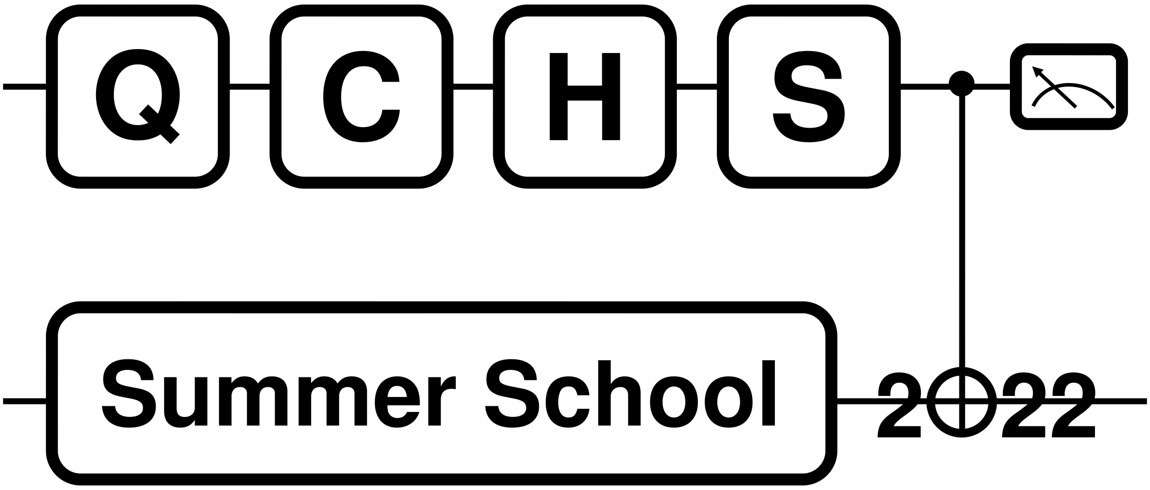
Leaflet



Quantum Computing Hard- and Software Summer School 2022

June 13 - 17, 2022

Organized by

Ivan Rojkov
Stefano Barison
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David Schlegel
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This is the version of the booklet for print use. Some of its information can be found in the electronic version at `https://qchs2022.epfl.ethz.ch/`

This booklet has been created using an open-source LaTeX template that is available at `https://github.com/maximelucas/AMCOS_booklet`

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About

Quantum Computing Hard- and Software summer school

The promise of opening up a whole new field of information technology has led to a rapid development of laboratory level quantum research into an emerging technology sector with huge transformative potential. A new generation of physics and engineering students is aiming to become the workforce that will ultimately fulfill this promise. The Quantum Computing Hard- and Software summer school aims to create an opportunity for those students to extend their knowledge as well as to connect to leading players in industry and academia across Switzerland and abroad.

The summer school program is designed to answer questions which naturally arise when thinking about the field of quantum computing. The program is divided into four parts: quantum algorithms, quantum hardware, a hands-on programming session, and a series of invited talks on the current state of research. Each part is tailored to give an answer to one question.

The four questions are: What makes quantum computers different from classical ones? How do you build a quantum processor? How do you implement quantum computation once you have the hardware? What are researchers actively working on?

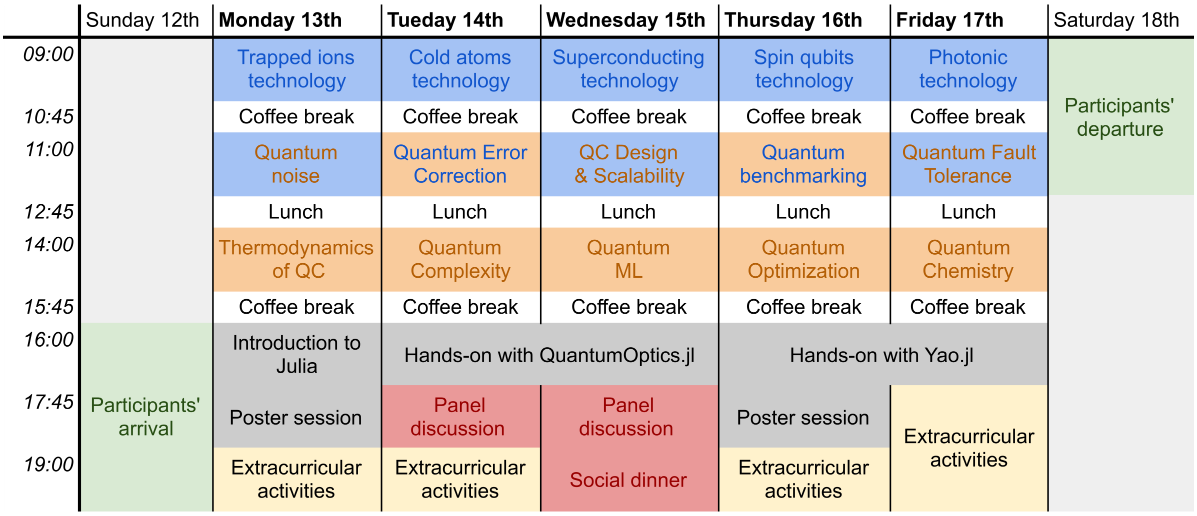
The first two questions will be answered through the keynote lectures each day, which not only focus on the topics of quantum hardware and quantum software, but also the crucial interplay between the two. Toward the end of the day, the participants will have a chance to put the newly learned concepts into practice during tutorials using a specific programming language (TBA). Finally, each day will close with talks given by leading professors and startups.

About this document

This document serves as participant's companion during the summer school. It includes a detailed schedule, information about accommodation, abstracts of the submitted posters and the procedure for getting the ECTS credits. It is a preliminary booklet which will be completed progressively until a few weeks away from the beginning of the school.

Schedule

Schedule by themes



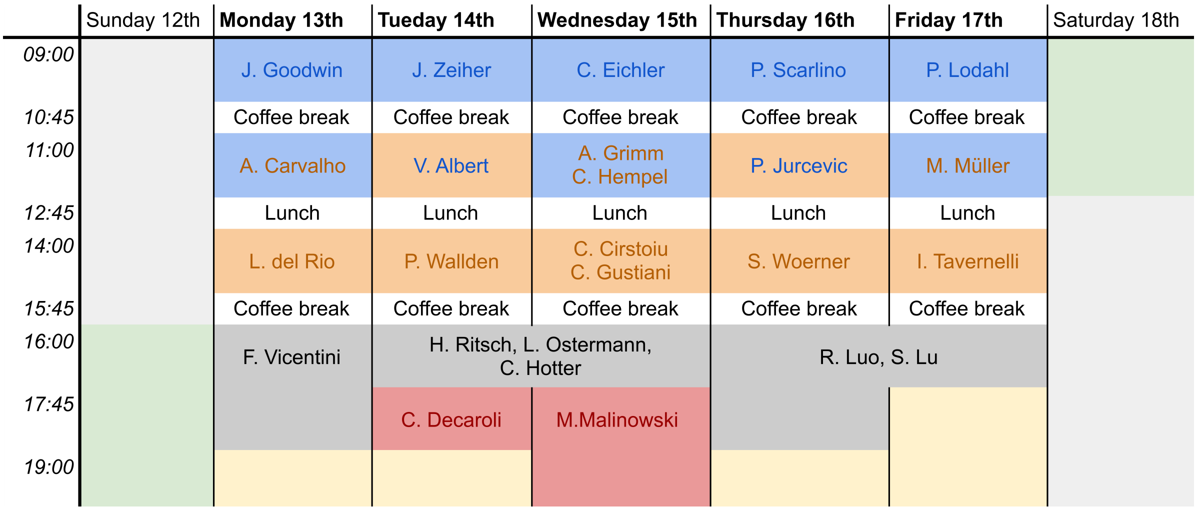
	Sunday 12th	**Monday 13th**	**Tueday 14th**	**Wednesday 15th**	**Thursday 16th**	**Friday 17th**	Saturday 18th
09:00		Trapped ions technology	Cold atoms technology	Superconducting technology	Spin qubits technology	Photonic technology	Participants' departure
10:45		Coffee break	Coffee break	Coffee break	Coffee break	Coffee break	
11:00		Quantum noise	Quantum Error Correction	QC Design & Scalability	Quantum benchmarking	Quantum Fault Tolerance	
12:45		Lunch	Lunch	Lunch	Lunch	Lunch	
14:00		Thermodynamics of QC	Quantum Complexity	Quantum ML	Quantum Optimization	Quantum Chemistry	
15:45		Coffee break	Coffee break	Coffee break	Coffee break	Coffee break	
16:00	Participants' arrival	Introduction to Julia	Hands-on with QuantumOptics.jl		Hands-on with Yao.jl		
17:45		Poster session	Panel discussion	Panel discussion	Poster session	Extracurricular activities	
19:00		Extracurricular activities	Extracurricular activities	Social dinner	Extracurricular activities		

Every morning will start with a keynote lecture focused on quantum hardware, thus presenting various methods of realizing and processing quantum information. The second part of each morning session will consist of a hybrid hardware-software lecture which will treat topics that lay at the intersection of experiment and theory. These will build the bridge towards the software-oriented lecture in the afternoon which will tackle theoretical aspects of quantum information processing. The lectures will be followed each day by a hands-on session where participants will simulate a quantum computer and implement quantum algorithms using a specific programming language. Finally, two poster sessions and two panel discussion will be organized throughout the week. The former will give the students a chance to present their recent projects and works in progress to their peers; while the panel discussions will offer them the opportunity interact with outstanding researchers from both academia and the private sector.

