QI 24: Verification and Benchmarking of Quantum Systems

Time: Thursday 9:30–13:30 Location: HFT-TA 441

Invited Talk QI 24.1 Thu 9:30 HFT-TA 441

Verification of quantum measurements via self-testing — •Laura Mančinska — QMATH, Department of Mathematical Sciences, University of Copenhagen, Denmark

Self-testing is the strongest form of quantum functionality verification which allows a classical user to deduce the quantum state and measurements used to produce measurement statistics. While self-testing of quantum states is well-understood, self-testing of measurements, especially in high dimensions, has remained more elusive. We demonstrate the first general result in this direction by showing that every real projective measurement can be self-tested in the 2-party Bell scenario. The standard definition of self-testing only allows for the certification of real measurements. Therefore, our work effectively broadens the scope of self-testable projective measurements to their full potential. To reach this result, we employ the idea that existing self-tests can be extended to verify additional untrusted measurements. This is known as 'post-hoc self-testing'. We formalize the method of post-hoc self-testing and establish a sufficient condition for its application.

We develop a new technique of iterative self-testing, which involves using post-hoc self-testing in a sequential manner. Starting from any established self-test, we fully characterize the set of measurements that can be verified via iterative self-testing. This provides a clear methodology for constructing new self-tests from pre-existing ones.

This talk is based on a joint work with Ranyiliu Chen and Jurij Volčič.

QI 24.2 Thu 10:00 HFT-TA 441

Verification-Inspired Quantum Benchmarking — •Johannes Frank[1,4], Elham Kashefi[2,3,4], Dominik Leichtle[4], and Michael Oliveira[4,5] — [1]Technical University of Munich, Germany — [2]School of Informatics, University of Edinburgh, 10 Crichton Street, EH8 9AB Edinburgh, United Kingdom — [3]National Quantum Computing Centre, Didcot, OX11 0QX, United Kingdom — [4]Laboratoire d'Informatique de Paris 6, CNRS, Sorbonne Université, 4 Place Jussieu, 75005 Paris, France — [5]International Iberian Nanotechnology Laboratory, Portugal

Currently available quantum devices suffer from significant noise and are limited in size which restricts their computational power. For this reason, quantum benchmarking, the task to judge and compare the usefulness of quantum hardware, is both important and nontrivial. Previously proposed benchmarking protocols and metrics however rely on heuristics or require strong assumptions on the behavior of the analyzed device. In this paper, we introduce a new approach to quantum benchmarking, inspired by quantum verification. As opposed to other benchmarking protocols, our proposal uses cryptographic tools to eliminate the reliance on heuristics and allow for provable statements about a device's computational power. It crucially offers scalability, customizability, and universality for quantum computation. Our work uncovers a deep connection between the fields of quantum verification and benchmarking. We give a concrete construction of a readily employable benchmarking protocol, and show that it achieves our improved standards for quantum benchmarking.

QI 24.3 Thu 10:15 HFT-TA 441

Collective operations can exponentially enhance quantum state verification — •Ferran Riera Sabat, Jorge Miguel-Ramiro, and Wolfgang Dür — Institut für Theoretische Physik, Universität Innsbruck, Technikerstraße 21a, 6020 Innsbruck, Austria

Maximally entangled states are a key resource in many quantum communication and computation tasks, and their certification is a crucial element to guarantee the desired functionality. Collective strategies for the efficient local verification of ensembles of Bell pairs that make use of initial information and noise transfer to a few copies prior to their measurement are introduced. In this way the number of entangled pairs that need to be measured and hence destroyed is significantly reduced as compared to previous, even optimal, approaches that operate on individual copies. Moreover, the remaining states are directly certified. We show that our tools can be extended to other problems and larger classes of multipartite states.

