit, mean-field QAOA, which can be classically simulated and present a criterion for its applicability, hence allowing to identify cases when full QAOA is not promising. Another relevant case is the study of quantum manybody systems with digital algorithms. Here, I will show an improved, physics-inspired algorithm to sample the key observable for studying theses systems. the single-particle Green's function.
  Work with Dmitry Bagrets, Aditi Misra-Spieldenner, Tobias Stollenwerk, Tim Bode, Peter Schuhmacher, and Gino Bishop

- **Speaker:** Tobias Stollenwerk
  Affiliation: Forschungszentrum Jülich

Title: Diagrammatic Analysis of Parameterized Quantum Circuits
Abstract: Diagrammatic representations of quantum algorithms and circuits offer novel approaches to their design and analysis. In this work, we describe extensions of the ZX calculus for computing expectation values of parameterized quantum circuits, which are important quantities in applications ranging from combinatorial optimization to quantum chemistry. We provide several new ZX rules and generalizations for this setting. In particular, we give formal rules for linear combinations of ZX diagrams, where the relative scale factors of each diagram must be kept track of, in contrast to most previously studied single-diagram cases where these coefficients can be ignored. We demonstrate that the diagrammatic approach offers novel insights into algorithm structure and performance by considering several ansätze from the literature including realizations of hardware-efficient ansätze and QAOA. Moreover, we find that by using a diagrammatic representation the calculation of more sophisticated ansätze, like deeper QAOA circuits, can become more intuitive and easier to calculate than by alternative means. Finally, we outline how diagrammatic approaches may aid in the design of new and more effective quantum circuit ansätze.

- **Speaker**: Jonas Helsen
  Affiliation: CWI Amsterdam
  Title: Shadow sequence estimation: a primitive for learning gate set noise
  Abstract: In this talk I want to introduce shadow sequence estimation. This is a protocol for learning noise in (random) quantum circuits in a flexible and scalable manner. It arises essentially as a combination of randomised shadow estimation (in the Huang-Kueng-Preskill sense) and randomised benchmarking, a time-honoured gate-fidelity estimation protocol. I will introduce the protocol, sketch the mathematics behind its correctness and scalability, and then I will (hopefully) demonstrate its usefulness through several example estimation protocols, namely unitary optimisation, crosstalk tomography and a robust state shadow estimation protocol.

- **Speaker**: Andreas Osterloh
  Affiliation: Technology Innovation Institute, Abu Dhabi
  Title: Condensed Matter applications of Multipartite SL-Entanglement
  Abstract: Multipartite entanglement is one of the big open riddles in quantum information. Many versions of multipartite measures are currently being applied to physical systems in order to characterize the system and respective phases due to the quality of their entanglement content. Decisive in this context is the mere possibility of calculating the respective measures for mixed states. I am focusing on the convex-roof construction itself that gives the extension to mixed states from an entanglement measure for pure states. First studies in this direction give hope that it could

be feasible to obtain reasonable bounds similar to perturbation theory. I will present excerpts out of various projects on the threetangle in the quasi-exact area of rank-two density matrices: for Vertraetes 9-fold way of four partite systems, the generalizations to the W-state with nothing but the threetangle, and finally its analysis in the XY models in a non-transversal field.

- **Speaker**: Andreas Wallraff
  Affiliation: ETH Zürich
  Title:Realizing Quantum Error Correction in Superconducting Circuits using the Surface Code
  Abstract: Superconducting electronic circuits are ideally suited for studying quantum physics and its applications. Since complex circuits containing hundreds or thousands of elements can be designed, fabricated, and operated with relative ease, they are one of the prime contenders for realizing quantum computers. Currently, both academic and industrial labs vigorously pursue the realization of universal fault-tolerant quantum computers. However, building systems which can address commercially relevant computational problems continues to require significant conceptual and technological progress. For fault-tolerant operation quantum computers must correct errors occurring due to unavoidable decoherence and limited control accuracy. Here, we demonstrate quantum error correction using the surface code, which is known for its exceptionally high tolerance to errors. Using 17 physical qubits in a superconducting circuit we encode quantum information in a distance-three logical qubit building up on our recent distance-two error detection experiments [5]. In an error correction cycle taking only 1.1 µs, we demonstrate the preservation of four cardinal states of the logical qubit. Repeatedly executing the cycle, we measure and decode both bit- and phase-flip error syndromes using a minimum-weight perfect-matching algorithm in an error-model-free approach and apply corrections in postprocessing. We find a low logical error probability of 3 % per cycle [21]. The measured characteristics of our device agree well with a numerical model. Our demonstration of repeated, fast, and high-performance quantum error correction cycles, together with recent advances in ion traps, support our understanding that fault-tolerant quantum computation will be practically realizable.

