Machine learning for Quantum Control and Quantum Computing, ML(QC)2

Monday, 29 August 2022 - Friday, 2 September 2022

Albano Building 3

MACHINE LEARNING

FOR QUANTUM CONTROL
AND QUANTUM COMPUTING

Book of Abstracts

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Adaptive Bayesian learning for quantum sensing and characterisation

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Sophisticated learning techniques, such as Bayesian inference, neural networks or reinforcement learning are becoming increasingly popular as powerful tools to characterise and optimise quantum systems.
Here, I will report on our theoretical and experimental work to speed up the characterisation of quantum systems by exploiting online adaptive measurements and Bayesian inference. We have developed a system, comprising a hard-realtime microcontroller, that implements real-time adaptation of measurement settings, based on previous measurement outcomes (through Sequential MonteCarlo, with <100 microseconds update time). Such a system always operate near maximum sensitivity, even in cases where the optimal settings depend on the unknown parameter to be estimated. We have used this system to characterise decoherence timescales for a single spin qubit associated to a nitrogen-vacancy centre in diamond, showing an improvement in speed of one order of magnitude. We have also benchmarked different adaptive heuristics based on different Bayesian and frequentist statistical estimation bounds. These results offer opportunities in the characterisation of large-scale quantum systems, and in quantum sensing, by considerably increasing the measurement bandwidth. Time permitting, I will also discuss our on-going work on learning models for quantum emitters from photon arrival times, utilising a Markov-chain MonteCarlo approach.

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New superconducting qubit and millikelvin electronics for it

Author: Mikko Möttönen[1]

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We recently discovered a new kind of a superconducting qubit, the unimon, that can be fabricated using standard materials and techniques out of a single Josephson junction and a superconducting resonator, yet having higher anharmonicity than the transmon and resilience against charge and flux noise. Our first experiments on the unimon demonstrate single-qubit-gate fidelity of 99.9% stable for several hours without recalibration. In addition, we have developed qubit readout, reset, and control electronics that operates at millikelvin temperatures and can be integrated with the unimon in the future. These results have been obtained by the Quantum Computing and Devices (QCD) group in collaboration with several other groups. See https://www.aalto.fi/en/department-of-applied-physics/qcd-media for highlighted results.

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Self-Correcting Quantum Many-Body Control using Reinforcement Learning with Tensor Networks

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Quantum many-body control is a central milestone en route to harnessing quantum technologies. However, the exponential growth of the Hilbert space dimension with the number of qubits makes it challenging to classically simulate quantum many-body systems and consequently, to devise reliable and robust optimal control protocols. I will present a novel framework for efficiently controlling quantum many-body systems based on reinforcement learning (RL). We tackle the quantum control problem by leveraging matrix product states (i) for representing the many-body state and, (ii) as part of the trainable machine learning architecture for our RL agent. The framework is applied to prepare ground states of the quantum Ising chain, including critical states. It allows us to control systems far larger than neural-network-only architectures permit, while retaining the advantages of deep learning algorithms, such as generalizability and trainable robustness to noise. In particular, I will demonstrate that RL agents are capable of finding universal controls, of learning how to optimally steer previously unseen many-body states, and of adapting control protocols on the fly when the quantum dynamics are subject to stochastic perturbations.

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Quantum variational learning for quantum error-correcting codes

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Quantum error-correcting codes (QECCs) are believed to be a necessity for large-scale fault-tolerant quantum computation. In the past two decades, various methods of QECC constructions have been developed, leading to many good families of codes. However, the majority of these codes are not suitable for near-term quantum devices. Here we present VarQEC, a noise-resilient variational quantum algorithm to search for quantum codes with a hardware-efficient encoding circuit. The cost functions are inspired by the most general and fundamental requirements of a QECC, the Knill-Laflamme conditions. Given the target noise channel (or the target code parameters) and the hardware connectivity graph, we optimize a shallow variational quantum circuit to prepare the basis states of an eligible code. In principle, VarQEC can find quantum codes for any error model, whether additive or non-additive, degenerate or non-degenerate, pure or impure. We have verified its effectiveness by (re)discovering some symmetric and asymmetric codes, e.g., $((n, 2^{n-6}, 3))_2$ for n from 7 to 14. We also found new $((6, 2, 3))_2$ and $((7, 2, 3))_2$ codes that are not equivalent to any stabilizer code, and extensive numerical evidence with VarQEC suggests that a $((7, 3, 3))_2$ code does not exist. Furthermore, we found many new channel-adaptive codes for error models involving nearest-neighbor correlated errors. Our work sheds new light on the understanding of QECC in general, which may also help to enhance near-term device performance with channel-adaptive error-correcting codes.