The Hands-on sessions will focus on the Julia programming language for quantum systems and algorithms simulations. In particular, the two following packages will be presented and used for practical exercises:

1. QuantumOptics.jl - Developed and maintained by the group of Prof. Helmut Ritsch
2. Yao.jl - Developed and maintained by Roger Luo

Schedule by lecturers



	Sunday 12th	**Monday 13th**	**Tueday 14th**	**Wednesday 15th**	**Thursday 16th**	**Friday 17th**	Saturday 18th
09:00		J. Goodwin	J. Zeiher	C. Eichler	P. Scarlino	P. Lodahl	
10:45		Coffee break	Coffee break	Coffee break	Coffee break	Coffee break	
11:00		A. Carvalho	V. Albert	A. Grimm C. Hempel	P. Jurcevic	M. Müller	
12:45		Lunch	Lunch	Lunch	Lunch	Lunch	
14:00		L. del Rio	P. Wallden	C. Cirstoiu C. Gustiani	S. Woerner	I. Tavernelli	
15:45		Coffee break	Coffee break	Coffee break	Coffee break	Coffee break	
16:00		F. Vicentini	H. Ritsch, L. Ostermann, C. Hotter		R. Luo, S. Lu		
17:45			C. Decaroli	M.Malinowski			
19:00							

The figure above presents in a glance the confirmed lecturers for the QCHS 2022 summer school. The blanks spots will be filled in progressively as the latter confirm their presence.

Among the confirmed lecturers (together with their topic of presentation), there are:

- Joseph Goodwin (Ion Trap Quantum Computing group, University of Oxford) - *Trapped atom technology for quantum computation*
- Andre R. R. Carvalho (Q-CTRL) - *Noise in quantum computing architectures*
- Lídia del Rio (Quantum Information Theory group, ETH Zürich) - *Thermodynamics of quantum computing*
- Johannes Zeiher (Max-Planck-Institute for Quantum Optics) - *Cold atom technology for quantum simulations*
- Victor V. Albert (Joint Center for Quantum Information and Computer Science, University of Maryland and NIST) - *Quantum error correction*
- Petros Wallden (Laboratory for Foundations of Computer Science, University of Edinburgh) - *Quantum algorithms and complexity*
- Christopher Eichler (Quantum Device Lab, ETH Zürich) - *Superconducting circuits for quantum computing*
- Alexander Grimm (Laboratory for X-ray Nanoscience and Technologies, Paul Scherrer Institute) - *Design of scalable quantum computing systems*
- Cornelius Hempel (Laboratory for Nano and Quantum Technologies, Paul Scherrer Institute) - *Design of scalable quantum computing systems*

- Cica Gustiani (Quantum Technology Theory Group, University of Oxford) - *Quantum machine emulation and variational quantum algorithms*
- Cristina Cirstoiu (Cambridge Quantum Computing) - *Impact of noise on NISQ applications*
- Pasquale Scarlino (Hybrid Quantum Circuits Laboratory, EPFL) - *Spin qubit technology and hybrid quantum systems*
- Petar Jurcevic (IBM New York) - *Benchmarking of quantum computing architectures*
- Stefan Woerner (IBM Zürich) - *Quantum optimization algorithms*
- Peter Lodahl (Niels Bohr Institute) - *Photonics for quantum technology*
- Markus Müller (RWTH Aachen University) - *Fault-tolerant quantum computation*
- Ivano Tavernelli (IBM Zürich) - *Quantum chemistry simulations*

As mentioned in the previous section, the hands-on sessions will focus on the Julia programming language and primarily on packages QuantumOptics.jl and Yao.jl. The introductory lecture about the the programming language will be given by Filippo Vicentini (Computational Quantum Science Lab, EPFL) whereas the packages mentioned earlier will be introduced by their creators/maintainers themselves, namely:

1. Laurin Ostermann and Christoph Hotter (Cavity Quantum Electrodynamics group, University of Innsbruck)
2. Roger Luo (Institute for Quantum Computing, University of Waterloo & Perimeter Institute) and Sirui Lu (Theory Division, Max-Planck Institute of Quantum Optics)

The two panel discussions will be organized and chaired by:

- Chiara Decaroli (Outreach and Engagement Officer at the National Quantum Computing Centre) - *Quantum computing: the Good, the Bad and the Ugly* with the panelists C. Eichler, J. Zeiher, J. Goodwin and P. Wallden.
- Maciej Malinowski (Quantum scientist at Oxford Ionics) - *Quo Vadis Quantum Computing?* with the panelists C. Hempel, V. Albert, P. Jurcevic and C. Cristoiu.

List of Posters

The list bellow presents the titles as well as the abstracts of the poster that the participants will present during the poster sessions of the QCHS 2022 summer school.

Ancilla-free implementation of generalized measurements for qubits embedded in a qudit space

Laurin Fischer, *IBM Research Zürich*

Informationally complete (IC) positive operator-valued measures (POVMs) are generalized quantum measurements that offer advantages over the standard computational basis readout of qubits. For instance, IC-POVMs enable efficient extraction of operator expectation values, a crucial step in many quantum algorithms. POVM measurements are typically implemented by coupling one additional ancilla qubit to each logical qubit, thus imposing high demands on the device size and connectivity. Here, we show how to implement a general class of IC-POVMs without ancilla qubits. We exploit the higher-dimensional Hilbert space of a qudit in which qubits are often encoded. POVMs can then be realized by coupling each qubit to two of the available qudit states, followed by a projective measurement. We develop the required control pulse sequences and numerically establish their feasibility for superconducting transmon qubits through pulse-level simulations. Finally, we present an experimental demonstration of a qudit-space POVM measurement on IBM Quantum hardware. This paves the way to making POVM measurements broadly available to quantum computing applications.

Steiner-tree-based compilation for NISQ devices

Arianne van de Griend, *Univeristy of Helsinki*

Quantum computers are no longer exclusive to sci-fi stories; they now exist in the real world. In order to make efficient use of these devices, we need efficient compilation procedures. Most current compilers for quantum computers use techniques that are based on classical scheduling problems. Although these methods can compile a quantum circuit to abide by e.g. the connectivity constraints of superconducting quantum computers, they do not make optimal use of the quantum semantics of the original quantum circuit. For this poster presentation, I will give an overview of compiling methods specific to satisfying qubit connectivity constraints that are based on Steiner trees. The core idea is that unlike traditional methods for quantum compilation, that try to optimally swap qubits around on the quantum registers, we synthesize a new semantically equivalent quantum circuit that natively abide by the connectivity constraints. We do this using Steiner trees, a special type of spanning tree. And it is a promising new paradigm for compilation of quantum circuits.

Quantum circuits for the preparation of spin eigenfunctions on quantum computers

Alessandro Carbone, *THEOS, EPFL*

The preparation of accurate and efficient approximations for Hamiltonian eigenstates on quan- tum computers is a crucial step for building the quantum advantage when studying many-body quantum systems. If we can describe molecules or materials with a coarse-grained spin Hamiltonian, spin eigenfunctions can be a useful starting point for simulations which aim to understand their electronic structure. In particular the purpose of this work is to delve into the description of the quantum circuits which prepare total spin eigenfunctions in the case of spin-1/2 systems.

We investigate the balance between generality, accuracy, and computational cost in the encoding of spin eigenfunctions by quantum circuits without ancillary qubits, by pursuing two approaches: an exact recursive construction of spin eigenstates, and a heuristic variational construction of approximate spin eigenstates.

The former approach mimics the addition theorem of angular momenta. In general the circuits returned have an exponential scaling of the circuit depth with the system size. In the second approach we use the Variational Quantum Eigensolver (VQE) algorithm to minimize a suitable cost function and find the target circuits. The latter method has polynomial scaling of the circuit depth and it could lead to efficient implementations on hardware.

We have tested the described quantum circuits on the available IBM (classical) simulators and quantum devices. In particular we show the fidelity values of several 3-spin and 5-spin quantum circuits with respect to the expected spin eigenstates, by focusing on both approaches.