QI 24.4 Thu 10:30 HFT-TA 441

Certifying the topology of quantum networks: theory and experiment — •Lisa T. Weinbrenner[1], Nidhin Prasannan[2], Kiara Hansenne[1], Sophia Denker[1], Jan Sperling[3], Benjamin Brecht[2], Christine Silberhorn[2], and Otfried Gühne[1] — [1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Germany — [2]Paderborn University, Integrated Quantum Optics, Institute of Photonic Quantum Systems (PhoQS), Germany — [3]Paderborn University, Theoretical Quantum Science, Institute for Photonic Quantum Systems (PhoQS), Germany

Distributed quantum information in networks is paramount for global secure quantum communication. Moreover, it finds applications as a resource for relevant tasks, such as clock synchronization, magnetic field sensing, and blind quantum computation. For quantum network analysis and benchmarking of implementations, however, it is crucial to characterize the topology of networks in a way that reveals the nodes between which entanglement can reliably be distributed. Here, we demonstrate an efficient scheme for this topology certification. Our scheme allows for distinguishing, in a scalable manner, different networks consisting of bipartite and multipartite entanglement sources, for different levels of trust in the measurement devices and network nodes. We experimentally demonstrate our approach by certifying the topology of different six-qubit networks generated with polarized photons, employing active feed-forward and time multiplexing. Our methods can be used for general simultaneous tests of multiple hypotheses with few measurements, being useful for other certification scenarios.

QI 24.5 Thu 10:45 HFT-TA 441

Verification of quantum memory in non-Markovian processes based on local information — •Charlotte Bäcker[1], Konstantin Beyer[1,2], and Walter Strunz[1] — [1]TUD Dresden University of Technology, 01062, Dresden, Germany — [2]Stevens Institute of Technology, Hoboken, New Jersey, 07030, USA

Non-Markovian processes in quantum physics may be the result of the environmental degrees of freedom acting as a memory. It is an ongoing debate whether the memory effects can be modeled by a classical memory or whether their origin is inherently quantum. We propose a witness based only on local information of the system dynamics, which allows to verify the quantum nature of the memory. Using physically motivated examples, we show that both classical and quantum memory can occur in non-Markovian dynamics and establish the link between classical memory and a physically measurable quantum trajectory representation.

QI 24.6 Thu 11:00 HFT-TA 441

Overlapping tomography: Reducing the number of measurement settings — •Kiara Hansenne, Lisa Weinbrenner, Carlos de Gois, and Otfried Gühne — Universität Siegen, Germany

Quantum state tomography aims at reconstructing the density operator of a quantum system using data acquired from measurements on several copies of the system's state. While the conventional approach demands an exponential increase in measurement settings with the growth of particle numbers, certain situations only necessitate access to the density operators of k-body reduced states. Notably, for n-qubit systems, prior studies have shown that the number of Pauli measurement settings scales as e^O(k) log^2(n). In this work, we present insights from a one-to-one correspondence with a well-studied problem in combinatorics, and show how to explicitly obtain optimal measurement settings. Furthermore, by dropping the Pauli measurement assumption, we demonstrate the feasibility of marginal tomography with 3^k measurement settings, independently of the number of qubits.

15 min. break

QI 24.7 Thu 11:30 HFT-TA 441

Parameterizing Pauli noise to capture crosstalk in quantum devices — •Matthias Zipper[1], Christopher Cedzich[2], and Martin Kliesch[1] — [1]Hamburg University of Technology, Germany — [2]Heinrich-Heine-Universität Düsseldorf, Universitätsstr. 1, 40225 Düsseldorf, Germany

Physically meaningful and efficient noise models are important for the development of reliable quantum devices. We propose a parameterization of Pauli noise that arises naturally from intuitive axioms and combines the following desirable properties: (i) Each parameter is associated with a subset of qubits, and hence is interpreted as describing regional noise. (ii) While a priori capable of representing any Pauli noise channel, the parameterization becomes efficient under physically motivated locality assumptions. (iii) Our approach is compatible with a wide range of SPAM-robust protocols from the RB family, which facilitates its practical use in quantum system characterization. Our model thus resolves the spatial structure of Pauli noise and addresses the topic of "crosstalk" for quantum gates and circuits.