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Learning Feedback Control Strategies for Quantum Metrology

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CANCELLED We consider the problem of frequency estimation for a single bosonic field evolving under a squeezing Hamiltonian and continuously monitored via homodyne detection. In particular, we exploit reinforcement learning techniques to devise feedback control strategies achieving increased estimation precision. We show that the feedback control determined by the neural network greatly surpasses in the long-time limit the performances of both the "no-control" strategy and the standard "open-loop control" strategy, which we considered as benchmarks. We indeed observe how the devised strategy is able to optimize the nontrivial estimation problem by preparing a large fraction of trajectories corresponding to more sensitive quantum conditional states. Reference: PRXQuantum 3, 020310 (2022)

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Towards Sample Complexity Reduction via Hybrid Reinforcement Learning for Quantum Control

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CANCELLED Model-free reinforcement learning (RL) shows promise in robustly solving noisy quantum control tasks involving state propagation and gate implementation compared to conventional gradient-based/free optimisation methods. RL methods are able to find high fidelity and highly robust controllers for two-qubit unitary gmon and transmon gates and robust spin transfer state preparations. The latter is a result based on our earlier work [1]. However, RL control methods in practice, even for classical problems, require a large amount of samples (10^6) to find controls, eluding the prospect of cost-effectively deploying these protocols on quantum devices with currently tractable Hilbert space sizes. In this work, we explore how to use model-based RL methods to reduce the sample complexity of popular RL control algorithms without explicitly computing gradients of the control problem that are likely obfuscated in a noisy setting. By leveraging an internal model, based on an analytical Hamiltonian Ansatz, we investigate whether a hybrid (model-free + model-based) RL algorithm has a lower sample complexity whilst retaining the advantage of robust, noisy optimization for realizing a quantum gate for transmons undergoing stochastic Lindbladian evolution. The key ingredient is a model, that is learnt, but also initialized with some physical insight, which allows the RL controller to bootstrap high quality simulated data. This model is refined using real data obtained during the RL process to incorporate real system

dynamics that are uncertain or not present in the initial model, such as Hamiltonian parameters and environmental interactions.

[1] - Khalid I, Weidner CA, Jonckheere EA, Schirmer SG, Langbein FC. Reinforcement learning vs. gradient-based optimisation for robust energy landscape control of spin-1/2 quantum networks. In: IEEE Conf. Decision and Control, pp. 4133-4139, 2021.

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Characterization of variational quantum algorithms using free fermions

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We study variational quantum algorithms from the perspective of free fermions. Using Lie theoretical techniques, we characterize the space of states that the Quantum Approximate Optimization Algorithm (QAOA) is able to prepare at arbitrary circuit depth on a one-dimensional lattice with and without decoupled angles. We show that this is the set of all fermionic Gaussian states respecting the symmetries of the circuit, and we numerically determine the minimum depth necessary to prepare any such state. In several cases we find that these protocols can be made into exact parameterizations of this space, so that global minima exist and are unique. We proceed to study the interplay between the symmetries of the circuit and the locality of the target state and find that an absence of symmetries makes nonlocal states easier to prepare. An efficient classical simulation of Gaussian states is leveraged in order to expose behavior not evident at smaller size. We exploit this in order to study the behavior of the overparameterized regime of optimization with increasing circuit depth, and to show that it saturates quadratically with the system size.

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Quantum Annealing for Neural Network optimization problems: a new approach via Tensor Network simulations

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Quantum Annealing (QA) is one of the most promising frameworks for quantum opti-mization. In this work, we focus on the problem of minimizing complex classical cost functions associated with prototypical discrete neural networks, specifically the paradigmatic binary perceptron and the Hopfield model. We show that the adiabatic time evolution of QA can be efficiently represented as a suitable Tensor Network. This representation allows for simple classical simulations, well-beyond small sizes amenable to exact diagonalization techniques. We show that the optimized state, expressed as a Matrix Product State (MPS), can be recast into a Quantum Circuit, whose depth scales only linearly with the system size and quadratically with the MPS bond dimension. This may represent a valuable starting point allowing for further circuit optimization on near-term quantum devices.