Bias in error-corrected quantum sensing

Ivan Rojkov, *Trapped Ion Quantum Information group, ETH Zürich*

Quantum-enhanced sensors use quantum systems and effects to sense an external signal in their environment, such as electromagnetic fields, temperature or pressure. They also, however, experience decoherence due to this same environment, which limits their sensitivity in practice. Quantum error correction (QEC) can enhance this sensitivity by suppressing decoherence [1]. We demonstrate that, in addition, error correction of a quantum sensor introduces a side-effect: in realistic settings, the finite strength of QEC biases the sensor's output [2]. If unaccounted for, this bias can systematically reduce the sensor's performance in experiment, and give misleading values for the minimum detectable signal in theory. We analyze this effect in the setting of continuous- and discrete-time QEC, showing both how one can remedy the bias through post-processing of measurement data, and how incorrect results can arise when one does not.

[1] F. Reiter, A. S. Sørensen, P. Zoller, and C. A. Muschik., Nat. Commun. 8, 1822 (2017).
[2] I. Rojkov, D. Layden, P. Cappellaro, J. Home, and F. Reiter, Phys. Rev. Lett. 128, 140503 (2022).

Boson bunching is not maximized by indistinguishable particles

Benoît Seron, *QUIC, Université Libre de Bruxelles*

Boson bunching is amongst the most remarkable features of quantum physics. A celebrated example in optics is the Hong-Ou-Mandel effect, where the bunching of two photons arises from a destructive quantum interference between the trajectories where they both either cross a beam splitter or are reflected. This effect takes its roots in the indistinguishability of identical photons. Hence, it is generally admitted – and experimentally verified – that bunching vanishes as soon as photons can be distinguished, e.g., when they occupy distinct time bins or have different polarizations. Here we disproof this alleged straightforward link between indistinguishability and bunching by exploiting a recent finding in the theory of matrix permanents. We exhibit a family of optical circuits where the bunching of photons into two modes can be significantly boosted by making them partially distinguishable via an appropriate polarization pattern. This boosting effect is already visible in a 7-photon interferometric process, making the observation of this phenomenon within reach of current photonic technology. This unexpected behavior questions our understanding of multiparticle interference in the grey zone between indistinguishable bosons and classical particles.

Towards large scale quantum computing – a many qubit ion trap at room temperature

Edgar Brucke & Philip Leindecker, *Trapped Ion Quantum Information group, ETH Zürich*

Large scale quantum computing is subject to extensive research and the ideal platform for general purpose quantum computers has yet to be found. Trapped ions as qubits excel in terms of gate fidelity and coherence times but so far systems have mostly been limited to only a small number of qubits. Our system is designed to support a linear chain of up to 50 ions which can be individually addressed, providing a versatile platform with many qubits and a high level of control. At the heart of the system is a 3-dimensional ion trap consisting of gold coated laser machined glass. The trap operates in ultra-high vacuum at room temperature. Individual addressing is implemented using a waveguide array. One application of this system is research towards large distance error correction, eventually enabling fault tolerant quantum computation. The high level of control is furthermore advantageous for the simulation of complex Hamiltonians, effectively performing quantum simulation at scale. Lastly, the segmented electrodes of the trap allow splitting of the ion chain into multiple segments for parallel quantum processing.

QuantumCumulants.jl: A Julia framework for generalized mean-field equations in open quantum systems

Christoph Hotter, *Ritsch Group, University of Innsbruck*

A full quantum mechanical treatment of open quantum systems via a Master equation is often limited by the size of the underlying Hilbert space. As an alternative, the dynamics can also be formulated in terms of systems of coupled differential equations for operators in the Heisenberg picture. This typically leads to an infinite hierarchy of equations for products of operators. A well-established approach to truncate this infinite set at the level of expectation values is to neglect quantum correlations of high order. This is systematically realized with a so-called cumulant expansion, which decomposes expectation values of operator products into products of a given lower order, leading to a closed set of equations. Here we present an open-source framework that fully automizes this approach: first, the equations of motion of operators up to a desired order are derived symbolically using predefined canonical commutation relations. Next, the resulting equations for the expectation values are expanded employing the cumulant expansion approach, where moments up to a chosen order specified by the user are included. Finally, a numerical solution can be directly obtained from the symbolic equations.

Variational certification of quantum devices

Akash Kundu, *Institute of Theoretical and Applied Informatics, Polish Academy of Sciences*

One of the requirements imposed on the realistic quantum computers is to provide computation results which can be repeated and reproduced. In the situation when one needs to repeat the quantum computation procedure several times, it is crucial that the copies of the quantum devices are similar in the sense of the produced results. In this work, we describe a simple procedure for based on variational quantum eigensolver which can be utilized to compare quantum devices. The procedure is developed by combining Choi-Jamiołkowski isomorphism with the variational hybrid quantum-classical procedure for matrix diagonalization. We compare the introduced procedure with the scheme based on the standard bounds for the similarity between quantum operations by analyzing its operation on random quantum operations. We also discuss the sensitivity of the described procedure to the noise, and we provide numerical results demonstrating its feasibility in realistic scenarios by running the procedure on IBM quantum computer.

Integrated optics for trapped-ion addressing: tailored beam emission

Gillenhaal Beck, *Trapped Ion Quantum Information group, ETH Zürich*

Chip-integrated optical systems have demonstrated significant advantages in the context of trapped-ion quantum information processing. Alongside experimental convenience, integrated beam emission intrinsically provides exceptional phase-stability, coherence times, and operation fidelity. We present new developments in out-coupler design which enable near-arbitrary beam emission from waveguides into free-space, including diffraction-limited focusing, higher-order beams, and optical vortices. In addition to being a route toward scalable trapped-ion quantum computing, this platform can enable new capabilities in the contexts of atomic clocks, optical trapping, Rydberg atoms, and more.

Quantum computing (2+1)-dimensional QED

Arianna Crippa, *Center of Quantum Technologies and Applications, DESY Zeuthen*

We describe a proposal to compute the running coupling for asymptotically free (2+1)-dimensional QED in the small and intermediate coupling regime using quantum computing techniques. To this end, we provide a Hamiltonian formulation of QED on a 2-dimensional spatial lattice. Using a variational quantum approach we compute the energy gap and the plaquette expectation value which can be related to the running coupling. We discuss different methods for an efficient encoding of the system on a quantum circuit and for the classical optimization. The overarching goal of the project is to match physical quantities such as the energy gap or the static force with Markov Chain Monte Carlo (MCMC) calculations in the regime where both approaches can be applied. This would allow to obtain a physical scale from the MCMC simulations and to follow the running of the coupling deep into the perturbative regime using quantum computations. The techniques and algorithms used here for asymptotically free QED as a prototype model can eventually also be used for future studies of QCD in (3+1)-dimensions on quantum computers.

Trapped-ion electric field gates

Louis Gallagher, *Gerritsma's group, University of Amsterdam*

With our new experimental setup we plan to implement electric field gates on an equidistant chain of +Yb171 ions in a segmented Paul trap. Based on theoretical work in our group we aim to implement a two-qubit geometric phase gate using a combination of optical tweezers and oscillating electric fields. We simulate electric field potentials of various trap geometries in order to achieve equidistance between the ions. We also design a novel architecture for implementing fast optical tweezer arrays on the ions. This presents a new platform for trapped-ion quantum computation.

Quantum information processing of trapped ions using integrated photonics

Alfredo Ricci Vasquez, *Trapped Ion Quantum Information group, ETH Zürich*

The use of surface-electrode ion traps with integrated photonics is a promising approach for manipulating the quantum states of individual or multiple ions: it reduces the complexity of the system, achieves higher coherence times by increasing the phase stability between the ion and the laser beam, and it can be used to generate light fields with non-trivial spatial structure. In our work we show the manipulation of the electronic and motional energy levels of an individual Ca+ ion, in a multizone surface-electrode trap where light at 729 nm, 854 nm and 866 nm is delivered to the ion using integrated photonics. We addressed a dipole-forbidden transition in Ca+ using two counter-propagating light beams emitted from the trap, forming a passively phase stable standing wave which interacts with the ion. By positioning the ion with resolutions well below the standing wave periodicity we show that it is possible to modulate the strength of the electronic or motional excitation as well as the AC Stark shift, a key feature for performing faster entangling gates using trapped ions. Finally, we present advances towards performing multizone operations in the trap, including the transport of ions between zones and light delivery in multiple zones.

