# QI 6: Quantum Information: Concepts and Methods

Time: Tuesday 9:30–12:45 Location: H9

**Invited Talk** QI 6.1 Tue 9:30 H9

**Towards an Artificial Muse for new Ideas in Quantum Physics** — •Mario Krenn — Max Planck Institute for the Science of Light (MPL), Erlangen, Germany

Artificial intelligence (AI) is a potentially disruptive tool for physics and science in general. One crucial question is how this technology can contribute at a conceptual level to help acquire new scientific understanding or inspire new surprising ideas. I will talk about how AI can be used as an artificial muse in quantum physics, which suggests surprising and unconventional ideas and techniques that the human scientist can interpret, understand and generalize.

[1] Krenn, Kottmann, Tischler, Aspuru-Guzik, Conceptual understanding through efficient automated design of quantum optical experiments. Physical Review X 11(3), 031044 (2021).

[2] Krenn, Pollice, Guo, Aldeghi, Cervera-Lierta, Friederich, Gomes, Häse, Jinich, Nigam, Yao, Aspuru-Guzik, On scientific understanding with artificial intelligence. arXiv:2204.01467 (2022).

[3] Krenn, Zeilinger, Predicting research trends with semantic and neural networks with an application in quantum physics. PNAS 117(4), 1910-1916 (2020).

QI 6.2 Tue 10:00 H9

**Learning variable quantum processes** — Marco Fanizza[1], Yihui Quek[2], and •Matteo Rosati[3] — [1]FT: IFQ, Universitat Autonoma de Barcelona, 08193 Bellaterra (Barcelona) Spain — [2]Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany — [3]Electrical Engineering and Computer Science, Technische Universität Berlin, 10587 Berlin, Germany

Much of the current research on characterizing quantum processes via statistical learning theory assumes a highly controlled learning setting. Typically, the learner is allowed to use the unknown process as a blackbox that may be applied to well-crafted inputs. In this work, we relax this assumption. How hard is it to learn a quantum process observed ‘in-the-wild’, without control over the inputs? This is the case, for instance, in learning astronomical processes induced by random celestial events, Hamiltonians at variable temperature and biological processes triggered by mechanisms which we can observe but not control. We reformulate this problem as one where a learner has access to a source that outputs classical-quantum states $\sum_x p(x)|x\rangle\langle x| \otimes \psi(x)$ where $\psi$ is the unknown process mapping an input classical random variable $x$ to an output quantum state. The goal is to learn $\psi$. When $\psi$ is drawn from a class of functions C, we show that the complexity of this task scales polynomially in a combinatorial dimension of C (a measure of its effective size) that we define, and further give algorithms that achieve this complexity. We show, for the first time to our knowledge, that quantum states and processes can be learned efficiently even when identical repetitions of the same experiment are not possible.

QI 6.3 Tue 10:15 H9

**Shortening Quantum Convolutional Neural Networks to Constant Depth** — •Nathan McMahon, Petr Zapletal, and Michael Hartmann — Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany

The quantum convolutional neural network (QCNN) is a quantum circuit that detects symmetry protected topological (SPT) phases, with its construction drawing from ideas of renormalisation theory. In this talk I will discuss a special class of these circuits that are equivalent to constant depth quantum circuits, local measurements, and classical post-processing, including an earlier example from Cong et al for a Z2 x Z2 SPT phase detection circuit. We modify this circuit and demonstrate how to shorten it to constant depth, while improving both the time complexity and signal fidelity.

Surprisingly, while the quantum component circuit is constant depth on N-qubits, we still observe a provably exponential (in N) sample complexity speed up compared to only local Pauli measurements and post-processing of the input state. To understand how this happens we demonstrate that a reduced complexity of the input state leads to a guaranteed reduction in the sample complexity speedup.

We finally consider how to explain the effectiveness of the QCNN as a phase recognition algorithm through quantum fidelity approaches to phase transitions. We do this by deriving a sufficient condition for the layers of the QCNN for its output to perform phase recognition. In the process, also making a tantalising connection between the renormalisation group and optimisation.