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Quantum Approximate Optimization Algorithm applied to the binary perceptron

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We apply digitized Quantum Annealing (QA) and Quantum Approximate Optimization Algorithm (QAOA) to a paradigmatic task of supervised learning in artificial neural networks: the optimization of synaptic weights for the binary perceptron.
At variance with the usual QAOA applications to MaxCut, or to quantum spin-chains ground state preparation, the classical Hamiltonian is characterized by highly non-local multi-spin interactions.

Yet, we provide evidence for the existence of optimal smooth solutions for the QAOA parameters, which are transferable among typical instances of the same problem, and we prove numerically an enhanced performance of QAOA over traditional QA.
We also investigate on the role of the QAOA optimization landscape geometry in this problem, showing that the detrimental effect of a gap-closing transition encountered in QA is also negatively affecting the performance of our implementation of QAOA.

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quantum-inspired generative models

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Generative models lie at the heart of unsupervised machine learning. Inspired by the probabilistic nature of quantum mechanics, the Born Machine is one category of quantum-inspired generative models. While Born Machines based on tensor networks have shown great success in learning both classical and quantum data, here, we use many-body localized states as a novel resource for learning. We present rigorous proof of expressibility of the MBL-Born Machine and show our numerical results that the driven quantum state via MBL dynamic is able to learn both MNIST data set and data from the quantum many-body state. At this end, we demonstrate that adding hidden unit boost the learnability power of the Born Machine. We further investigate the connection between disorder and the learnability power of the Born Machine in various phases such as MBL, thermal, and Anderson in learning the parity dataset.

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Improving quantum computer performance with machine learning

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Quantum control provides a powerful framework for augmenting the performance of quantum devices, improving processes from gate design and calibration through to readout. In particular, measurement-based feedback control using machine learning techniques provides a path to control large systems, by allowing autonomous agents to determine the best control solutions even in the absence of a detailed model of the system.

In this talk, we will show how this fully automated closed-loop approach can be used to design logical gates that are resilient to hardware noise and more stable over time, showing robustness to system drift up to a month. We will also show a protocol that allows for autonomous and parallel gate tune up across entire devices. Next, we present an automated hardware-informed compilation, crosstalk mitigation, and optimized gate replacement routine, as well as a highly scalable neural-network-based measurement-error-mitigation protocol in post-processing after the execution on the quantum device.

We conclude by presenting the results of the implementation of these strategies in a 16-qubit superconducting quantum computer. We demonstrate benefits that increase with system size, reaching a 9000 times enhancement in quantum algorithm performance.

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Quantum process tomography with gradient descent

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Quantum process tomography (QPT) obtains the representation of a quantum process using experimentally obtained measurement data. We can cast the QPT problem into a learning task where machine learning methods have been recently successful in using generative models for QPT. In this talk, we show how simple gradient-based learning with appropriate constraints on the representation of process, along with restrictions on the gradients can solve QPT. We will demonstrate gradient-based learning of processes for 2- 5 qubits as well as single-mode bosonic systems. We compare our simple approach to existing techniques such as compressed sensing and projected least squares QPT. We also show that using neural networks rather than standard process representations provides no significant advantage which may indicate that good representations of process combined with gradient-based learning might be sufficient for QPT tasks.

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Machine-learning tools for rapid development of quantum technology

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Development of quantum technology devices, and quantum technology in particular, is an arduous process, as it requires both scale and extreme accuracy.

Detailed and precise models of the devices are extremely rare, as characterization procedures of the numerous parameters comprising such models are often ad-hoc - requiring design of parameter-specific experiments and hand-coded scripts to execute and analyze the data.

The most-often used alternative are much simplified models which fail to predict gate fidelities to high accuracy and are therefore of limited utility for optimal control.