QI 24.8 Thu 11:45 HFT-TA 441

ACES on correlated noise - promises and challenges of frontend noise metrology — •Michael Ronen, Joris Kattemölle, and Guido Burkard — Universität Konstanz, Konstanz, Deutschland

Correlated noise poses a severe challenge to the advantage of many practical quantum algorithms. Error mitigation is indispensable for achieving a quantum advantage with noisy intermediate-scale quantum technology. It relies heavily on our ability to measure and quantify the noise affecting the circuits in quantum computers. Averaged circuit eigenvalue sampling (ACES) promises to be an effective frontend method of noise metrology that can compete with randomized benchmarking and noise tomography. We mark out the capabilities of ACES in measuring spatially and temporally correlated noise. We demonstrate that it can meet expectations when estimating spatially correlated errors but find limits in characterizing their temporally correlated counterparts. These difficulties arise since the error models' complexity grows exponentially with the depth of the circuit while the amount of extractable information stays constant with the number of qubits. By shining a light on ACES' capabilities, we better understand the promises and challenges of frontend noise metrology. Thereby, we point to future lines of inquiry that will improve the accuracy of correlated error model estimation. This will ultimately move us closer to achieving a practical quantum advantage.

QI 24.9 Thu 12:00 HFT-TA 441

Stability of classical shadows under gate-dependent noise — •Raphael Brieger[1,3], Markus Heinrich[1], Ingo Roth[2], and Martin Kliesch[1,3] — [1]Heinrich Heine University Düsseldorf, Faculty of Mathematics and Natural Sciences, Germany — [2]Quantum Research Center, Technology Innovation Institute, Abu Dhabi, UAE — [3]Hamburg University of Technology, Institute for Quantum Inspired and Quantum Optimization, Germany

Expectation values of observables are routinely estimated using so-called classical shadows—the outcomes of randomized bases measurements on a repeatedly prepared quantum state. In order to trust the accuracy of shadow estimation in practice, it is crucial to understand the behavior of the estimators under realistic noise. In this work, we prove that any shadow estimation proto- col involving Clifford unitaries is stable under gate-dependent noise for observables with bounded stabilizer norm—originally introduced in the context of simulating Clifford circuits. For these ob- servables, we also show that the protocol's sample complexity is essentially identical to the noiseless case. In contrast, we demonstrate that estimation of "magic" observables can suffer from a bias that scales exponentially in the system size. We further find that so-called robust shadows, aiming at mitigating noise, can introduce a large bias in the presence of gate-dependent noise compared to unmitigated classical shadows. On a technical level, we identify average noise channels that affect shadow estimators and allow for a more fine-grained control of noise-induced biases.

QI 24.10 Thu 12:15 HFT-TA 441

Shadow tomography with noisy readouts — •Hai-Chau Nguyen — University of Siegen

Shadow tomography emerges as a scalable technique to characterise the quantum state of a quantum computer or quantum simulator. Unfortunately, shadow tomography is by construction intrinsically sensitive to readout noise. In fact, the complicated structure of the readout noise due to crosstalk appears to be detrimental to the scalability of the most practical shadow tomography scheme. We show that shadow tomography accepts much more flexible constructions beyond the standard ones, which can eventually be made conformable with readout noise. With this construction, we show that readout errors in shadow tomography with randomised qubit measurements can be efficiently mitigated simply by randomly flipping the qubit before, and the classical outcome bit after the measurement. That a single X-gate is sufficient for mitigating readout noise for classical shadows is in contrast to Clifford-twirling, where the implementation of random Clifford gates is required.

QI 24.11 Thu 12:30 HFT-TA 441

User-friendly confidence regions for quantum state tomography — •Carlos de Gois and Matthias Kleinmann — Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany

Quantum state tomography is the standard technique for reconstructing a quantum state from measurement data. In practice, only a finite number of copies of the unknown state can be measured, thus the estimated state will almost surely diverge from the true state. A common way to express this limited knowledge about the true state is by providing confidence regions that contain the true state with high probability. Although some methods to construct such confidence regions already exist, they all have drawbacks such as requiring too many samples, not generalizing to arbitrary measurements, or being difficult to describe. In this talk, I will discuss a new construction that overcomes these issues. The resulting regions are described by ellipsoids in the space of Hermitian operators, have an asymptotically optimal sample cost, and can be straightforwardly applied to any measurement scheme. To investigate their performance in practice, I will use simulated tomography experiments to compare the sample costs with respect to previous proposals, and show that our construction leads to tighter regions, especially for high-dimensional systems.