Autoencoders for Semivisible Jets Searches

Jeremi Niedziela, *Cosa's group, ETH Zürich*

One of the largest mysteries of the modern physics is the nature of Dark Matter, which so far has not been directly detected, but which constitutes around 85% of the mass of the Universe. Our study is aimed at detection of Dark Matter by observing anomalous, so-called semi-visible jets - streams of particles composed of both regular and dark particles - in proton-proton collisions at the Large Hadron Collider. We propose autoencoders focused on the jet substructure a tool to search for anomalous jets containing Dark Matter particles.

Quantum variational learning for entanglement witnessing

Francesco Scala, *Università degli Studi di Pavia*

Several proposals have been recently introduced to implement Quantum Machine Learning (QML) algorithms for the analysis of classical data sets employing variational learning means. There is, however, a limited amount of work on the characterization and analysis of quantum data by means of these techniques. This work focuses on one such ambitious goal, namely the potential implementation of quantum algorithms allowing to properly classify quantum states defined over a single register of n qubits, based on their degree of entanglement. This is a notoriously hard task to be performed on classical hardware, due to the exponential scaling of the corresponding Hilbert space as 2^n. We exploit the notion of "entanglement witness", i.e., an operator whose expectation values allow to identify certain specific states as entangled. More in detail, we made use of Quantum Neural Networks (QNNs) in order to successfully learn how to reproduce the action of an entanglement witness. This work may pave the way for combining QML algorithms and quantum information protocols and to outperform classical approaches for analysing quantum data. All these topics are discussed and then properly demonstrated through a simulation of the relative quantum circuit model.

Dynamical Decoupling Error Mitigation on Quantum Algorithms

Siyuan Niu, *LIRMM, University of Montpellier, CNRS*

Today's quantum computers are in the Noisy Intermediate-Scale Quantum era and prone to errors. Since there are not enough resources to realize quantum error correction, an alternative technique named quantum error mitigation was proposed. Dynamical decoupling is one of the simplest methods for suppressing decoherence error without any additional circuit overhead. Different DD sequences have been introduced, including non-universal, universal, and robust ones with distinct impacts. In our work, we implement all the popular DD strategies to date and evaluate their performances on different IBM quantum machines for various well-known quantum algorithms. Based on our experimental results, we provide guidelines and insights for the community to better utilize DD error mitigation method to achieve high circuit fidelity.

An efficient quantum algorithm for the time evolution of parameterized circuits

Stefano Barrison, *Computational Quantum Science Lab, EPFL*

I will present a novel hybrid algorithm to simulate the real-time evolution of quantum systems using parameterized quantum circuits. The method, named "projected - Variational Quantum Dynamics" (p-VQD) realizes an iterative, global projection of the exact time evolution onto the parameterized manifold. In the small time step limit, this is equivalent to the McLachlan's variational principle. This approach is efficient in the sense that it exhibits an optimal linear scaling with the total number of variational parameters. Furthermore, it is global in the sense that it uses the variational principle to optimize all parameters at once. The global nature of the approach then significantly extends the scope of existing efficient variational methods, that instead typically rely on the iterative optimisation of a restricted subset of variational parameters. Through numerical experiments, we also show that this approach is particularly advantageous over existing global optimisation algorithms based on the time-dependent variational principle that, due to a demanding quadratic scaling with parameter numbers, are unsuitable for large parameterized quantum circuits.

Nuclear Excitation by Muon Capture

Simone Gargiulo, *Laboratory for Ultrafast Microscopy and Electron Scattering, EPFL*

Efficient excitation of nuclei via exchange of a real or virtual photon has a fundamental importance for nuclear science and technology development. Here, we present a new mechanism of nuclear excitation based on the capture of a free muon into the atomic orbits (NEμC). The cross section of such a new process is evaluated using the Feshbach projection operator formalism and compared to other known excitation phenomena, i.e. photo-excitation and nuclear excitation by electron capture (NEEC), showing up to ten orders of magnitude increase in cross section.

Solving Rubik's Cube via Quantum Mechanics and Deep Reinforcement Learning

Sebastiano Corli, *CNR, Politecnico di Milano*

Rubik's Cube is one of the most famous combinatorial puzzles, involving more than $10^1$9 possible configurations. We develop a unitary representation of the Rubik's group and a quantum formalism to describe the Cube from its geometrical constraints. We build Hamiltonian operators, whose ground state matches the solved configuration of the Cube. To reach such ground state which represents the solution of the game, we exploit a Deep Reinforcement Learning algorithm to minimize the Hamiltonian, which is exploited as the reward function itself. Via the implementation of a physical reward, we managed to solve the Cube over 94% of the time.

Generation and Measurement of Entangled Phonon States in a Bulk Acoustic Resonator

Michael Alexander Eichenberger, *Hybrid Quantum Systems, ETH Zürich*

Hybrid quantum systems consisting of a superconducting qubit and a high-overtone bulk acoustic resonator are a promising platform for quantum information processing. Due to the spectral properties of the acoustic resonator, a single superconducting qubit can couple to a multitude of phonon modes. By encoding qubits in these modes, a compact and controllable multi-qubit system is achieved. As a proof of principle of quantum information encoding and control, we want to generate and tomographically measure maximally entangled states between multiple phonon modes. This poster presents the experimental platform and elaborates on the techniques used to generate and measure multi-phonon entangled states. Additionally, current simulations for entangled states between 2, 3 and 4 phonon modes and an experimentally measured 2-phonon bell state are discussed.

Robust Camera Pose Estimation: Classical and Quantum

Mikhail Terekhov, *Computer Vision and Geometry Group, ETH Zürich*

Recovering relative and absolute poses of cameras from photos and videos is a fundamental problem in the field of Geometric Computer Vision. It has been extensively studied for a long time in the classical setup, bringing to life amazing applications, like dense reconstruction of 3D scenes from unordered sets of images from the internet [1]. I will present some classical and quantum ways to tackle camera pose estimation. The de-facto standard classical algorithm is based on the Random Sample Consensus framework (RANSAC) [2] for robust fitting. Along with recent advances in quantum computing, the quantum RANSAC [3] has been first proposed. Since then, alternative methods to robust fitting were also developed [4,5]. All these approaches will be presented together with my recent work on classical multi-camera relative pose estimation, also based on RANSAC. It was recently submitted to the European Conference on Computer Vision. Potential approaches to making it quantum will also be discussed.

[1] Schonberger J. L., Frahm J. M., Structure-from-motion revisited, Proceedings of the IEEE conference on computer vision and pattern recognition. – 2016. – C. 4104-4113.
[2] Fischler M. A., Bolles R. C., Random sample consensus: a paradigm for model fitting with applications to image analysis and automated cartography, Communications of the ACM. – 1981. – T. 24. – №. 6. – C. 381-395.
[3] Caraiman S., Manta V. I., New applications of quantum algorithms to computer graphics: the quantum random sample consensus algorithm, Proceedings of the 6th ACM conference on Computing frontiers. – 2009. – C. 81-88.
[4] Chin T. J. et al., Quantum robust fitting, Proceedings of the Asian Conference on Computer Vision. – 2020.
[5] Doan A. D. et al., A Hybrid Quantum-Classical Algorithm for Robust Fitting, arXiv preprint arXiv:2201.10110. – 2022.

Error propagation in NISQ devices for solving classical optimization problems

Guillermo Gonzalez Garcia, *Theory Division, Max Planck Institute of Quantum Optics*

We propose a random circuit model to analyze the impact of noise on the performance of variational quantum circuits for classical optimization problems. Our model accounts for the propagation of arbitrary single qubit errors through the circuit. We find that even with a small noise rate, the quality of the obtained classical optima is low on average. As a consequence, a single-qubit error rate of the order of $1/(nD)$ is needed for the possibility of a quantum advantage, where n is the number of qubits and D is the circuit depth. We estimate that this translates to an error rate lower than 10^{-6} using QAOA for classical optimization problems with 2D circuits.

Translating RISC-V to Quantum Computers

Stefanie Muroya Lei, *Henzinger's group, IST Austria*

Unicorn is an open-source toolchain for running any classical algorithm written in a Turing-complete subset of C on quantum annealers (QAs), effectively turning them into easy-to-program, potential accelerators. Moreover, unicorn shows a construction that allows studying, with a different perspective, relationships between classical and quantum complexity classes. For instance, it has allowed to establish a relation between classical execution time and quantum space. Our toolchain uses the RISC-V machine code of source codes to build a finite state machine(FSM). Then it translates the FSM to a combinational circuit of n state transitions over the FSM and builds Quadratic Unconstrained Binary Optimization (QUBO) models representing such circuits. The purpose of the models is to determine the input(s) that make a machine state of the FSM reachable in n or fewer state transitions. After applying diverse optimization techniques, we successfully executed 32-bit and 64-bit code, written in a subset of C that uses dynamic memory allocations, on a quantum annealer using less than 1500 qubits in each case. The quantum annealer correctly determined the inputs leading to a "bad memory-access" machine state. However, machine states can be anything (e.g. a solution to an NP problem). Eventually, unicorn will cover all RISC-V and output hamiltonians and oracles for gate-model quantum computers.