Subsequent closed-loop calibration of control pulses leave us with an equally unsatisfying situation of pulses whose precise operation we do not understand. Worst - they don't provide insight as to the causes of remaining infidelities.

Novel algorithmic and machine-learning techniques can go a long to rectify the situation. In this talk I will describe the ongoing work to develop such tools, including highly detailed TensorFlow digital twins of quantum devices, generalized model learning, optimizations based on reinforcement-learning, and automated Bayesian experiment design.

Together with more mundane quantum optimal control tools, they form a toolset which can help gain insight into the behavior of our systems, and significantly accelerate their development.

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Realizing a deep reinforcement learning agent for the discovery of real-time feedback control strategies for a quantum system

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Finding strategies to control quantum information processing devices in real-time becomes increasingly demanding as they grow in size and complexity. Reinforcement learning promises to overcome this challenge by uncovering the underlying system dynamics without relying on a specific model. Here, we implement a deep neural network on a field-programmable gate array (FPGA) and demonstrate its use as a real-time reinforcement learning agent to efficiently initialize a superconducting qubit into its ground state. The agent repeatedly measures the state of the qubit and chooses on a sub-microsecond time scale whether to idle, to apply a bit-flip gate, or to terminate. After the agent chooses to terminate the initialization process, we perform a validation measurement to infer the probability of having successfully initialized the ground state. To train the agent, we use model-free reinforcement learning that is based solely on measurement data.

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Adaptive Characterisation of Quantum Devices with Implicit Deep Adaptive Design

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CANCELLED Modern quantum computers are severely limited not by the number of qubits but by the high error and noise characteristics. The detailed system characterization required to understand the underlying error sources is an arduous process and impractical with increasing chip size. Typical textbook characterisation routines do not scale efficiently to large multi-qubit chips, requiring the development of advanced data-driven techniques [1] based on statistical and information theoretic foundations. We present a Bayesian Experiment Design process that adaptively recommends the most optimal experiments at every step to maximise the expected information gain about the system. The cost of calculating expensive Bayesian posteriors is amortised by the use of Reinforcement Learning assisted likelihood-free Deep Adaptive Design methods [2]. A high-fidelity differentiable digital twin [3] that models the open quantum dynamics, complete electronic control stack and noise & transfer functions for various superconducting quantum devices lies at the heart of this closed loop adaptive calibration and characterisation process. The practical usability of this Bayesian Experiment Design method is demonstrated on a multi-qubit superconducting transmon chip.

References:
1. N. Wittler, F. Roy et al., "Integrated tool set for control, calibration, and characterization of quantum devices applied to superconducting qubits," Physical Review Applied, vol. 15, no. 3, p. 034080, 2021.
2. D. R. Ivanova, A. Foster et al, "Implicit Deep Adaptive Design: Policy-Based Experimental Design without Likelihoods," Conference and Workshop on Neural Information Processing Systems, 2021.
3. A. Saha Roy, K. Pack et al., "Software tool-set for automated quantum system identification and device bring up," arXiv preprint:2205.04829, 2022

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Bandits and Bayesian Optimization for Quantum Circuits

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We survey bandit and Bayesian optimization approaches for optimizing parameters for Quantum circuits.

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Machine learning optimization of Majorana hybrid nanowires

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As the complexity of quantum systems such as quantum bit arrays increases, efforts to automate expensive tuning become increasingly worthwhile. We study machine learning-based tuning of gate arrays using the CMA-ES algorithm for the case study of Majorana wires with strong disorder. We find that the algorithm is able to efficiently improve the topological signatures, learn intrinsic disorder profiles, and completely eliminate disorder effects. For example, with only 20 gates, it is possible to fully recover Majorana zero modes destroyed by disorder with optimized gate voltages.

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Machine Learning Renormalization Group and Generative Modeling

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In this talk, I will introduce the machine learning renormalization group method, a hierarchical flow-based generative model motivated by the idea of the renormalization group in physics. Given the action of a field theory, the algorithm learns the optimal renormalization group transformation and maps the field configuration from the holographic boundary to the bulk, which enables efficient sampling and error correction. Beyond physics applications, I will also demonstrate the application of this method in the image and language processing domain.