- **Speaker:** Peter Orth
  Affiliation: Iowa State U
  Title: Quantum algorithms for many-body dynamics simulations on noisy intermediate-scale quantum computers
  Abstract: Simulating quantum dynamics of interacting many-body systems is one of the primary potential applications of quantum computing, since the growth of entanglement makes such simulations exponentially hard on classical computers. The most straightforward approach to simu-

lating quantum dynamics is via the Trotter product formula. Due to the presence of hardware noise, however, Trotter simulations are limited to early times. We discuss how to extend the final time that can be reached in Trotter simulations on NISQ hardware using quantum error mitigation methods [8], [14]. An alternative approach to extend the final simulation time is to employ variational methods and we here present a few different methods. First, we discuss an adaptive approach to construct a variational wave function ansatz for accurate quantum dynamics simulations based on McLachlan's variational principle [16]. The key idea is to dynamically expand the variational ansatz along the time-evolution path such that the McLachlan distance, which is a measure of the simulation accuracy, remains below a set threshold. We apply this adaptive variational quantum dynamics simulation approach nonintegrable quantum spin models and find the circuits to contain up to two orders of magnitude fewer CNOT gates than those obtained from the first-order Trotter expansion. Then, we present results from an algorithm that combines Trotterized state evolution over short times with a variational compression step that uses the state overlap as a cost function [4]. We implement the algorithm on IBM hardware and show quantum dynamics simulation results for a few site Heisenberg spin chain beyond the coherence time of the device.

- **Speaker:** Sabrina Maniscalco
  Affiliation: University of Helsinki
  Title: Unlocking practical quantum advantage in near-term quantum computers
  Abstract: Todays quantum computers are imperfect. They are made of dozens or hundreds of qubits that can be prepared in highly nonclassical states but, being very sensitive to noise, their ability to preserve quantum properties is very limited. Noise not only arises from the interaction with their external environment, but encompasses all the imperfections in the sophisticated quantum hardware and control system. This is why, despite the discovery of algorithms that, in principle, would allow us to simulate interesting and currently intractable problems in chemistry and materials, many scientists in academia and companies are shifting their attention away from near-term quantum computers and towards fault-tolerant devices.
  In this talk I will argue that, as we move towards fault-tolerant quantum computers, hybrid quantum algorithms on near-term quantum computers can lead to quantum advantage already in the near future. One of the key ingredients to unlock quantum advantage in noisy devices is the use of informationally complete (IC) generalised measurements (IC POVMs) [9], [2], [12], [10]. I will present results showing how hybrid variational quantum-classical algorithms using IC data allow for unprecedented noise mitigation [10], runtime reduction [9], and ansatz generation.
  The combination of these three achievements will unlock quantum advan-

tage on near-term devices.

- **Speaker:** Matthias Christandl
  Affiliation: U Copenhagen
  Title: Quantum Communication with Noisy Devices
  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, 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 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.
  In the presented work, we initiate the study of these questions and show how techniques from quantum computation and communication can be combined to arrive at a communication analog of the famous threshold theorem. The threshold theorem says that one can compute (and now also communicate), when the noise per gate is below a certain threshold. We expect our results to be relevant for satellite communication as well as the execution of quantum software on distributed quantum processor cores.

