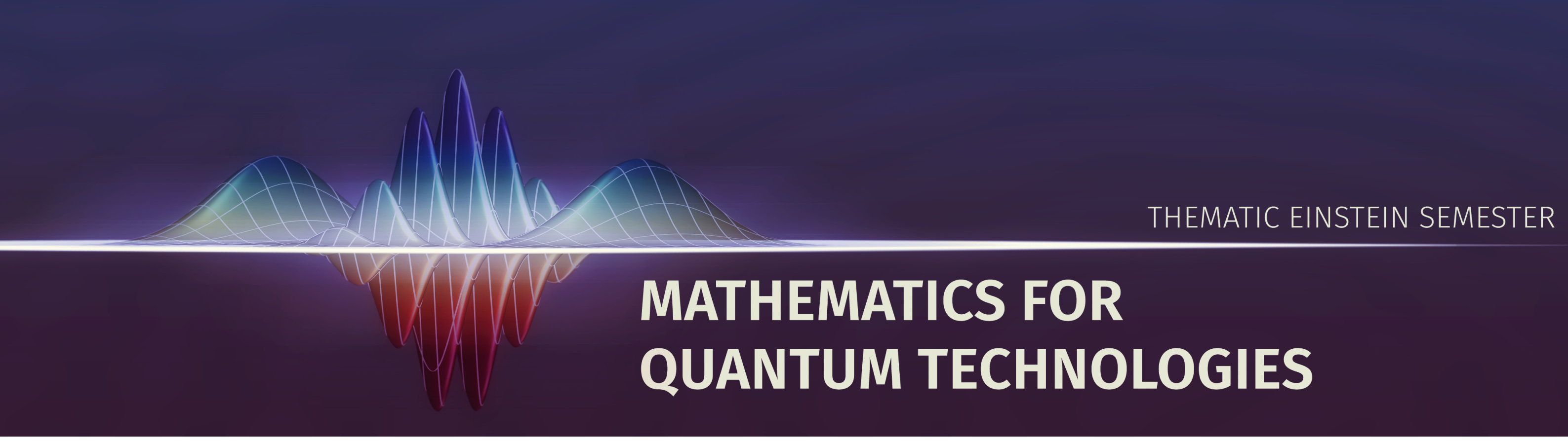

Research Workshop

Quantum Optimal Control

From Mathematical Foundations to Quantum Technologies

May 21–24, 2024

Free University Berlin and Zuse Institute Berlin

Organizers

Tobias Breiten
Technical University Berlin

Patrick Gelß
Zuse Institute Berlin

Markus Kantner
Weierstrass Institute for Applied Analysis and Stochastics

Christiane P. Koch
Free University Berlin

1 Schedule

May 21 (Tuesday)	**May 22** (Wednesday)	**May 23** (Thursday)	**May 24** (Friday)
8:50 – 9:00 | **Opening**			
9:00 – 9:45 | **Rouchon** *Quantum Error Correction and Feedback*	9:00 – 9:45 | **Egger** *Scaling quantum computing with dynamic circuits*	9:00 – 9:45 | **Calarco** *Quantum firmware: optimal control for quantum computers and quantum simulators*	9:00 – 9:45 | **Arenz** *Approximating Riemannian gradient flows on quantum computers for ground state problems*
9:45 – 10:30 | **Whaley** *Open loop control of continuously monitored quantum systems*	9:45 – 10:30 | **Goerz** *Modernizing the Quantum Control Stack with the QuantumControl.jl Framework*	9:45 – 10:30 | **Kuprov** *Simulation and design of shaped pulses beyond the piecewise-constant approximation*	9:45 – 10:30 | **Metelmann** *High-Purity Entanglement of Hot Propagating Modes Using Nonreciprocity*
Coffee Break	*Coffee Break*	*Coffee Break*	*Coffee Break*
11:00 – 11:20 | **Erdman** *Optimal control of quantum thermal machines with reinforcement learning*	11:00 – 11:20 | **Schulte-Herbrüggen** *Symmetry Decides Observability in Quantum Dynamics*	11:00 – 11:20 | **Sugny** *Quantum optimal control of a Bose-Einstein Condensate in an optical lattice*	11:00 – 11:20 | **Stefanatos** *Fast charging of an Ising spin pair quantum battery using optimal control*
11:20 – 11:40 | **Campbell** *Quantum work statistics of controlled evolutions*	11:20 – 11:40 | **Pozzoli** *Time-zero controllability and Lie algebraic properties of infinite-dimensional closed quantum systems*	11:20 – 11:40 | **Cuestas** *A quantum engine in the BEC-BCS crossover*	11:20 – 11:40 | **Kiely** *Universally Robust Quantum Control*
11:40 – 12:25 | **Kosloff** *Quantum control of noisy gates*	11:40 – 12:25 | **Borzì** *The Pontryagin Maximum Principle for Solving Quantum Optimal Control Problems with Sparsity Promoting Cost Functionals*	11:40 – 12:25 | **Weidner** *Controlling ultracold atoms in optical lattices: theory and practice (but mostly practice)*	11:40 – 12:25 | **Shermer** *Robust Quantum Control*
Lunch Break	*Lunch Break*	*Lunch Break*	
14:00 – 14:45 | **Tse** *Quantum Computing with Rydberg-atom quantum processors*	14:00 – 16:00 | **Social Event** Guided tour across the historic campus Berlin-Dahlem. Meeting point: Harnack Haus Tour A: 100 Years of Science at "Germany's Oxford" Tour B: "Science Heaven" Dahlem's Nobel Laureates	14:00 – 16:00 | **Tutorial**	
14:45 – 15:05 | **Hegade** *Digitized Counterdiabatic Quantum Computing*			
15:05 – 15:25 | **Grech** *Optimising Quantum Gate Fidelity with Deep Reinforcement Learning*			
15:25 – 16:10 | **Wilhelm-Mauch** *Controlling and calibrating superconducting qubits in practice*			
	Coffee Break	*Coffee Break*	
from 16:30 | **Poster-Session**	16:30 – 16:50 | **Petersson** *Mitigating scaling barriers through time-parallel multiple shooting method*	16:30 – 16:50 | **Gago Encinas** *Testing systems for universal quantum computing: a controllability test using parametric quantum circuits*	
	16:50 – 17:10 | **Schneider** *Compositional Tensor Networks*	16:50 – 17:10 | **Bruschi** *Towards exact factorization of quantum dynamics via Lie algebras*	
	17:10 – 17:55 | **Boscain** *Ensemble controllability for n-level quantum systems*	17:10 – 17:30 | **Petiziol** *Optimized Floquet engineering of many-body interactions*	
		from 18:30 | **Dinner**	