QI 6.4 Tue 10:30 H9

**Quantum Convolutional Neural Network as a Phase Detection Circuit on the Toric Code** — •Leon Sander, Nathan McMahon, and Michael Hartmann — Chair of Theoretical Physics, Friedrich-Alexander-Universität Erlangen Nürnberg, Germany

Understanding macroscopic behaviour of quantum materials is an interesting challenge in the field of quantum technologies. This macroscopic behaviour can be evaluated by the examination of quantum phases. Consequently, recognising the phase of a given input state is an important problem, which is often solved by measuring the corresponding order parameter. However, previous work by Cong et al. and Hermann et al. suggests quantum convolutional neural networks (QCNN) are an alternative method of phase detection that can also improve sampling efficiency near the phase boundary compared to direct measurements.

We construct a QCNN designed to act as a phase recognition circuit that determines whether certain magnetic/Ising type perturbations are sufficient to induce a phase transition in the toric code. The choice to study this quantum error correcting code can be motivated as it promises to reveal connections between quantum information and quantum phase transitions.

QI 6.5 Tue 10:45 H9

**Evaluating the power and performance of sigmoid quantum perceptrons.** — •Samuel Wilkinson and Michael Harman — Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstr. 7, 91058 Erlangen, Germa

Quantum neural networks (QNN) have been proposed as a promising architecture for quantum machine learning. There exist a number of different quantum circuit designs being branded as QNNs, however no clear candidate has presented itself as more suitable than the others. Rather, the search for a “quantum perceptron” – the fundamental building block of a QNN – is still underway.

One candidate is quantum perceptrons designed to emulate the nonlinear activation functions of classical perceptrons. Such sigmoid quantum perceptrons (SQPs) inherent the universal approximation property that guarantees that classical neural networks can approximate any continuous function. However, this does not guarantee that QNNs built from SQPs will have any quantum advantage over their classical counterparts. Here we critically investigate both the capabilities and performance of SQP networks by computing general measures of the dimension and capacity of the network, as well as its performance on real learning problems. The results are compared to those obtained for other candidate networks which lack activation functions. It is found that simpler, easier-to-implement parametric quantum circuits actually perform better than SQPs. This indicates that the universal approximation theorem, which a cornerstone of the theory of classical neural networks, is not a relevant criterion for QNNs.

**15 min. break**

QI 6.6 Tue 11:15 H9

**An algorithm to factorize quantum walks into shift and coin operations** — •Christopher Cedzich[1], Tobias Geib[2], and Reinhard F. Werner[2] — [1]Quantum Technology Group, Heinrich Heine Universität Düsseldorf, Universitätsstr. 1, 40225 Düsseldorf — [2]Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstr. 2, 30167 Hannover

Quantum walks provide a basic architecture for implementing quantum information processing and computing. It is therefore important to resolve a given task into available operations, i.e., to ”compile” a targeted program. We provide such a method, showing that an arbitrary one-dimensional quantum operation can be resolved into a protocol of two basic operations: A fixed conditional shift that transports particles between cells and suitable coin operators that act locally in each cell. This allows to tailor quantum walk protocols to any experimental setup by rephrasing it on the cell structure determined by the experimental limitations.

QI 6.7 Tue 11:30 H9

**Improved Bell state measurement** — •Simone D'Aurelio, Matthias Bayerbach, and Stefanie Barz — Institute for Functional Matter and Quantum Technologies & IQST, University of Stuttgart, 70569 Stuttgart, Germany

Bell-state measurements play an important role in many quantum technologies, e.g. in quantum repeaters, certain quantum communication protocols and photonic quantum computing. However, using linear-optics only, such a Bell-state measurement has a success probability of 50%. Here, we show the implementation of a novel scheme that allows overcoming this limit.

We give details on the experimental setup. We show how we generate Bell-states in a linear Mach-Zehnder-like scheme as well as how we create ancilliary N00N states from single photons. Both states interfere in a linear-optical setup and photon-number measurements at the output allow determining the respective Bell state.