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Increasing the complexity of quantum devices in an algorithmic age

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Advances in fabrication and quantum control methods are leading to gate-controlled nanoscale devices becoming progressively more complex, yet affording more and more exquisite local control over gate potentials. Automated solutions for tuning and characterisation are also advancing, as the parameter space of these complex devices are quickly becoming too large to manually investigate. In this talk, I will present our efforts to harness these two complementary advances, to impact the fields of quantum information as well as fundamental condensed matter physics. Hardware and software techniques working in concert assist us to find operation points in spin qubit arrays, as well as to read them out; subsequently, these techniques are also applied to mesoscopic regimes such as quantum Hall systems. Our results propose a path towards the application of algorithmic techniques to fundamental problems in the solid state.

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Recommender System Expedited Quantum Control Optimization

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CANCELLED Quantum control optimization algorithms are routinely used to synthesize optimal quantum gates or to realize efficient quantum state transfers. The computational resource required for the optimization is an essential consideration in order to scale toward quantum control of larger registers. Here, we propose and demonstrate the use of a machine learning method, specifically the recommender system (RS), to deal with the challenge of enhancing computational efficiency. Given a sparse database of a set of products and their customer ratings, RS is used to efficiently predict unknown ratings. In the quantum control problem, each iteration of a numerical optimization algorithm typically involves evaluating a large number of parameters, such as gradients or fidelities, which can be tabulated as a rating matrix. We establish that RS can rapidly and accurately predict

elements of such a sparse rating matrix. Using this approach, we expedite a gradient ascent based quantum control optimization, namely GRAPE, and demonstrate the faster construction of two-qubit CNOT gate in registers with up to 8 qubits. We also describe and implement the enhancement of the computational speed of a hybrid algorithm involving simulated annealing as well as gradient ascent. Moreover, the faster construction of three-qubit Toffoli gates further confirmed the applicability of RS in larger registers.

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New superconducting qubit and millikelvin electronics for it

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We recently discovered a new kind of a superconducting qubit, the unimon, that can be fabricated using standard materials and techniques out of a single Josephson junction and a superconducting resonator, yet having higher anharmonicity than the transmon and resilience against charge and flux noise. Our first experiments on the unimon demonstrate single-qubit-gate fidelity of 99.9% stable for several hours without recalibration. In addition, we have developed qubit readout, reset, and control electronics that operates at millikelvin temperatures and can be integrated with the unimon in the future. These results have been obtained by the Quantum Computing and Devices (QCD) group in collaboration with several other groups. See https://www.aalto.fi/en/department-of-applied-physics/qcd-media for highlighted results.

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Frame-Based Filter-Function Formalism for Quantum Characterization and Control

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A key obstacle to achieve optimal control performance is the interaction between the target system and its unknown environment. Thus, obtaining a quantitative characterization of such environment is instrumental. We introduce a new framework for resource-efficient characterization and control of non-Markovian open quantum systems, which allows for the integration of given, experimentally motivated, control capabilities and constraints. This is achieved by developing a transfer filter-function formalism based on the notion of a frame and by tying the choice of frame to the available control. While recovering the standard frequency-based filter-function formalism as a special instance, this control-adapted generalization affords intrinsic flexibility and allows us to overcome

limitations of existing approaches. In particular, we show how to implement quantum noise spectroscopy in the presence of non-stationary noise sources, and how to achieve control-driven model reduction for noise-tailored optimized quantum gate design.

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Optimising quantum circuits with machine learning

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tbd

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RG using information bottlenecks - venturing into unsolved models.

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The information bottleneck (IB), an abstract mathematical framework for compressing relevant information, has attracted some attention recently due to newly discovered relations with deep learning. Specifically, state-of-the-art deep learning approaches now enable us to access IB quantities numerically. Having this new tool at our disposal, it is interesting to explore its relationship with the Renormalization Group (RG) where an apriori different notion of relevant information exists— that of relevant operators. In a related manner, IB shows promise as an automated method of identifying relevant/slow degrees of freedom in complex interacting models. In this talk, I'll introduce the concept of IB and then report some of the progress we made on these theoretical and applicative fronts. I'll describe a concrete dictionary between relevant operators and bifurcation points in IB compression. In addition, I'll report some recent applications of this approach to self-dual criticality in 3 dimensions.