QI 24.12 Thu 12:45 HFT-TA 441

Pathological Behavior of Point Estimators with Minimum Bias (in Quantum Tomography, etc.) — •Yien Liang[1,2,3] and Matthias Kleinmann[1] — [1]Universität Siegen, Walter-Flex-Straße 3, D-57068 Siegen, Germany — [2]Peking University, Beijing 100871, China — [3]Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Universitätsstr. 1, D-40225 Düsseldorf, Germany

Being unbiased can be a desirable property for a statistical point estimator, that is, that the mean estimated value of a parameter coincides with the actual value of the parameter. While this property can be traded for other desiderata, it has been noted that in quantum physics, specifically in quantum state tomography, any estimator that always yields a physical estimate is necessarily biased. This affects the possible meaning of a state estimator, however, only if this effect is sizable enough to warrant a discussion. So far, no quantitative account of this effect was given and it could be possible that the bias of such an estimator is arbitrary small. Here we ask a more general question concerning the quantitative account of the minimum bias in situations where no unbiased estimator is available. For the example of Bernoulli trails with a constrained parameter space, we find that the least biased estimator is unique, but also pathological, in a certain sense.

QI 24.13 Thu 13:00 HFT-TA 441

Overcoming scalability bottlenecks of detecting quantum entanglement — •Daniel Miller[1], Lukas Postler[2], Antonio Anna Mele[1], Kyano Levi[1], Christian Marciniak[2], Ivan Pogorelov[2], Milena Guevara-Bertsch[2], Alex Steiner[2], Robert Freund[2], Rainer Blatt[2,3], Philipp Schindler[2], Jose Carrasco[2], Martin Ringbauer[2], Thomas Monz[2,4], and Jens Eisert[1] — [1]Freie Universität Berlin — [2]Universität Innsbruck — [3]IQOQI — [4]AQT

Concomitant with the rapid development of architectures in quantum technologies, increasingly sophisticated methods of quantum system identification are being developed. Mature schemes of quantum system identification should be (i) sample efficient in the system size, including an (ii) efficient classical post-processing, must be (iii) provably robust under realistic error models for a large class of states and (iv) should solely rely on experimentally feasible capabilities when resorting to quantum data processing. In this work, we identify sufficient requirements on the quality of a quantum device to permit provably scalable entanglement detection. Our proof is enabled by novel techniques that further strengthen the already deep connection between the theories of quantum entanglement and quantum error correction.

QI 24.14 Thu 13:15 HFT-TA 441

Proposed method to produce large multipartite nonlocality and to benchmark quantum computers — •Jan Lennart Bönsel[1], Otfried Gühne[1], and Adán Cabello[2] — [1]Universität Siegen, Germany — [2]Universidad de Sevilla, Spain

Nonlocality is a characteristic of quantum mechanics that does not occur in local realistic models. The violation of a Bell inequality can thus be used to verify nonclassicality.

In this contribution, we address the problem of producing n-partite Bell nonlocality with a very large number of qubits n. The main limiting factors are: (i) A restricted connectivity of the quantum computer might not allow an easy preparation of arbitrary entangled states. (ii) Noise limits the observable violation, and (iii) the number of different combinations of local measurements grows exponentially with n. Here, we point out that, for a given two-qubit connectivity, there is a particular entangled state that can be efficiently prepared, effectively overcoming (i). For the extreme cases of connectivity, we consider the GHZ and the linear cluster state. For these states, there exist n-partite Bell inequalities for which the resistance to white noise increases exponentially with n, which limits the impact of (ii). Finally, we introduce a method to address (iii). As a result, we show how to produce n-partite Bell nonlocality with unprecedented large n using quantum computers under the assumption that there is no qubit communication after the local measurements. The n-partite nonlocality allows to quantify the nonclassicality and thus benchmark quantum computers. We test our approach on the IBM Quantum platform.