QI 6.8 Tue 11:45 H9

**Preparation of maximally entangled states with digital-analog quantum computing** — •Nicola Wurz[1], Julia Lamprich[1], Manish Thapa[1], Vicente Pina Canelles[1], Stefan Pogorzalek[1], Antti Vepsäläinen[2], Miha Papic[1], Jayshankar Nath[1], Florian Vigneau[1], Daria Gusenkova[1], Ping Yang[1], Hermanni Heimonen[2], Hsiang-Sheng Ku[1], Adrian Auer[1], Johannes Heinsoo[2], Frank Deppe[1], and Inés de Vega[1] — [1]IQM Quantum Computers, Munich, Germany — [2]IQM Quantum Computers, Espoo, Finland

Digital-Analog Quantum Computing (DAQC) is a novel approach, which combines digital single qubit gates with analog multi-qubit blocks. The DAQC concept distinguishes between stepwise and banged DAQC, where the single qubit gates are placed in between analog blocks or applied simultaneously with the analog (entangling) evolution, respectively. We have identified relevant sources of error for both DAQC protocols. When preparing a maximally entangled two-qubit state using either stepwise or banged DAQC, we reach similar fidelities as in the purely digital case. The multi-qubit version of the implemented circuit allows us to create GHZ states by parallelizing several two-qubit interactions. For the case of three qubits, we have investigated infidelities arising due to the multi-qubit nature of the interaction, including parasitic and higher order couplings.

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QI 6.9 Tue 12:00 H9

**Momentum-Space Entanlgement and the Wilsonian Effective Action** — •Matheus Henrique Martins Costa[1,2], Gastao Inacio Krein[2], Flavio de Souza Nogueira[1], and Jeroen van den Brink[1] — [1]Institute for Theoretical Solid State Physics - IFW Dresden, Dresden, Germany — [2]Instituto de Física Teórica - Universidade Estadual Paulista, Sao Paulo, Brazil

The entanglement between momentum modes of a quantum field theory at different scales is not as well studied as its counterpart in real space, despite the natural connection with the Wilsonian idea of integrating out the high-momentum degrees of freedom. Here, we push such connection further by developing a novel method to calculate the Rényi and entanglement entropies between slow and fast modes which is based on the Wilsonian effective action at a given scale and apply it to the perturbative regime of some scalar theories, comparing the lowest-order results with those from the literature and giving them an interpretation in terms of Feynman diagrams. Our results open the way for further work in exploring the relation between renormalization and entanglement and the role of the latter in phase transitions.

QI 6.10 Tue 12:15 H9

**Holographic code in the laboratory** — •Gerard Anglès Munné[1], Valentin Kasper[2], and Felix Huber[1] — [1]Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, 30-348 Kraków, Poland. — [2]Institut de Ciències Fotòniques (ICFO), Mediterranean Technology Park, 08860 Castelldefels, Barcelona, Spain

We propose a method to prepare the holographic pentagon code in the laboratory. The code states can be described by graph states whose interactions patterns are optimized for experimental purposes. Taking a small instance of the holographic code on 12 qubits, we show how to do encoding and decoding. Furthermore, we demonstrate how to test the holographic property - any bulk part is determined by its nearby boundary - through a partial recovery procedure.

QI 6.11 Tue 12:30 H9

**Universal ground state entanglement entropy in strongly biased bipartite systems** — •Ohad Shpielberg — University of Haifa, Haifa, Israel

Consider the AB bipartite system with a single conserved quantity, say a particle number. The particle bias R is defined as the expectation of the particle number in subsystem A over the expectation in subsystem B. At the limit of large R, the ground state entanglement entropy is shown to universally scale like $\log R/R$, independent of the Hamiltonian details. A $1/\sqrt{R}$ universal power law is obtained for multiple conserved quantities. Moreover, the analysis shows a similar universal structure of the Rényi entropy.

This universal behavior could be exploited to optimize entanglement-assisted control over large many body systems, using systems with a small degree of freedom. Alternatively, one can use the different scaling of the entanglement entropy to detect hidden conserved quantities.

Part of the announced results are available at Phys. Rev. A 105, 042420 (2022).