Pulse-efficient circuit transpilation for quantum applications on cross-resonance-based hardware

Caroline Tornow, *ETH Zürich*

We show a pulse-efficient circuit transpilation framework for noisy quantum hardware. This is achieved by scaling cross-resonance pulses and exposing each pulse as a gate to remove redundant single-qubit operations with the transpiler. Crucially, no additional calibration is needed to yield better results than a CNOT-based transpilation. This pulse-efficient circuit transpilation therefore enables a better usage of the finite coherence time without requiring knowledge of pulse-level details from the user. As demonstration, we realize a continuous family of cross-resonance-based gates for SU(4) by leveraging Cartan's decomposition. We measure the benefits of a pulse-efficient circuit transpilation with process tomography and observe up to a 50% error reduction in the fidelity of RZZ(θ) and arbitrary SU(4) gates on IBM Quantum devices. We apply this framework for quantum applications by running circuits of the quantum approximate optimization algorithm applied to MAXCUT. For an 11-qubit nonhardware native graph, our methodology reduces the overall schedule duration by up to 52% and errors by up to 38%.

A Bayesian Perspective on Variational Quantum Algorithms

Sam Duffield, *Quantinuum*

Variational quantum algorithms represent a collection of hybrid quantum-classical techniques whereby a parameterised quantum circuit is trained using a classical optimiser in order to minimise some cost function. In this work, we adopt a probabilistic point of view and consider the task of approximating a Bayesian posterior distribution over the circuit parameters. This perspective opens numerous avenues for research, calling upon the vast toolbox of techniques from classical Bayesian statistics.

Fault-tolerant quantum error detection with a Kerr-cat qubit

Francesco Adinolfi, *Quantum Photon Science, Paul Scherrer Institute*

In order to explore the potential benefits of quantum computing, we first need to be able to encode quantum information in. a robust manner. The goal of quantum error correction is to achieve this by encoding quantum information redundantly in the form of a logical qubit. In an error correction cycle, the logical qubit interacts with an auxiliary qubit (ancilla) such that an error syndrome is mapped onto the latter which can then be measured. During this process, it is crucial to avoid the propagation of non-correctable errors from the ancilla to the logical qubit. A promising avenue to tackle this challenge is to use strongly noise-biased qubits as ancillas. In this project we investigate the use of Kerr-cat qubits for this task. I will present the main experimental results for this novel qubit and discuss the benefits of using it as an ancilla qubit for quantum error correction.

Machine learning methods for superconducting quantum simulator readout

Andras Di Giovanni, *Ustinov's group, Karlsruhe Institute of Technology*

Quantum simulators promise insights into quantum many-body problems in regimes where classical simulation methods hit a complexity wall. One challenge towards this goal is to develop well characterized building blocks that allow to scale up system sizes while conserving reliability in terms of errors. A promising platform for building such NISQ (noisy, intermediate-scale quantum) devices are superconducting quantum circuits. Our goal is to characterize small scale quantum processors with at minimal experimental and post-processing cost. For this we implement schemes for machine learning assisted adaptive Bayesian tomography and apply them to experimental data obtained from a prototype few-qubit superconducting chip.

Wigner state and process tomography on near-term quantum devices

Amit Devra, *Technical University of Munich*

With the growing interest and rapid development in near-term quantum devices, the migration of theoretical and experimental approaches from existing devices to near-term quantum devices is imperative. We present an experimental scanning-based tomography approach in the context of finite-dimensional Wigner representations. These representations characterize and visualize operators using shapes assembled from linear combinations of spherical harmonics. The shapes can be recovered experimentally by measuring the expectation values of rotated axial tensor operators. Here, we reformulate the theory of Wigner state and process tomography for the case of a general-purpose pure state quantum computer. We, therefore, present the experimental approach for implementing the scanning-based tomography technique on the IBM quantum experience and showcase the results. We also show the methodology for estimating the density and process matrices from the experimentally created droplet functions.

Algorithmic phases in variational quantum ground-state preparation

Nikita Astrakhantsev, *Neupert's group, Universität Zürich*

The fidelity of a variational quantum circuit state prepared within stochastic gradient descent depends on, in addition to the circuit architecture, the number N_s of measurements performed to estimate the gradient components. Simulating the variational quantum eigensolver (VQE) approach applied to two-dimensional frustrated quantum magnets, we observe that this dependence has systematic features. First, the algorithm manifests pronouncedly separated regimes on the N_s axis with state fidelity $\mathcal{F}$ vanishing at $N_s < N_s^c$ and rapidly growing at $N_s > N_s^c$. The point of transition N_s^c is marked by a peak of energy variance, resembling the behaviour of specific heat in second-order phase transitions. The extrapolation of the system-dependent threshold value N_s^c to the thermodynamic limit suggests the possibility of obtaining sizable state fidelities with an affordable shots budget, even for large-scale spin clusters. Second, above N_s^c, the state infidelity $\mathcal{I} = 1 - \mathcal{F}$ satisfies $\mathcal{I} - \mathcal{I}_0 \propto 1/(\Delta^2 N_s)$, with $\mathcal{I}_0$ representing the circuit's inability to express the exact state, $\mathcal{F}$ is the achieved state fidelity, and Δ represents the system energy gap. This $1/\Delta^2$ empirical law implies optimization resources increase inversely proportional to the squared gap of the system. We provide a symmetry-enhanced simulation protocol, which, in case of a closing gap, can significantly reduce the frustrated magnets simulation costs in quantum computers.

Belief Propagation Decoder for Quantum LDPC Codes

Josias Old, *Theoretical Quantum Technology Group, Forschungszentrum Jülich and RWTH Aachen University*

Quantum computing devices suffer from operational errors and decoherence. Methods to keep errors in check and advance towards fault-tolerant quantum computing involve quantum error correcting codes. A class of codes which recently received a lot of attention because of their good performance are Quantum Low-Density Parity-Check codes (QLDPC codes). We show basics of QLDPC codes and their decoding with a classical algorithm for statistical inference, the belief propagation (BP) algorithm. With numerical simulations we present success and limitations of this decoding scheme. We then introduce a new, generalized decoder building on region-based free energy approximations. This new decoder has a higher flexibility and improved error rate than present BP decoders. In particular, apart from the original implementation of BP it shows the emergence of a threshold under bit-flip and depolarizing noise for the surface code.

Spin relaxation (T1) time in bilayer graphene quantum dots

Jonas Gerber, *The Ensslin Nanophysics Group, ETH Zürich*

A promising qubit type for quantum computing are graphene-based spin qubits due to the expectation of long coherence times. One characteristic figure of metric is the spin relaxation time T1. We measured the T1 time via time-resolved electronic transport in electrostatically defined bilayer graphene quantum dots. Our sample structure allows the quantum dot to be probed by a nearby detector, which enables us to detect electrons tunneling in and out of the quantum dot. Using a three-level pulse, T1 is accessed by the Elzerman readout technique. We measured relaxation times of up to 50 ms, which is far higher than the lower limits reported in state-of-the-art literature [Banszerus et al. arXiv 2210.13051 (2021)]. A strong dependence between the relaxation time and the magnetic field B is extracted. This dependence enables us to envision relaxation times far higher than the measured 50 ms. These results are consequently a major milestone in realizing spin qubits for graphene-based quantum computing.

Quantifying Causal Influence in Quantum Mechanics

Llorenç Escolà Farràs, *University of Amsterdam and Qusoft*

We extend Pearl's definition of causal influence to the quantum domain, where two quantum systems A, B with finite-dimensional Hilbert space are embedded in a common environment C and propagated with a joint unitary U. For finite dimensional Hilbert space of C, we find the necessary and sufficient condition on U for a causal influence of A on B and vice versa. We introduce an easily computable measure of the causal influence and use it to study the causal influence of different quantum gates, its mutuality, and quantum superpositions of different causal orders. For two two-level atoms dipole-interacting with a thermal bath of electromagnetic waves, the space-time dependence of causal influence almost perfectly reproduces the one of reservoir-induced entanglement.

Parameter estimation for creating Schrödinger cat states in an electromechanical system

Alessandro Bruno, *Quantum Technologies group, Paul Scherrer Institute and Bruder's Theory Group, Basel University*

Schrödinger cat states are defined as macroscopic superpositions of distinct states and have not yet demonstrated in an acoustic resonator. We investigate the process of creating such states in a mechanical oscillator. The device employed consists of a superconducting qubit coupled to a High-overtone Bulk Acoustic wave Resonator (HBAR). We present three different protocols for generating a cat state, each with their positives and negatives. We simulate the device and the control operations through a simulator framework based on QuTiP and analyze each necessary step of the cat state protocols. Control parameters for the experimental realization of the simulated results are extracted and used for the creation of an approximate cat state up to an average phonon number of n=3. We simulate the state coherence to characterize the macroscopic nature of these massive quantum states.