- **Speaker:** Cecilia Lancien
  Affiliation: U Grenoble
  Title: Random tensor network states & Holography
  Abstract: Holographic models of quantum gravity conjecture a duality between the geometry of a bulk gravitational theory and the entanglement properties of a boundary conformal field theory. Tensor networks provide discrete toy-models for such correspondence, which appear to successfully reproduce several of the conjectured formulas. In particular, boundary states constructed from a bulk tensor network satisfy by construction an area law of entanglement, which is the primary expected feature of holographic states. In this talk, I will explain how picking the tensors composing the network at random provides a mathematically tractable model. Indeed, when doing so, the asymptotic spectral distribution of the corresponding random boundary states can be precisely characterized, and hence their asymptotic entanglement entropy as well. The latter turns out to be, as wanted, proportional to the area of the minimal surface inside the bulk enclosing the boundary subregion (rather than to its volume), with a correction term that depends on the number of such minimal surfaces. I will show how results of this kind can be obtained using tools from random matrix theory and free probability.
  Based on joint work with Newton Cheng, Geoff Penington, Michael Walter

and Freek Witteveen, available at arXiv:2206.10482.

- **Speaker**: Sevag Gharibian
  Affiliation: U Paderborn
  Title: Optimizing the depth of variational quantum algorithms is strongly QCMA-hard to approximate
  Abstract: Variational Quantum Algorithms (VQAs), such as the Quantum Approximate Optimization Algorithm (QAOA) of [Farhi, Goldstone, Gutmann, 2014], have seen intense study towards near-term applications on quantum hardware. A crucial parameter for VQAs is the depth of the variational "ansatz" used - the smaller the depth, the more amenable the ansatz is to near-term quantum hardware in that it gives the circuit a chance to be fully executed before the system decoheres. This potential for depth reduction has made VQAs a staple of Noisy Intermediate-Scale Quantum (NISQ)-era research.
  In this work, we show that approximating the optimal depth for a given VQA ansatz is intractable. Formally, we show that for any constant $eps > 0$, it is QCMA-hard to approximate the optimal depth of a VQA ansatz within multiplicative factor $N^(1 - eps)$, for N denoting the encoding size of the VQA instance. (Here, Quantum Classical Merlin-Arthur (QCMA) is a quantum generalization of NP.) We then show that this hardness persists even in the "simpler" setting of QAOAs. To our knowledge, this yields the first natural QCMA-hard-to-approximate problems. To achieve these results, we bypass the need for a PCP theorem for QCMA by appealing to the disperser-based NP-hardness of approximation construction of [Umans, FOCS 1999].
  Joint work with Lennart Bittel (Heinrich Heine Uni Düsseldorf) and Martin Kliesch (Heinrich Heine Uni Düsseldorf and Hamburg Uni of Technology).

- **Speaker:** Vladislav Golyanik
  Affiliation: MPI for Informatics, Saarbrücken
  Title: Advances in Quantum Computer Vision
  Abstract: Among the two quantum computing paradigms, i.e., universal (gate-based) and adiabatic, the latter recently attracted attention in the computer vision and graphics communities thanks to the advances in experimental hardware realisations. Compared to universal quantum machines, adiabatic quantum computers (AQC) are more noise-tolerant and provide sufficient resources for practical applications in terms of the number of qubits, qubit connectivity and admissible problem sizes they can address. At the same time, AQC are designed to optimise quadratic unconstrained binary optimisation (QUBO) objectives only. Therefore, many researchers believe that at this stage, it is essential to identify the potential advantages of AQC for the field. Thus, this talk will focus on how challenging problems such as permutation synchronisation, motion

segmentation, and mesh alignment can be formulated in QUBO forms and solved on modern AQC. Noteworthy, the resulting methods show unique characteristics and can often compete with the classical state of the art in solution accuracy. Before diving into the details, we will review recent projects of the 4DQV research group (MPI for Informatics, VCAI Department) and the foundations of AQC. In this talk we introduce the definition of non-local games and show on the basis of the CHSH game why quantum strategies are better than classical strategies.