2 Venue

The workshop will take place in the lecture hall of the Zuse Institute Berlin (ZIB).
Address: Takustraße 7, D–14195 Berlin

Public Transport

There are multiple possibilities to reach the venue by public transport:

- U3: Dahlem-Dorf
- S1: Botanischer Garten
- Bus 101: Limonenstraße
- Bus X83: Museum Dahlem, Arnimallee or U Dahlem-Dorf
- Bus M11: U Dahlem-Dorf

Lunch

① eßkultur: Daily changing dishes, incl. vegetarian

② Luise Dahlem: Steak, burger, pizza, tart
Ristorante Piaggio: Italian cuisine
really good life: Burger (meat/ vegan)
+ coffee shop, bakeries, supermarket

③ Alter Krug: German cuisine

④ FU Mensa: wide selection of inexpensive food

⑤ Pi Cafe: coffee shop with rooftop terrace

Workshop Dinner

The workshop dinner will take place on Thursday evening (May 23, start 6:30 p.m.) at *Luise Dahlem*, see map above.

WiFi

Free WiFi will be provided via eduroam.

3 Contact

Please contact our office if you have any questions.

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D–14195 Berlin
Phone: +49 30 838 58271

E-Mail: qoc2024@mathplus.de

4 Poster Session

The poster session will take place on Tuesday afternoon (May 21, start: 4.30 p.m.) in the lobby of the Zuse Institute next to the lecture hall. Please bring your printed poster (DIN A0, format: portrait) and hang it up in the slot with your poster number (see list of posters below) during the lunch break.

5 Social Event

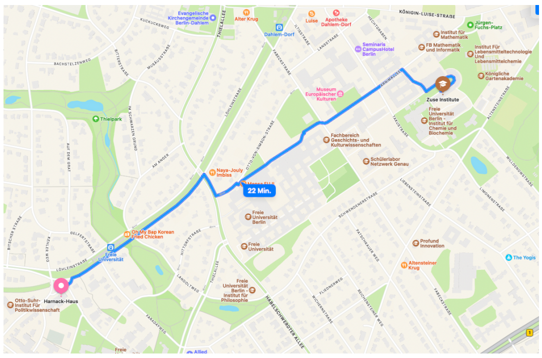
On Wednesday afternoon (May 22, 2–4 p.m.), we will take part in a guided tour across the historic campus Berlin-Dahlem and gain insights into an exciting period in the history of science. The tour starts at the **Harnack Haus** at 2 p.m.

Meeting point:
Harnack Haus
Ihnestraße 16–20
D–14195 Berlin

You can choose between two tours

- Tour A: 100 Years of Science at "Germany's Oxford"
- Tour B: "Science Heaven" Dahlem's Nobel Laureates

Both tours are offered with an english speaking guide and will take about 90 minutes. Participants are asked to distribute equally between the tours.



6 Software-Tutorial

The software tutorial will take place on Thursday afternoon (May 21, 2–4 p.m.).

The tutorial will give you a chance to explore numerical quantum dynamics and optimal control through a series of Jupyter notebooks. It will cover basic concepts of light-matter-interaction, tuning control parameters with gradient-free methods, all the way to the optimization of entangling quantum gates with Krotov's method and GRAPE. There will be examples from a variety of physical systems and at different levels of complexity. Thus, different parts of the tutorial will be suitable for students first dipping their toes into numerical quantum control as well as seasoned researchers wanting to get familiar with some of the latest cutting-edge tools.

We will offer versions of the notebooks in Python and the Julia language. For the most part, these will cover the same material, although Julia will allow to explore more advanced topics, like a comparison of GRAPE and Krotov's method, larger quantum systems, and modern methods such as automatic differentiation.

For **Python**, the main packages that will be explored are:

- QuTiP – Quantum Toolbox in Python.
- krotov – An implementation of Krotov's method built on top of QuTiP 4.
- NLopt – A nonlinear optimization package.

For **Julia**, the main packages are:

- QuantumControl.jl – A Julia framework for quantum dynamics and control. Includes QuantumPropagators.jl, Krotov.jl and GRAPE.jl.
- Optimization.jl – Optimization package (wraps around NLopt and many other optimizers).

Parts of the tutorial will be self-directed, depending on your interests and level of experience. **You will be running it on your own laptop.** The notebooks and detailed installation instructions will be made available before the workshop. The tutorial is conducted by Michael Goerz.

7 List of Posters

P1 Davide Lonigro (FAU Erlangen-Nürnberg)
Global approximate controllability of quantum systems by form perturbations

P2 Omar Kebiri (BTU Cottbus-Senftenberg)
Deep learning methods for stochastic optimal control

P3 Juhi Singh (Forschungszentrum Jülich)
Optimal control methods for two-qubit gates in optical lattices

P4 Robert de Keijzer (Eindhoven University of Technology)
Do qubits like Metallica?

P5 Mirko Consiglio (University of Malta)
Variational Gibbs State Preparation on NISQ devices

P6 Thomas Reisser (Forschungszentrum Jülich)
Closed-loop gate-set optimization via quantum optimal control for an ensemble of nitrogen vacancy centers in diamond

P7 Boxi Li (Forschungszentrum Jülich)
Analytical pulse design for crosstalk and leakage suppression

P8 Robert Zeier (Forschungszentrum Jülich)
Symmetry obstructions to the quantum approximate optimization algorithm

P9 Ressa Said (University of Ulm)
Optimal control using phase-modulated driving fields in diamond

P10 Lukas Tarra (TU Wien)
Adaptive nonlinear stabilization of ultrashort laser pulses

P11 William Steadman (Qruise GmbH)
Adaptive system characterization and quantum optimal control competitive with closed loop calibration

P12 Emanuel Malvetti (Technical University Munich)
Reduced Control Systems for Optimal Cooling and Entangling