Hybrid Kernel Polynomial Method

Alessandro Summer, *QuSys, Trinity College Dublin*

The evaluation of spectral quantities and correlation functions of large entangled systems is a core problem in computational physics today. As technology progresses, classical computers struggle to keep pace with the growing size of the quantum systems to be described. Quantum computers appear to be the solution to keep advancing in the field of quantum simulations. However, currently available machines are still prone to errors and noise when dealing with long, dense, wide, and ultra-connected algorithms. So far, what appears to be the primary benefit of using them is the creation of random (pseudo-) circuits (as in Google's recent Sycamore processor experiment).
Decades of scientific research on quantum simulation techniques have resulted in sophisticated classical algorithms. A well-known example is the kernel polynomial method (KPM) [1], which is used to obtain the density of states (DOS), local-DOS and correlation functions through their Chebyshev expansion. The bottleneck of the algorithm resides in the computation of the Chebyshev moments, namely Tr[Hn A] for different n, where A is an observable and H the Hamiltonian of the system. Our goal is to use quantum computers to solve this last step. We are building a hybrid algorithm that uses a set

of random states to perform a stochastic evaluation of trace to calculate the moments of the expansion. The powers of the Hamiltonian are implemented as derivatives of the time-evolution operator, in the manner of Ref.[2]. The trace is evaluated using a DQC1-like circuit, with a random state in place of the identity state, which cannot be directly built on a digital quantum computer. We are currently applying Richter's technique to create a random state [3], which we checked to be extremely performing in the simulation of Haar distribution and with the Trotterisation in high-dimensional Hilbert spaces. We are using the XXZ model as testing Hamiltonian, but the algorithm can be generalized to a broader class of systems.

[1] A. Weiße, G. Wellein, et al., Rev. Mod. Phys. 78, 275 (2006)
[2] K. Seki, S. Yunoki, PRX Quantum 2, 010333 (2021)
[3] J. Richter, A. Pal, PRL 126, 230501 (2021)

Dispersive read-out of holes in industrially-fabricated silicon quantum dots

Frederic Schlattner, *John Morton's group and Quantum Motion Technologies, University College London*

Electrons trapped in gate-defined quantum dots in silicon are commonly regarded as a promising approach to build a scalable quantum computer. Less attention has been devoted towards holes, the charge carriers in the valence band. They exhibit interesting properties for qubit manipulation like the ability for fast electrical control (EDSR) using the same metallic gate which defines the quantum dot itself. One can further simplify the on-chip architecture by removing electrometers in the vicinity of the quantum dots and instead use gate-based radio-frequency reflectometry techniques for qubit read-out. This could ultimately lead to a compact design allowing a dense qubit layout.

Quantum error correction using squeezed Schrödinger cat states

David Schlegel, *Laboratory of Theoretical Physics of Nanosystems, EPFL*

Bosonic quantum codes redundantly encode quantum information in the states of a quantum harmonic oscillator, making it possible to detect and correct errors. Schrödinger cat codes – based on the superposition of two coherent states with opposite displacements – can correct phase-flip errors induced by dephasing, but they are vulnerable to bit-flip errors induced by photon loss. Here, we develop a bosonic quantum code relying on squeezed cat states, i.e. cat states made of a linear superposition of displaced-squeezed states. Squeezed cat states allow to partially correct errors caused by photon loss, while at the same time improving the protection against dephasing. We present a comprehensive analysis of the squeezed cat code, including protocols for code generation and elementary quantum gates. We characterize the effect of both photon loss and dephasing and develop an optimal recovery protocol that is suitable to be implemented on currently available quantum hardware. We show that with moderate squeezing, and using typical parameters of state-of-the-art quantum hardware platforms, the squeezed cat code has a resilience to photon-loss errors that significantly outperforms that of the conventional cat code.

Wigner inequalities in the systems of neutral pseudoscalar mesons

Anna Efimova, *Trapped Ion Quantum Information group, ETH Zürich*

Quantum correlations is one of the very useful benefit of quantum technologies. The usual way to describe the difference between quantum and classical correlations are Bell inequalities. In this work I will present Wigner inequalities which are based on the same assumptions as Bell inequalities but more convenient in calculations. I am going to use this inequalities to show their violations in particle physics, especially in systems on neutral pseudoscalar mesons. However, there are some difficulties in experimental part if one wants to prove such violations. I will discuss this hazards and improve inequalities formalism to make such experiments possible!

Cooperative subwavelength molecular quantum emitter arrays

Raphael Holzinger, *Ritsch Group, University of Innsbruck*

Dipole-coupled subwavelength quantum emitter arrays respond cooperatively to external light fields as they may host collective delocalized excitations (a form of excitons) with super- or subradiant character. Deeply subwavelength separations typically occur in molecular ensembles, where in addition to photon-electron interactions, electron-vibron couplings and vibrational relaxation processes play an important role. We provide analytical and numerical results on the modification of super- and subradiance in molecular rings of dipoles including excitations of the vibrational degrees of freedom. While vibrations are typically considered detrimental to coherent dynamics, we show that molecular dimers or rings can be operated as platforms for the preparation of long-lived dark superposition states aided by vibrational relaxation.

Characterization of QAOA in 1D linear lattices

Gabriel Matos, *Theoretical Physics Group, University of Leeds*

Recently, variational quantum algorithms have received much attention as a potential candidate for displaying quantum advantage in the near future. Given a variational family of circuits, however, it is not clear which states it is able to prepare at specific circuit depths, or how feasible such a family is to optimise classically, as a general theory determining such aspects is still absent. In this paper, we numerically show that the original QAOA protocol on a 1D lattice can be made into an exact parameterization of a submanifold of efficiently simulable states respecting the protocol's symmetries. We proceed to study how hard the associated variational families are to optimise and the effects that overparameterization, locality, and symmetries have in the associated landscape. We leverage this efficient classical simulation in order to reach system sizes beyond finite size effects.

Isotope-engineered Group IV Epitaxy for Qubits

Yujia Liu, *Spin qubit quantum computer group, Leibniz-Institut für Kristallzüchtung*

Starting from middle of last century, Ge served as the material for first semiconducting transistor and Si took over the race as the foundation materials for integrated circuit chips. Nowadays, when the information technology goes to the advanced generation by using quantum computing and quantum communication, hardwares that can be applied with quantum technologies are under exploration. Fortunately, group IV semiconductors, such as silicon, germanium can be applied also in the new generation circuits. In this work, we will present the concepts of how to build quantum hardwares on group IV material as well as our results about the successful epitaxial heterostructures for quantum information.

Classification of Earth Observation Images using Quantum Convolutional Neural Networks

Su Yeon Chang, *LTPN, EPFL and CERN*

Earth Observation (EO) has experienced promising progress in the modern era via an impressive amount of research on establishing a state-of-the-art Machine Learning (ML) technique to learn a large dataset of un- or partially labelled samples. Meanwhile, the scientific community has also extended the boundary of ML to the quantum system and exploited a new research area, so-called Quantum Machine Learning (QML), in an effort of integrating advantages from both ML and Quantum Computing (QC). More recently, several papers investigated the application of QML in EO domain, in particular, based on Variational Quantum Circuits (VQCs). But more contributions are still required in depth and various challenges should be tackled, such as large EO image size for the current quantum simulators, trainability of the quantum circuit, etc.

In this work, we explore the application of a quantum multiclass classifier on realistic EO use-cases, using features of a manageable size, extracted from the original images. More specifically, the classifier consists of a quantum analogue of classical Convolutional Neural Networks (CNNs), or so-called Quantum CNNs (QCNNs) which have a form of a hierarchical VQC. We also introduce a hybrid classical-quantum multi-task neural network that performs the reconstruction and classification of images at the same time. The results prove that this multi-task hybrid model achieves the classification successfully with high accuracy, even comparable to that of the classical classifier, while using fewer parameters.

Random Number Characterization via Quantum Inspired Machine Learning

Samuele Piccinelli, *Università di Padova and Forschungszentrum Jülich*

The generation of good random numbers impacts research and applications beyond pure academic interests, in countless fields such as cryptography and simulations. For most of them, it is of utmost importance to understand if a set of numbers is truly random or it contains some residual correlations. In this work, we introduce an innovative approach that exploits Tensor Networks (TNs), powerful data structures that spring from quantum many-body physics and are now increasingly applied to machine learning applications. We first review these architectures and properties, investigating their power to study strings of random numbers. Results show that TNs allow to detect long-range correlations ($\mathcal{O}(2^21)$) in pseudo-random sequences, whereas a fully-connected neural network architecture fails the same task. While providing strong interpretability of the results, TNs do not succeed in discriminating quantum randomness from state of the art pseudo-random sequences, thus proving to be a possible method of certifying the quality of the latter.