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The vacuum provides quantum advantage to otherwise simulatable architectures

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Identifying the physical resources underlying quantum advantage — i.e., yielding the ability of quantum computers to solve computational problems faster than classical computers — is of crucial importance for the design of meaningful architectures for quantum computation. Often, the resource depends on the model. In the framework of infinite-dimensional continuous-variable (CV) systems, associated to bosonic fields, Gaussian circuits (where the input state, operations and measurements are all described by Gaussian functions) are classically efficiently simulatable. In other words, for these circuits a classical algorithm exists that can reproduce the outcome of the computation. To promote them to universal quantum computation specific non-Gaussian resources have to be provided, such as the so-called Gottesman-Kitaev-Preskill (GKP) state. The cost of producing these enabling resources with sufficient quality generally requires a significant overhead and their distinct features are typically complex and in stark contrast with respect to the elements of the corresponding simulatable architectures. It is a natural question to ask: are resources always complex and costly to produce?
In this work we provide a specific example of a CV quantum computing architecture that is classically efficiently simulatable, and that becomes universal by adding the vacuum state. The latter state is widely regarded as the simplest quantum state of a bosonic field, and in particular it is a Gaussian state. The architecture considered is based on GKP states, Gaussian operations and measurement of the quadratures of the bosonic field. First we prove that this class of circuits is classically efficiently simulatable for most Gaussian operations. Then, we leverage on recent results where the same architecture combined with the vacuum (or a thermal) state was shown to be universal for quantum computation, to conclude that the vacuum provides quantum advantage.

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Variational Neural Annealing

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(Streamed) Many important challenges in science and technology can be cast as optimization problems. When viewed in a statistical physics framework, these can be tackled by simulated annealing, where a gradual cooling procedure helps search for ground state solutions of a target Hamiltonian. While powerful, simulated annealing is known to have prohibitively slow sampling dynamics when the optimization landscape is rough or glassy. In this talk I will show that by generalizing the target distribution with a parameterized model, an analogous annealing framework based on the variational principle can be used to search for ground state solutions. Autoregressive models such as recurrent neural networks provide ideal parameterizations since they can be exactly sampled without slow dynamics even when the model encodes a rough landscape. We implement this procedure in the classical and quantum settings on several prototypical spin glass Hamiltonians, and find that it significantly outperforms traditional simulated annealing in the asymptotic limit, illustrating the potential power of this yet unexplored route to optimization.

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WACQT overview and airline logistics

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PastaQ.jl: design and benchmarking quantum hardware

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How to learn a quantum state (and how not to)

streamed
Learning an unknown n-qubit quantum state is a fundamental challenge in quantum computing. Full tomography, however, requires exponential-in-n many copies of \rho for a good estimate. Is it possible to circumvent this exponential tax on resources? We consider two variants of this question:
1. "Pretty-good tomography" (based on https://arxiv.org/abs/2102.07171, NeurIPS 2021 (Spotlight)): Aaronson and others introduced several "reduced" models of learning quantum states which impose weaker requirements on the learner: PAC-learning, shadow tomography for learning "shadows" of

a quantum state, online learning, whose complexities scale only linearly in n. We show implications and reductions between the many models in this menagerie, and further introduce a combinatorial parameter that characterizes the complexity of learning. As an application, we improve shadow tomography (for classes of quantum states).
2. Probabilistic modelling (based on https://arxiv.org/abs/2110.05517 and https://arxiv.org/pdf/2207.03140.pdf): Deep generative models have recently empowered many impressive scientific feats, ranging from predicting protein structure to atomic accuracy (Alpha-Fold) to achieving human-level language comprehension (GPT-3). At the heart of these models is the question: by drawing very few samples from a probability distribution, can we learn an algorithm that generates more samples from the same distribution? Even more intriguingly: could there be a quantum advantage for such a task? We present both go and no-go results for this setting.

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Coffee

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Open time slot

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Closing remarks

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A tutorial on designing quantum gates with optimal control theory and automatic differentiation

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I will present a hands-on tutorial (with code) on optimal coherent control for quantum gate design, leveraging automatic differentiation and tensor networks.

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Nordita Director

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Word from Nordita Director

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Quantum simulation and Rydberg atom arrays