P13 Lasse Ermoneit (Weierstrass Institute for Applied Analysis and Stochastics, Berlin)
Optimal Control of a Si/SiGe Quantum Bus for Scalable Quantum Computing Architectures

P14 Jingjun Zhu (Université de Bourgogne)
Optimal control and ultimate bounds of 1:2 nonlinear quantum systems

P15 Shimshon Kallush (Holon Institute Technology, Hebrew University)
Controlling the uncontrollable: Quantum control of open-system dynamics

P16 Alejandro Ramos (University of Rostock)
Shaping Laser Control Pulses by an Automatic Differentiation Direct Optimal Control Approach

P17 Cristina Cicali (Forschungszentrum Jülich)
Atom transport optimization: theoretical frameworks, algorithms, and experimental integration

P18 Qi Zhang (Kipu Quantum)
Analog Counterdiabatic Quantum Computing to Push the Boundaries of Neutral Atom Hardware Towards Quantum Usefulness

P19 Ashutosh Mishra (Forschungszentrum Jülich)
Superconducting Qubit Reset by Demolition Measurement

P20 Adrian Köhler (Free University of Berlin)
Optimal control of arbitrary perfectly entangling gates for open quantum systems

P21 Matthias Krauss (Free University of Berlin)
Parameter Optimization of Transmon Arrays and Crosstalk Mitigation

P22 Anton Halaski (Free University of Berlin)
Quantum Feedback Control for Quantum Error Correction on Superconducting Qubits

P23 Roberto Sailer (University of Ulm)
Implementing control optimization strategy for decoherence protected quantum register in diamond

P24 Yannick Strocka (Humboldt University of Berlin)
Optimal Control Aspects for Cluster State Generation with Group-IV Color Centers in Diamond

P25 Monika Leibscher (Free University of Berlin)
A graph-theoretical approach to analyze controllability of driven quantum systems

P26	Mohammad Abedi (Forschungszentrum Jülich) *Reinforcement learning entangling operations for spin qubits*
P27	Armin Römer (Forschungszentrum Jülich) *JuMPO: A Quantum Optimal Control Library for Open System Magnetic Resonance Experiments with Arbitrary Inhomogeneities*
P28	Nicolas Wittler (Forschungszentrum Jülich) *Co-design of quantum computing devices with optimal control*
P29	Dirk Heimann (University of Bremen) *Synthesizing optimal pulse sequences with an iterative linear quadratic regulator (iLQR) for IBM superconducting qubits*
P30	Alexander Simm (Forschungszentrum Jülich) *Control of analog qubit-resonator gates in the strong coupling regime*
P31	Martino Calzavara (Forschungszentrum Jülich) *Quantum control landscapes of piecewise-constant pulses*
P32	Luke Visser (Eindhoven University of Technology) *Simulating the stochastic Schrödinger equation with semi-martingale noise*
P33	Maurice Beringuier (Max Planck Institute for Nuclear Physics) *Measuring and predicting the performance of atomic-scale systems as quantum classifiers*
P34	Tangyou Huang (Chalmers University of Technology) *High-fidelity superconducting two-qubit gate with optimal control*
P35	Kapil Goswami (Zentrum für Optische Quantentechnologien, University of Hamburg) *Solving optimization problems on quantum systems.*
P36	Aviv Aroch (Hebrew University of Jerusalem) *Mitigating controller noise in quantum gates using optimal control theory*

8 Program and Abstracts

May 21 (Tuesday)

Session 1

9:00 – 9:45 | **Pierre Rouchon** (Mines Paris PSL) (invited talk)
Quantum Error Correction and Feedback
Quantum error correction relies on a feedback loop. This feedback generally corresponds to a classical controller. Quantum error correction can also exploit the dissipation associated with the phenomenon of decoherence. Called autonomous correction by physicists, it then uses feedback where the controller is a dissipative quantum auxiliary system. This talk focuses on the development of such quantum controllers to stabilize logical qubits encoded in harmonic oscillators (bosonic code). Two types of encoding will be considered: cat-qubit encoded in two coherent states of opposite phases for which bit-flip errors induced by usual noises can be experimentally almost suppressed and GKP-qubit encoded in finite energy grid-states approximating position/impulsion Dirac combs where, in principle, bit-flips and phase-flips could be also almost suppressed.

9:45 – 10:30 | **Birgitta Whaley** (University of California, Berkeley) (invited talk)
Open loop control of continuously monitored quantum systems
Continuous weak measurements provide a unique framework for combining the monitoring quantum systems with methods of optimal control. I shall describe two examples, one realizing controlled non-Hermitian quantum dynamics, and the other exploring the optimal control of quantum state steering ('dragging') by continuously implemented quantum Zeno dynamics and acceleration of this with a unitary drive.

Session 2

11:00 – 11:20 | **Paolo Andrea Erdman** (Free University of Berlin) (contributed talk)
Optimal control of quantum thermal machines with reinforcement learning
A quantum thermal machine is an open quantum system that converts between heat and work at the micro-scale through time-dependent controls. Optimally controlling such out-of-equilibrium open quantum systems is a crucial task with applications to quantum technologies and to quantum devices for heat management.

However, the multi-objective optimization of their performance is an extremely challenging task involving (i) out-of-equilibrium open quantum system dynamics, (ii) a search over the exponentially large space of time-dependent controls, and (iii) possibly a limited knowledge of the model describing an experimental device. We introduce a framework, based on Reinforcement Learning, to discover optimal time-dependent cycles for quantum thermal machines. We find Pareto-optimal trade-offs between high power and high efficiency in various models, including a superconducting-circuit implementation of a refrigerator, outperforming previous proposals made in literature.

11:20 – 11:40 | **Steve Campbell** (University College Dublin, Free University of Berlin) (contributed talk)
Quantum work statistics of controlled evolutions
We use the quantum work statistics to characterize the controlled dynamics governed by a counterdiabatic driving field. Focusing on the Shannon entropy of the work probability distribution, we demonstrate that the thermodynamics of a controlled evolution serves as an insightful tool for studying the non-equilibrium dynamics of complex quantum systems. In particular, we show that the entropy of the distribution recovers the expected scaling according to the Kibble-Zurek mechanism for the Landau-Zener model. Furthermore, we propose that the entropy of the work distribution provides a useful summary statistic for characterizing the need and complexity of the control fields for many-body systems.
Ref: S. Campbell, EPL 143, 68001 (2023).