Digital quantum simulation of the Schrödinger equation with adaptive piecewise approximations of potential function

Tenzan Araki, *ETH Zürich*

An efficient approach to perform digital quantum simulation of the Schrödinger equation converts the kinetic term into a quadratic polynomial by utilizing the quantum Fourier transform (QFT). While the QFT and quadratic polynomials can be efficiently computed, the implementation of the potential term remains problem-dependent. In this work, we demonstrate an efficient implementation of diagonal unitaries generated by piecewise polynomial functions, which does not involve any ancilla qubits, has an asymptotic total gate count that is comparable to a polynomial of the same degree, and which consists only of rotation-Z and CNOT gates. The method can be applied to perform Hamiltonian simulation under adaptive piecewise approximations for an arbitrary potential function, and we demonstrate the method with several examples.

List of Participants

The table bellow presents the exhaustive list of all the participants of the Quantum Computing Hard- and Software 2022 summer school and their affiliations.

1	Héloïse Albot	*Group of Ulrich Schollwöck, Ludwig-Maximilians-Universität München*
2	Laurin Fischer	*IBM Research Zürich*
3	Arianne van de Griend	*Univeristy of Helsinki*
4	Frederike Brockmeyer	*Trapped Ion Quantum Information group, ETH Zürich*
5	Alessandro Carbone	*THEOS, EPFL*
6	Ivan Rojkov	*Trapped Ion Quantum Information group, ETH Zürich*
7	Anqi Gong	*ETH Zürich*
8	Benoît Seron	*QUIC, Université Libre de Bruxelles*
9	Christoph Hotter	*Ritsch Group, University of Innsbruck*
10	Akash Kundu	*Institute of Theoretical and Applied Informatics, Polish Academy of Sciences*
11	Gillenhaal Beck	*Trapped Ion Quantum Information group, ETH Zürich*
12	Arianna Crippa	*Center of Quantum Technologies and Applications, DESY Zeuthen*
13	Louis Gallagher	*Gerritsma's group, University of Amsterdam*
14	Alfredo Ricci Vasquez	*Trapped Ion Quantum Information group, ETH Zürich*
15	Jeremi Niedziela	*Cosa's group, ETH Zürich*
16	Francesco Scala	*Università degli Studi di Pavia*
17	Kaizhao Wang	*Trapped Ion Quantum Information group, ETH Zürich*
18	Siyuan Niu	*LIRMM, University of Montpellier, CNRS*
19	Elena Acinapura	*ETH Zürich*
20	Stefano Barrison	*Computational Quantum Science Lab, EPFL*
21	Simone Gargiulo	*Laboratory for Ultrafast Microscopy and Electron Scattering, EPFL*
22	Sebastiano Corli	*CNR, Politecnico di Milano*
23	Tereza Viskova	*AQUA, EPFL*
24	Paulin de Schoulepnikoff	*Computational Quantum Science Lab, EPFL*

25	Michael Alexander Eichenberger	*Hybrid Quantum Systems, ETH Zürich*
26	Mikhail Terekhov	*Computer Vision and Geometry Group, ETH Zürich*
27	Davide Materia	*University of l'Aquila*
28	Edgar Brucke	*Trapped Ion Quantum Information group, ETH Zürich*
29	Guillermo Gonzalez Garcia	*Theory Division, Max Planck Institute of Quantum Optics*
30	Philip Leindecker	*Trapped Ion Quantum Information group, ETH Zürich*
31	Marc Vandelle	*EPFL*
32	Marchand Charles Edouard	*Chair of condensed matter theory, EPFL*
33	Stefanie Muroya Lei	*Henzinger's group, IST Austria*
34	Caroline Tornow	*ETH Zürich*
35	Sam Duffield	*Quantinuum*
36	Tianyang Shen	*Quantum Photon Science Group, Paul Scherrer Institut and Quantum Technologies Group, ETH Zürich*
37	Francesco Adinolfi	*Quantum Photon Science, Paul Scherrer Institute*
38	Andras Di Giovanni	*Ustinov's group, Karlsruhe Institute of Technology*
39	Sacha Lerch	*LTPN, EPFL and CERN*
40	Luca Hofele	*Quantum Device Lab, ETH Zürich*
41	Moritz Fontboté Schmidt	*Trapped Ion Quantum Information group, ETH Zürich*
42	Amit Devra	*Technical University of Munich*
43	Nikita Astrakhantsev	*Neupert's group, Universität Zürich*
44	Josias Old	*Theoretical Quantum Technology Group, Forschungszentrum Jülich and RWTH Aachen University*
45	Jonas Gerber	*The Ensslin Nanophysics Group, ETH Zürich*
46	Llorenç Escolà Farràs	*University of Amsterdam and Qusoft*
47	Alessandro Bruno	*Quantum Technologies group, Paul Scherrer Institute and Bruder's Theory Group, Basel University*
48	Nikunj Sangwan	*EPFL*
49	Alessandro Summer	*QuSys, Trinity College Dublin*
50	Julian Moser	*Ritsch Group, University of Innsbruck*
51	Frederic Schlattner	*John Morton's group and Quantum Motion Technologies, University College London*
52	David Schlegel	*Laboratory of Theoretical Physics of Nanosystems, EPFL*
53	Anna Efimova	*Trapped Ion Quantum Information group, ETH Zürich*

54	Raphael Holzinger	*Ritsch Group, University of Innsbruck*
55	Gabriel Matos	*Theoretical Physics Group, University of Leeds*
56	Yujia Liu	*Spin qubit quantum computer group, Leibniz-Institut für Kristallzüchtung*
57	Su Yeon Chang	*LTPN, EPFL and CERN*
58	Samuele Piccinelli	*Università di Padova and Forschungszentrum Jülich*
59	Tenzan Araki	*ETH Zürich*

Examination Information

Method of examination

As mentioned on the website, participants can earn some ECTS credits for participating the QCHS summer school. The method of examination will be a scientific report to hand-in to the organizers. The following details hold

1. The deadline of the report is fixed at 1 month after the end of the school;
2. The report must be 2-4 A4 pages long.
3. It is done individually.
4. The outcome is "pass" or "fail".
5. It will be evaluated by the organizers and graded by one of the three professors endorsing the school (cf. last page of the leaflet).

Two options are available for the topic of the report:

Option A

> During the hands-on sessions, the students will be taught to a specific programming language (TBA) to simulate quantum systems and to implement quantum algorithms studied earlier in the day. At the end of each hands-on session, the speaker will present a problem on the same topic of the session. Students can choose one of the problems thus assigned and write a report in which they present the solution and discuss it.
>
> Particularly, they are asked to:
>
> - introduce the problem they chose;
> - draw the corresponding quantum circuit or explain the underlying mechanism of the simulation;
> - comment the assumptions and the results, particularly in comparison to the corresponding classic algorithm.
>
> The exam is regarded as "passed" if it will be complete in all the three points listed above and if there will not be errors denoting a serious lack of understanding.

Option B

In alternative to this, students can choose to write a report where they summarize the main qubit technologies studied in the school (superconducting qubits, trapped ions, spin qubits, neutral atoms, photonic qubits), presenting their working principles and underlying their advantages/disadvantages. Another choice is to write a summary about one of the software oriented technologies (quantum noise characterization, quantum error correction, quantum machine learning, ...) where the participants would present its concept, explain the existing models and highlight their advantages/disadvantages.

For EPFL students

Both Master's and PhD students from EPFL will receive 2 ECTS credit points upon successful completion of the examination requirements. In order to receive these points the participants must communicate their SCIPER number when registering to the summer school. After acceptance, the summer school will appear as a course on their IS Academia portal.

For ETH Zürich students

From ETH Zürich, unfortunately **only** PhD students can obtain credit points for participating in the summer school. To do so they can enrol to the corresponding course in their myStudies portal. They have to specify their supervisor as "lecturer" who with a course confirmation will be able grant the credit points. For any specific question please contact your doctoral studies administration.

For students outside EPFL and ETH Zürich

For students from other universities, please contact your study administration to find out if and how you can earn credits. After receiving clear requirements from them, contact the organizing committee of the QCHS summer school. They will do all their best to satisfy these requirements.

Venue Information

QCHS 2022 will be taking place on EPFL's campus. Bellow you will find practical information on how to get there, details about accommodation as well as organizational aspects during the school.

Coming to EPFL

Source: Coming to EPFL, `https://www.epfl.ch/campus/visitors/coming-to-epfl/`

The EPFL campus is served by metro line M1 (from the Renens and Lausanne-Flon metro stations) and by bus (from Morges).