- **Speaker**: Michael Hartmann
  Affiliation: Friedrich-Alexander-Universität
  Title: Quantum Convolutional Neural Networks
  Abstract: Quantum computing has made significant progress in recent years so that substantial gate sequences can now be run, and the output states become too complex to be fully analyzed by classical techniques. Here Quantum Convolutional Neural Networks, gate sequences that condense the relevant quantum information of the output state onto just a few qubits, can become a highly valuable tool. In this talk I will discuss how Quantum Convolutional Neural Networks can be used for recognizing a symmetry protected topological phase with a non-local order parameter by reading out just a single qubit on a superconducting quantum processor. In particular, I will focus on making Quantum Convolutional Neural Networks robust by reducing the number of quantum gates that they require and by equipping them with error tolerance mechanisms that allow to detect quantum phases despite imperfections in the prepared state.

- **Speaker:** Renato Renner
  Affiliation: ETH Zürich
  Title: What quantum information theory tells us about black holes
  Abstract: tba

- **Speaker**: Ferdinand Schmidt-Kaler
  Affiliation: Johannes Gutenberg Universität Mainz
  Title:
  Abstract:

- **Speaker**: Ivan Todorov
  Affiliation: U Belfast
  Title: Quantum hypergraph homomorphisms and non-local games
  Abstract: In this talk, I will define homomorphisms and isomorphisms between hypergraphs relative to a given no-signalling correlation type. I will then specialise this setup to the case where the hypergraphs arise from non-local games, arriving at a definition of quantum non-local game

homomorphisms/isomorphisms. I will show that homomorphisms between games give rise to an inequality between the corresponding game values. The talk is based on a joint work with Gage Hoefer.

- **Speaker:** Vivien Kendon
  Affiliation: U Strathclyde
  Title: Finding spin glass ground states with quantum walks
  Abstract: quantum walks have long been known to solve the search problem efficiently. Until recently, they have not been tested on other problems that can be solved by quantum annealing or adiabatic quantum computing. Finding the ground state of spin glasses is a hard problem that shares features with problems of practical interest. I will show how to use continuous-time quantum walks to find spin glass ground states, then discuss the mechanisms and potential for beating classical algorithms for this and similar problems. I will conclude with some open questions for future research.

- **Speaker**: Sofia Vallecorsa
  Affiliation: CERN
  Title: Quantum Generative Models in High Energy Physics
  Abstract: Theoretical and algorithmic advances, availability of data, and computing power have opened the door to exceptional perspectives for application of classical Deep Learning in the most diverse fields of science, business and society at large, and notably in High Energy Physics (HEP). Generative models, in particular, are among the most promising approaches to analyse and understand the amount of information the next generation HEP detectors will produce.
  Generative modeling is also a promising task for near-term quantum devices that can leverage compressed high dimensional representations and use the stochastic nature of quantum measurements as random source. Several architectures are being investigated. Quantum implementations of Generative Adversarial Networks (GAN) and Auto-Encoders, among the most popular classical approaches, are being proposed for different applications. Born machines are purely quantum models that can generate probability distributions in a unique way, inaccessible to classical computers.
  This talk will give an overview of the current state of the art in terms of generative modeling on quantum computers with focus on their application to HEP. Examples will include the application of Born machines and quantum GAN to the problem of joint and conditional distributions learning.

- **Speaker**: Antonio Macaluso
  Affiliation: German Research Center for Artificial Intelligence (DFKI), Saarbrücken

Title: Quantum Computing for AI applications

Abstract: Quantum computing represents a promising alternative to cope with the need to analyse ever-increasing amounts of information. This talk introduces the domain of Quantum Artificial Intelligence, with a focus on how quantum computation can help to improve classical AI methods in solving challenging tasks with demanding computational requirements. In particular, we will discuss some typical AI problems in the context of machine learning, multi-agent systems, scheduling and planning, and we will examine several quantum approaches, with particular care to the advantages with respect to their classical counterparts.

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