11:40 – 12:25 | **Ronnie Kosloff** (Hebrew University of Jerusalem) (invited talk)
Quantum control of noisy gates
Control of quantum systems is essential for the realization of contemporary quantum technology. In reality, any quantum system is open subject to external noise. The decoherence caused by this noise is currently the main limitation to achieve quantum computing. We have developed optimal control theory for quantum gates under the influence of noise. One objective is control of entropy changing transformations used to supply cold ancillas. Control of quantum gates mitigating thermal environmental noise. and stochastic noise generated by the controller. Control based on weak measurement and quantum feedback. The theoretical framework is based on optimal control theory and the theory of quantum open systems and quantum thermodynamics. This leads to consistent equations of motion which are the base for the control theory. Results demonstrate the ability to mitigate environmental and controller noise by employing quantum optimal control.

Session 3

14:00 – 14:45 | **Oliver Tse** (Eindhoven University of Technology) (invited talk)
Quantum Computing with Rydberg-atom quantum processors
Quantum computing is presently in the noisy intermediate-scale quantum (NISQ) era, where the available quantum computers cannot outperform their classical counterparts. Nevertheless, even in the NISQ era, quantum computers can be used for specific and well-designed cases—finding the ground state energy of a molecule is one such case. In this talk, I will briefly introduce quantum computing with Rydberg-atom quantum processors and discuss current methods (and bottlenecks) used in solving several problems, eg. the electronic structure problem using variational quantum optimal control, learning quantum channels, and understanding quantum noise.

14:45 – 15:05 | **Narendra Hegade** (Kipu Quantum) (contributed talk)
Digitized Counterdiabatic Quantum Computing
In this talk, I discuss “Digitized-counterdiabatic Quantum Computing” (DCQC) as a new paradigm for implementing adiabatic quantum algorithms enhanced by counterdiabatic protocols on a gate model quantum computer. This novel approach not only accelerates the adiabatic process by suppressing non-adiabatic excitations but also allows for the realization of any arbitrary interactions, making it suitable for noisy intermediate-scale quantum computers. Additionally, I explore various applications of DCQC protocols in many-body ground state preparation, quantum chemistry, and combinatorial optimization problems, and their implementation on current trapped-ion quantum computers, demonstrating superior performance compared to existing methods.

15:05 – 15:25 | **Leander Grech** (University of Malta) (contributed talk)
Optimising Quantum Gate Fidelity with Deep Reinforcement Learning
Quantum optimal control (QOC) is concerned with designing EM pulses for precise qubit evolution, however, it encounters scalability challenges with an increasing number of qubits. Algorithms such as GRAPE, CRAB, and GOAT struggle in scalability and in the quality of pulses generated. Recently, reinforcement learning (RL)

has been shown that it can adjust pulse parameters within a simulated environment. The qubits evolution is assessed based on fidelity and leakage metrics. Notably, an RL agent can be trained to be hardware-agnostic, enabling it to function effectively under varying machine parameters such as anharmonicity and decay time. This work aims to improve upon recent literature concerning the use of RL in QOC. Here we will set up an RL environment which simulates transmon qubits controlled by pulses, train various RL algorithms on this environment, and compare it to QOC baselines, i.e. using numerical optimisers.

15:25 – 16:10 | **Frank Wilhelm-Mauch** (Forschungszentrum Jülich) (invited talk)
Controlling and calibrating superconducting qubits in practice
An important application of quantum optimal control is to optimize the performance of quantum operations on given hardware. We are reporting our efforts to make this a reality on superconducting quantum computing systems. Here, the application of numerically obtained, often counterintuitive pulses is challenged by the effective models of the device being imprecise or incomplete. This can be tackled by a combination of online calibration, model learning, and robust control. I will describe the C3 software package that brings these elements together as well as highlight the transition of many of these techniques into a professional commercial toolset. I will then discuss various applications and aspects, including learning of noise spectra, exploring control landscapes with different optimizers, learning transfer functions and automatically correcting their effect, and simultaneously designing pulses and hardware.

Poster Session

P1 | **Davide Lonigro** (FAU Erlangen-Nürnberg) (poster)
Global approximate controllability of quantum systems by form perturbations
We provide sufficient conditions for the approximate controllability of infinite-dimensional quantum control systems corresponding to form perturbations of the drift Hamiltonian modulated by a control function. We rely on previous results on controllability of quantum bilinear control systems and obtain a priori L1-bounds of the controls for generic initial and target states. We apply a stability result for the non-autonomous Schrödinger equation to extend the results to systems defined by form perturbations, including singular perturbations. As an application of our results, we prove approximate controllability of a quantum particle in a one-dimensional box with a point-interaction with tuneable strength at the centre of the box. Based on arXiv:2402.02955. Joint work with A. Balmaseda and J.M. Pérez-Pardo.

P2 | **Omar Kebiri** (BTU Cottbus-Senftenberg) (poster)
Deep learning methods for stochastic optimal control
I will present deep learning methods to solve stochastic optimal control problems. The dynamic is an application for solving initial path optimization of mean-field systems with memory where we consider the problem of finding the optimal initial investment strategy for a system modeled by a linear McKean-Vlasov (mean-field) stochastic differential equation with delay delta > 0, driven by a Brownian motion and a pure jump Poisson random measure. The problem is to find the optimal initial values for the system in this period [-delta,0] before the system starts at t=0. Because of the delay in the dynamics, the system will after startup be influenced by these initial investment values. It is known that linear stochastic delay differential equations are equivalent to stochastic Volterra integral equations. By using this equivalence we can find implicit expression for the optimal investment. We deep machine learning algorithms to solve explicitly some examples

P3 | **Juhi Singh** (Forschungszentrum Jülich) (poster)
Optimal control methods for two-qubit gates in optical lattices
We use quantum optimal control to identify fast collision-based two-qubit gates in ultracold atoms trapped in superlattices based on classical Fermi-Hubbard simulations. We manipulate the hopping and interaction strengths inherent in the Fermi-Hubbard model by optimizing the lattice depth and the scattering length. We show that a significant speedup can be achieved by optimizing the lattice depths in a time-dependent manner, as opposed to maintaining a fixed depth. We obtain non-adiabatic fast gates by including higher bands of the Hubbard model in the optimization. Furthermore, in addition to two-qubit states, our optimized control pulses retain their effectiveness for one, three, or four atoms in the superlattice. We compare our Fermi-Hubbard approach with real-space simulations using Wannier functions.