From Lausanne station

Take the metro m2 towards Croisettes and get off at Lausanne-Flon.
Then take the Metro m1 towards Renens-CFF and get off at EPFL.
Approximate travel time: 30 min. from Lausanne station.

From Renens station

Take the metro m1 direction Lausanne-Flon and get off at EPFL.
Approximate travel time: about 10-15 min.

From Morges

Take the MBC line 701 towards Lausanne Bourdonnette.
Get off at St-Sulpice Paqueret or St-Sulpice Science Park.
Approximate travel time: about 20 min.

Timetables

- Swiss national railway company: CFF
- Lausanne public transport company: tl
- Morges public transport company: MBC

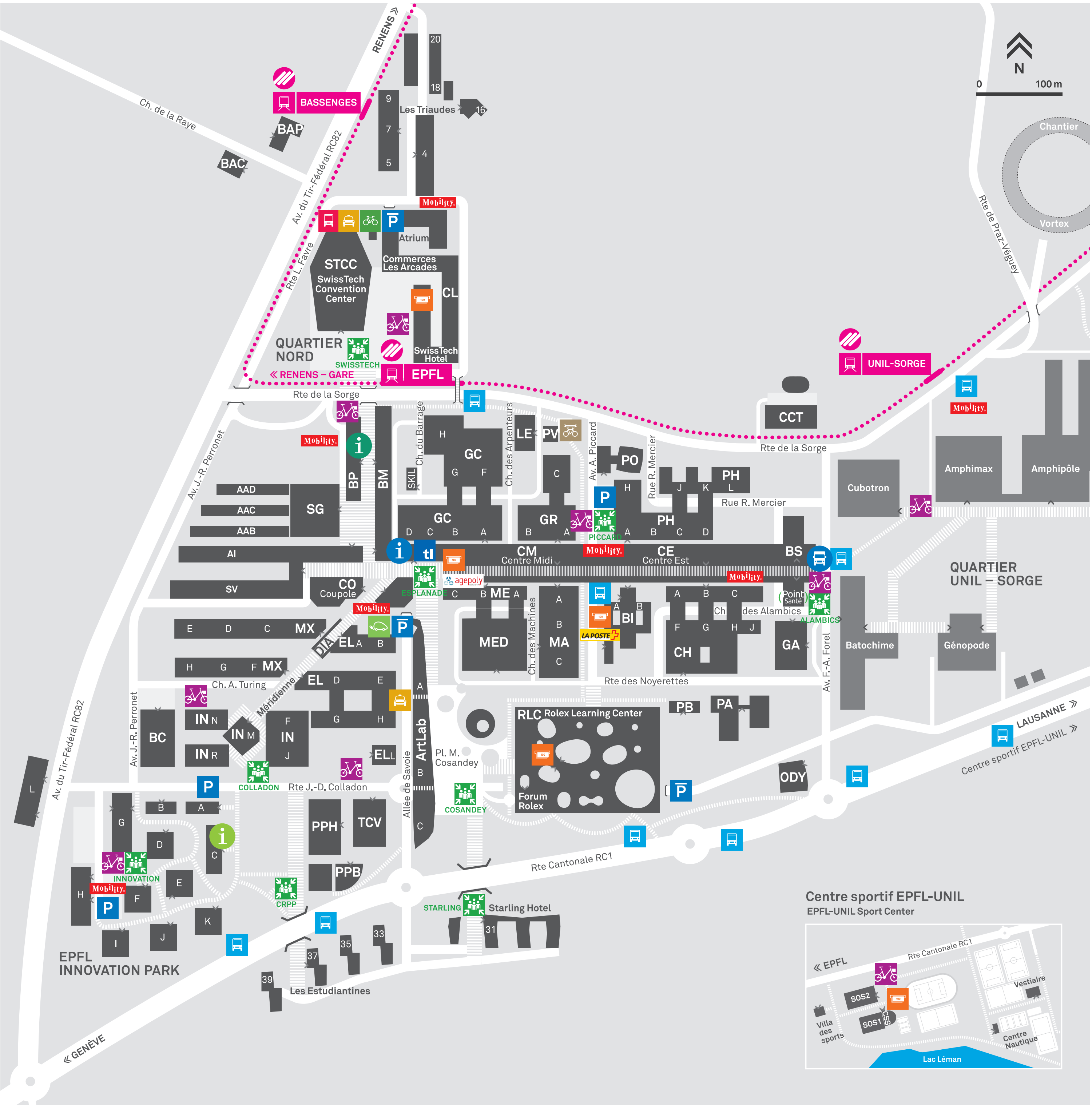
Campus map

A map of the campus is presented on the next page. It indicates the metro station, the hotel as well as the lecture halls location which will be important throughout the summer school.

EPFL

Plan d’orientation

25.04.2019



- **Accueil/Information**
  Reception/Information
- **Guichet étudiants**
  Students Services Desk
- **Accueil EPFL Innovation Park**
  EPFL Innovation Park Reception
- **Information livraisons**
  Delivery Information
- **Point de rassemblement**
  Assembly point
- (Point Santé) **Point Santé**
  Health Point
- agepoly **Association des étudiants de l’EPFL**
  EPFL General Student’s Association
- tl **Point de vente tl**
  Point of sale tl
- LA POSTE **La Poste**
  Post Office
- **Bancomat**
  ATM
- P **Parking public**
  Public Parking
- **Métro m1**
  m1 metro
- **Bus**
  Bus
- **Station de taxi**
  Taxi rank
- **Dépose-minute bus**
  Bus drop-off/pick-up point
- **Vélostation**
  BikePark
- **PubliBike**
  PubliBike
- **Point Vélo réparations**
  Bike Center
- Mobility **Mobility**
  Mobility
- **Borne de recharge**
  Charging station

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emergencies
115
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App EPFL Campus
pocketcampus.org/epfl
m.epfl.ch

Accommodation

The non-EPFL participants will be staying at the SwissTech Hotel. Every room will be furnished with twin beds and will thus accommodate two people. For practical reasons, QCHS organizers will ensure that there are only single gender rooms. If you have any particular demand (e.g. desire to share the room with a specific participant) do not hesitate to contact the organizers which will find a way to satisfy this demand.

The hotel cost **is included** in the registration fee.

Breakfasts, coffee breaks and lunch times

Breakfasts are not included in the accommodation cost. However, it will be served to all the participants before the start of the first lecture of the day (∼ 8:30) at the entrance of the lecture hall. Furthermore, throughout the summer school, the participants will have the opportunity to discuss the presented topics with their peers and the lectures over a cup of coffee. For the lunch breaks, everyone will receive a voucher allowing them to have a meal at one of the campus' cafeteria.

These expenses **are included** in the registration fee.

Registration fees

The registration fees for Master's and Doctoral students are 100.- and 250.- CHF, respectively. These prices do not include the value-added tax of 8%. The effective registration fees are then 108.- and 270.- CHF. These fees have to be transferred to the QCHS bank account via EPFL's PayOnline platform in Swiss francs (CHF). If the transferred amount ends up to be lower than the one specified above the participant will be asked to pay the difference at their arrival.

Scholarships and other financial aids

The organizing committee of the QCHS summer school has decided not to issue any scholarships or financial aid. For participants dependent on financial support please verify whether your home institution can assist you in covering the travel and summer school costs. Some private funds such as the Unitary fund represent alternative financial helps.

Lecture halls' number

All the lectures, hands-on sessions and panel discussions of the summer school will be given in the CO2 auditorium in the Coupole building, not too far away from the Esplanade meeting point. The poster sessions will be held in front of the auditorium, or eventually outside of the building if the weather forecast allows it.

Live streaming

Some of the lectures, hands-on sessions and panel discussions will be broadcasted online on the streaming platform Twitch. The link to the channel is the following www.twitch.tv/qchs2022. No account is required to follow the talks, whereas to be able to ask questions in the chat you will be asked to login. Please be aware that every speaker will be free to choose whether to stream their lecture or not.

Partner Institutions and Sponsors

The QCHS summer school is part of the *Create your own EPFL – ETH Zürich summer school* project, funded by both academic institutions. An additional financial support has been obtained by the Doctoral School of Physics at EPFL as well as from the Quantum Center at ETH and the EPFL's Center for Quantum Science and Engineering representing central hubs for coordinating various scientific and structural activities in quantum science and technology across departments of both academic institutions.

The organizing committee acknowledge the support of these parties as well as the endorsement of the school by their respective professors, namely Profs. Jonathan Home (Trapped Ion Quantum Information group, ETH Zürich), Giuseppe Carleo (Computational Quantum Science Lab, EPFL) and Vincenzo Savona (Laboratory of Theoretical Physics of Nanosystems, EPFL).