P4 | **Robert de Keijzer** (Eindhoven University of Technology) (poster)
Do qubits like Metallica?
Environmental noise on a controlled quantum system is generally modeled by a dissipative Lindblad equation. One way of deriving this Lindblad equation is by introducing a stochastic operator evolving under white noise

in the Schrödinger equation. However, white noise is not a realistic noise profile, as lower frequencies generally dominate the spectrum. In this presentation, we introduce a method for solving for the full distribution of qubit fidelity driven by important stochastic Schrödinger equation cases, where qubits evolve under more realistic noise profiles, e.g. Ornstein-Uhlenbeck noise (or Metallica songs). This allows for predictions of the mean, variance, and higher-order moments of the fidelities of these qubits, which can be of value when deciding on the allowed noise levels for future quantum computing systems. Furthermore, these methods will prove to be integral in the optimal control of qubit states under (classical) control system noise.

P5 | **Mirko Consiglio** (University of Malta) (poster)
Variational Gibbs State Preparation on NISQ devices
The preparation of an equilibrium thermal state of a quantum many-body system on noisy intermediate-scale devices is an important task in order to extend the range of applications of quantum computation. We propose a variational quantum algorithm (VQA) to prepare Gibbs states of a quantum many-body system. The novelty of our VQA consists in implementing a parameterized quantum circuit acting on two distinct, yet connected, quantum registers. The VQA evaluates the free energy, where the von Neumann entropy is obtained via post-processing of computational basis measurements on one register, while the Gibbs state is prepared on the other register, via a unitary rotation in the energy basis. Finally, we benchmark our VQA by preparing Gibbs states of the Ising model and achieve remarkably high fidelities across a broad range of temperatures in statevector simulations. We also assess the performance of the VQA on IBM quantum computers, showcasing its feasibility on current NISQ devices.

P6 | **Thomas Reisser** (Forschungszentrum Jülich) (poster)
Closed-loop gate-set optimization via quantum optimal control for an ensemble of nitrogen vacancy centers in diamond
Precise control of a quantum system is a prerequisite for quantum information, quantum computing, and quantum metrology. Quantum gates on ensembles of nitrogen vacancy centers usually suffer from decoherence, large amplitude errors, imperfect state preparation and therefore limited total operation fidelity. Large state preparation and measurement errors cause the typically used quantum process tomography to fail. We investigate the applicability of quantum process tomography, linear inversion gate-set tomography, randomized linear gate-set tomography, and randomized benchmarking as measures for closed-loop quantum optimal control experiments. Closed-loop optimizations are performed and evaluated with all measures to find a gate-set with universally improved performance and demonstrate the relative trade-offs between the methods.
Co-Authors: Philipp J. Vetter, Maximilian G. Hirsch, Felix Motzoi, Tommaso Calarco, Fedor Jelezko, Matthias M. Müller

P7 | **Boxi Li** (Forschungszentrum Jülich) (poster)
Analytical pulse design for crosstalk and leakage suppression
To overcome the challenges posed by finite coherence time, an important task in quantum control involves devising rapid and precise driving schemes. Rather than relying solely on numerical optimization, analytical control based on the knowledge of the Hamiltonian and error dynamics is especially beneficial for experimental calibration and can serve as a starting point for more sophisticated optimization. In this context, we introduce a method of analytical control with multi-derivative based pulse Ansatz, originated from the Derivative Removal via Adiabatic Gate (DRAG) technique, widely used for superconducting qubits architecture. This approach provides efficient but concise parameterized pulse Ansatz that simultaneously suppress multiple control errors, including nonperturbative and multi-photon dynamics. Our analysis demonstrates the versatility of this method across various applications, including two-qubit gate operations, crosstalk suppression, and qutrit operations.

P8 | **Robert Zeier** (Forschungszentrum Jülich) (poster)
Symmetry obstructions to the quantum approximate optimization algorithm
The quantum approximate optimization algorithm (QAOA) approximates ground states related to the maximum-cut graph problem. We describe symmetries and algebraic properties of QAOA ansätze and the related control-theoretic analysis of their controllability and expressivity. For the multi-angle ansatz of QAOA, the Lie algebras observed for any connected graph split into six classes corresponding to path, cycle, bipartite, and remaining graphs. We predict that polynomially and exponentially deep quantum circuits will suffer from barren plateaus for the multi-angle ansatz applied to the remaining graphs. But shallow circuits of logarithmic depth will likely lack the resources to approximately reach the ground state. Even for the so-called standard ansatz, we indicate why the effectiveness of QAOA might be negatively affected. Our results are paradigmatic for numerical quantum optimal control.
Joint work with Sujay Kazi, Martin Larocca, Marco Farinati, Patrick J. Coles, and Marco Cerezo.

P9 | **Ressa Said** (University of Ulm) (poster)
Optimal control using phase-modulated driving fields in diamond
We present a variant of gradient-free optimal control by introducing phase-modulated (PM) driving fields, evaluate its performance and demonstrate advantages over standard Fourier-basis (SFB) in controlling ensemble of NV centers in diamond with inhomogeneous broadening [PRA 102, 043707 (2020)]. The optimized fields provide increased robustness against inhomogeneities, field fluctuations, and environmental noise, with faster average search time. Robustness enhancement of single gates is also achieved giving XY8 sequence that extends spin coherence improving precision of signal detection for sensing. Applying Bayesian [Sensors 23, 3244 (2023)], PM reduces the time by 90% compared with SFB while increasing fidelity. In AC magnetometry, the fields achieve 8-fold extension of coherence compared with the rectangular pulse. PM has been also exploited for rapid control strategies to prepare and control decoherence-protected quantum registers [PRA 109, 022614 (2024)].

P10 | **Lukas Tarra** (TU Wien) (poster)
Adaptive nonlinear stabilization of ultrashort laser pulses
Ultrafast pulsed lasers are indispensable tools to probe and excite non-thermal dynamics at atomic scales. Their pulse-to-pulse dynamics, which couple subsequent pulses via the gain medium, can become unstable and even chaotic. Even if the pulse-to-pulse dynamics are initially stable, parameter variations due to, for instance, fluctuating pump power or the heating of optical elements can cause drifts in the mean pulse energy or re-introduce dynamical instabilities. In this presentation, we propose an adaptive nonlinear control concept to stabilize the pulse-to-pulse dynamics of ultrafast lasers. While the model adaptation steps are performed by means of traditional recursive parameter estimators or neural networks, the controller is obtained by a novel methodology based on invariant manifold theory. The robustness and performance of the approach are demonstrated in realistic simulations and benchmarked against reinforcement learning methods.

P11 | **William Steadman** (Qruise GmbH) (poster)
Adaptive system characterization and quantum optimal control competitive with closed loop calibration
Open-loop optimal control is limited by the accuracy of the quantum system model. In this work, we addressed the issue of system model inaccuracies by optimising our model parameters using a likelihood measure as our loss function, to best match benchmarking data obtained with interleaved experiments . The system model adapted to drifts in the parameters and we demonstrate how the optimised model closely approximates the system dynamics and optimal control provides updated pulses competitive with closed loop calibration.

P12 | **Emanuel Malvetti** (Technical University Munich) (poster)
Reduced Control Systems for Optimal Cooling and Entangling
We develop a method of reduced control systems and apply it to two problems in quantum control theory, namely optimal cooling and optimal entanglement generation. The method states that for certain control systems with fast control over a Lie group action, there exists a reduction to an equivalent control system of significantly lower dimension. We explain this reduction process and present the central Equivalence Theorem. Then we discuss two applications to quantum control theory: for Markovian systems with fast unitary control we characterize coolable systems are show how one can derive time-optimal cooling strategies. For closed bipartite systems with fast local unitary control we prove controllability and deduce time-optimal entanglement generation strategies.

P13 | **Lasse Ermoneit** (Weierstrass Institute for Applied Analysis and Stochastics, Berlin) (poster)
Optimal Control of a Si/SiGe Quantum Bus for Scalable Quantum Computing Architectures
Spin qubits in Si/SiGe heterostructures are one of the major candidates for fault-tolerant, universal quantum computing. Scalable architectures require a quantum bus for coherent shuttling of electrons across the chip to interlink different functional units of the processor. The shuttling fidelity is typically limited by hardly avoidable material defects and fabrication imperfections, which can cause spin dephasing. We present a numerical simulation framework for conveyor-mode spin qubit shuttling in a realistic Si/SiGe quantum bus and investigate the impact of charged defects on the orbital dynamics of the transported electron. Quantum optimal control theory is employed to engineer control pulses that enable a nearly deterministic passage of the electron through the channel by minimizing the accumulated energy uncertainty. Optimization is carried out using a quasi-Newton method. The resulting control protocol facilitates quasi-adiabatic driving without reducing the shuttling speed.

P14 | **Jingjun Zhu** (Université de Bourgogne) (poster)
Optimal control and ultimate bounds of 1:2 nonlinear quantum systems
Using optimal control, we establish and link the ultimate bounds in time (referred to as the quantum speed

limit) and energy of two- and three-level quantum nonlinear systems which feature 1:2 resonance. Despite the unreachable complete inversion, by using the Pontryagin maximum principle, we determine the optimal time, pulse area, or energy for a given arbitrary accuracy. We show that the third-order Kerr terms can be absorbed in the detuning in order to lock the dynamics to the resonance. In the two-level problem, we determine the nonlinear counterpart of the optimal π-pulse inversion for a given accuracy. In the three-level problem, we obtain an intuitive pulse sequence similar to the linear counterpart but with different shapes. We prove the (slow) logarithmic increasing of the optimal time as a function of the accuracy.

P15 | **Shimshon Kallush** (Holon Institute Technology, Hebrew University) (poster)
Controlling the uncontrollable: Quantum control of open-system dynamics
Control of open quantum systems is essential for the realization of contemporary quantum science and technology. We demonstrate such control using a thermodynamically consistent framework, taking into account the fact that the drive can modify the system's interaction with the environment. Such an effect is incorporated within the dynamical equation, leading to control-dependent dissipation. This relation serves as the key element for open-system control. The control paradigm is displayed by analyzing entropy-changing state-to-state transformations, such as heating and cooling. The difficult task of controlling quantum gates is achieved for nonunitary reset maps with complete memory loss. In addition, we identify a mechanism for controlling unitary gates by actively removing entropy from the system to the environment. We demonstrate a universal set of single- and double-qubit unitary gates under dissipation.

P16 | **Alejandro Ramos** (University of Rostock) (poster)
Shaping Laser Control Pulses by an Automatic Differentiation Direct Optimal Control Approach
We propose here the application of a direct optimal control approach to manage population dynamics in a Fermi-resonance model and control H-atom transfer within a lossy Fabry-Pérot cavity experiencing vibrational strong coupling. The direct optimal control method is characterized by a simultaneous simulation and optimization paradigm, where the equations of motion are discretized in time and transformed into a set of holonomic constraints for a nonlinear optimization problem defined by the performance functional. This approach, combined with automatic differentiation, presents several advantages, including optimization of final time, Hamiltonian parameters, and initial state. Additionally, it allows for the incorporation of a diverse set of terms in the performance functional and constraints that could be implemented easily in a plug-and-play fashion. These capabilities prove particularly valuable when striving for enhanced control strategies and mitigating potential decay mechanisms.

P17 | **Cristina Cicali** (Forschungszentrum Jülich) (poster)
Atom transport optimization: theoretical frameworks, algorithms, and experimental integration
Quantum simulation has emerged as a powerful paradigm for investigate complex quantum systems that elude classical computational methods. The unique characteristics of trapped neutral atoms as extended coherence times and precise control over external parameters, make them optimal candidates to explore optimization procedures. Atom transport optimization occupies a prominent position in the implementation of quantum gates, providing control over the transport of individual atoms within quantum platforms as optical lattices. In the project FemiQP we aim to develop theoretical frameworks for optimizing atom transport trajectories, including strategies aimed at maximizing the fidelity. Quantum algorithms, such as d-CRAB, specifically tailored for optimizing atom transport paths, are compared and employed to attain the quantum speed limit inherent to the considered system. Collaborating with the experimental group the optimized protocols are integrated into the experimental setup.

P18 | **Qi Zhang** (Kipu Quantum) (poster)
Analog Counterdiabatic Quantum Computing to Push the Boundaries of Neutral Atom Hardware Towards Quantum Usefulness
Analog Counterdiabatic Quantum Computing (ACQC), a new paradigm by Kipu Quantum GmbH, aims to extend neutral atom hardware to combinatorial optimization. Counterdiabaticity (CD) was previously introduced to accelerate adiabatic processes, enabling shorter evolution times and higher solution quality. However, no instances of CD protocol being implemented on neutral atom quantum computers exist due to well-known hardware limitations: encoding problems in the native Hamiltonian and restricted parameter ranges, which limit the number of treatable computational problems. In this contribution, we introduce a CD protocol directly implementable on current commercial neutral atom hardware. We demonstrate for the example of a combinatorial optimization problem that ACQC enhances the performance by a factor of two on average without applying additional optimization on the hardware or post-processing algorithms. This allows us to tackle larger computational problems at lower computational costs.

P19 | **Ashutosh Mishra** (Forschungszentrum Jülich) (poster)
Superconducting Qubit Reset by Demolition Measurement
In this project we propose a scheme for performing a "demolition measurement" of the qubit without using active feedback, to obtain the qubit in the ground state at the end of the measurement, by combining readout and reset of the qubit and reset of the readout resonator. This scheme doesn't require any additional hardware, either on the control stack or on-chip, and hence does not affect the scalability. We demonstrate that one can make measurements and reset the whole experiment, including qubit readout, clear leakage population of the qubit, empty the resonator, and then reset the qubit to the ground state, within 1μs.

P20 | **Adrian Köhler** (Free University of Berlin) (poster)
Optimal control of arbitrary perfectly entangling gates for open quantum systems
Perfectly entangling gates (PE) are crucial for various applications in quantum information. One method to realize these gates is with the help of an external control field, whose concrete shape is found using optimal control theory. Instead of optimizing the shape that realizes a specific gate, the optimization target can be extended to the full set of PE. This increases the flexibility of optimization and allows to find the best PE from the set of all PE. For unitary dynamics, the PE optimization functional can readily be evaluated. In contrast, for non-unitary dynamics, one has to approximate the unitary part of the dynamics first. We employ this technique to superconducting qubits, where we apply a cross-resonant drive to two coupled fixed-frequency transmons to generate entangled states.

P21 | **Matthias Krauss** (Free University of Berlin) (poster)
Parameter Optimization of Transmon Arrays and Crosstalk Mitigation
Superconducting qubits are the basis for numerous modern quantum computing platforms, for which crosstalk presents a significant source of noise. Crosstalk is an undesired side effect of quantum gates that leads to corruption of the multi-qubit quantum state. We utilize optimal control to mitigate the effects of crosstalk between transmon qubits coupled to a central bus. The focus is on the physical interpretation of the results to gain insights into the mechanism used by the optimization algorithm. Identifying such control strategies often allows for easy amendments to existing protocols, leading to experimentally feasible pulses. Further, we apply optimal control to determine optimal parameters for transmon arrays, facilitating the fastest gate implementation. In particular, we study how anharmonicities of a driven tunable bus influence the optimal system parameters and their corresponding gate times.

P22 | **Anton Halaski** (Free University of Berlin) (poster)
Quantum Feedback Control for Quantum Error Correction on Superconducting Qubits
Continuous quantum error correction (QEC) is required in many situations in which the limit of a strong projective measurement cannot be applied. We investigate how to realize a recent proposal for a continuous QEC protocol by Atalaya et al. [Phys. Rev. A 103, 042406 (2021)] in current circuit QED architecture. This scheme relies on a sufficiently strong and continuous two-qubit parity measurement to extract the error syndromes. However, recent proposals for continuous parity measurements in this field rely on the so-called dispersive regime in which the qubits and the meter are only weakly coupled and the measurement is slow. We explore how one can achieve speedups by going to the quasi-dispersive regime. Measurements based on the quasi-dispersive regime could then be utilized to enhance the resilience of Atalaya et al.'s and future QEC protocols.

P23 | **Roberto Sailer** (University of Ulm) (poster)
Implementing control optimization strategy for decoherence protected quantum register in diamond
Future quantum technology applications will essentially benefit from the applications of optimal control theory in room-temperature decoherence-protected quantum registers. Our recent work provides a ready-to-implement and experimentally realistic recipe of rapid transform optimization strategy for improving the performance of a such quantum register based on a decoherence-free subspace electron-nuclear spin system in diamond [J. Tian et. al., Phys. Rev. A, 109, 022614 (2024)]. The strategy is built upon the comparison analyses performed numerically on three commonly used optimal control methods, namely GRAPE, CRAB, and Phase Modulated methods, and their experimental feasibilities implemented using a set of control devices used in typical experiments with nitrogen-vacancy centers in diamond. Here, the such experimental implementation of the optimization strategy is presented and elaborated.

P24 | **Yannick Strocka** (Humboldt University of Berlin) (poster)
Optimal Control Aspects for Cluster State Generation with Group-IV Color Centers in Diamond
The control of the spin of negatively charged Group-IV color centers in diamond plays an important role in various applications such as quantum repeaters and measurement-based quantum computing. The latter relies

on single qubit measurements of large multipartite entangled states, so-called cluster states. An emission based cluster state generation protocol requires fast high fidelity control of the spin qubit, which is formed by the two lowest lying energy eigenstates of the system. Here we theoretically analyze a Raman control scheme, involving two laser pulses with two destinct central frequencies. The Raman pulses implement a spin gate. Optical pulses allow the control over a larger range of ground state splittings compared to microwave control. In a closed system perfect gates are in theory possible. Phononic decay of the involved levels, however, greatly impacts the gate fidelity. In this work we use global optimization strategies to reduce the phononic impact on fidelities.

P25 | **Monika Leibscher** (Free University of Berlin) (poster)
A graph-theoretical approach to analyze controllability of driven quantum systems
Analyzing controllability of driven quantum systems is an important prerequisite to control the dynamics of the system with external fields. Multiple transitions with the same energy gap – which are ubiquitous e.g. in atomic systems, quantum rotors and in coupled qubit systems - pose a challenge to controllability analysis. We present a graphical method that is suitable to analyze controllability in systems with multiple resonant transitions [1-3] and demonstrate its applications to driven quantum rotors [1,2] as well as to qubit systems [3].
Refs:
[1] Leibscher, Pozzoli, Pérez, Schnell, Sigalotti, Boscain, Koch, Commun. Phys. 5, 110 (2022).
[2] Pozzoli, Leibscher, Sigalotti, Boscain Koch, J. Phys. A 55, 215301 (2022).
[3] Gago-Encinas, Leibscher, Koch, Quantum Sci. Technol. 8 045002 (2023)

P26 | **Mohammad Abedi** (Forschungszentrum Jülich) (poster)
Reinforcement learning entangling operations for spin qubits
Traditional methods of optimising control pulses rely on the ability to compute gradients of a model of the system dynamics. We investigate reinforcement learning (RL) is a model-free alternative, which optimises entangling operations directly from experience by interacting with a quantum dot spin qubit system. While employing a detailed numerical model of the quantum chip at this point, we explore how the realistically limited observation on quantum systems can be augmented via sequential autoregressive learning with transformer models.

P27 | **Armin Römer** (Forschungszentrum Jülich) (poster)
JuMPO: A Quantum Optimal Control Library for Open System Magnetic Resonance Experiments with Arbitrary Inhomogeneities
In order to help establishing more magnetic resonance optimal control methods in applied science we present the quantum optimal control package JuMPO (Jülich Magnetic Pulse Optimization). Apart from robust broadband pulses, it enables the engineering of pattern pulses, where for each combination of resonance frequency offset and inhomogeneity a separate target state can be specified. This allows the selective targeting of specific experiment domains, e.g. in catalysis or material science, by encoding them via a suitable relationship of offset and inhomogeneity. The latter can take the form of arbitrary transfer functions. For experiments with non-negligible dissipation, JuMPO features the option to use custom dissipators and state-of-the-art open system quality functions. Appropriate penalties can guide optimizations towards experimentally implementable pulse shapes. Several experimental validations exemplify the package's functionality and versatility.

P28 | **Nicolas Wittler** (Forschungszentrum Jülich) (poster)
Co-design of quantum computing devices with optimal control
We use optimal control tools to derive the gates required by a toy two-qubit algorithm consisting of simultaneous single-qubit gates followed by an entangling gate and, in tandem, explore the model space of superconducting quantum computer design, from dispersively coupled to strongly interacting qubits, to maximize gate fidelity. The use of perfect entangler theory provides a flexibility to the search for a general two-qubit gate on a given platform and enables a comparison between designs with different entangling mechanisms, e.g. CPHASE and root-iSWAP.

P29 | **Dirk Heimann** (University of Bremen) (poster)
Synthesizing optimal pulse sequences with an iterative linear quadratic regulator (iLQR) for IBM superconducting qubits
The control of gate operations using microwave pulses is a challenging task and a key aspect of enabling high-quality quantum systems. We utilize iLQR to find optimal pulse sequences in simulation by modeling a single transmon with 3 levels to account for leakage. For the optimization we use the analytic solution for the exponential map of SU(3) to calculate the dynamics following the Schrödinger equation. Our 32ns pulses for SX and X gates do not have Gaussian envelops like DRAG pulses, but still the optimizer finds solutions

where the second quadrature control is inversely proportional to the derivative of the first. We validate our experiments on the zero qubit of the ibm_osaka system and obtain state fidelities of 0.9989 for SX, and 0.9672 for X, after applying the gate once. As a next step, we plan to use the analytic derivatives of the exponential function, evaluate our gate's quality with randomized benchmarking, and extend our approach to two qubit gates.

P30 | **Alexander Simm** (Forschungszentrum Jülich) (poster)
Control of analog qubit-resonator gates in the strong coupling regime
Electron-phonon interaction is a fundamental process in condensed-matter physics, responsible for a variety of phenomena ranging from polaron formation in semiconductors and molecules to charge-density waves and superconductivity. In a quantum simulation on a superconducting chip, the building block to realize these couplings is given by the quantum Rabi model. From a control perspective, it is natural to operate in the rotating-wave approximated (Jaynes-Cummings) regime to keep qubit and resonator isolated when parked off-resonance. However, the approximation breaks down in the ultrastrong-coupling regime which recently has been realised experimentally. We simulate the analog (not approximated) gate under strong coupling and show that it can be realised for realistic device parameters without too much leakage.

P31 | **Martino Calzavara** (Forschungszentrum Jülich) (poster)
Quantum control landscapes of piecewise-constant pulses
Since the introduction of the GRAPE algorithm for the efficient computation of fidelity gradients, piecewise-constant controls have become a widely adopted ansatz for studying Quantum Optimal Control problems. The time evolution for this class of time-dependent Hamiltonians can be represented through a parametrized quantum circuit, allowing us to analyze the properties of fidelity as a function of the control pulses - the so-called control landscape - by employing concepts and techniques from the field of Quantum Machine Learning. Among these techniques, Fourier spectrum analysis has proven valuable in gaining insights into the representational power of these quantum circuits. In this study, we present a Fourier representation of GRAPE landscapes that enables us to numerically and analytically investigate relevant landscape properties. Notably, these properties are found to depend on a non-dimensional parameter that expresses the time-energy budget of the time evolution.

P32 | **Luke Visser** (Eindhoven University of Technology) (poster)
Simulating the stochastic Schrödinger equation with semi-martingale noise
Quantum computers are controlled by control systems that experience classical noise. In simulations and theory, this noise is often approximated by white noise or Ornstein-Uhlenbeck noise. However, the physical control mechanisms often experience noise with less favourable properties. For this poster, we look at how to simulate the evolution of quantum states under arbitrary semi-martingale noise. We do this by sampling from a power spectral density, which fully characterizes the noise. The end result is incorporated into the stochastic Schrödinger equation. With this method, we can fully simulate the loss of qubit fidelity due to noisy hardware. We also remark that this method is very similar to how one would derive the Lindblad equation from a system coupled to a heatbath.

P33 | **Maurice Beringuier** (Max Planck Institute for Nuclear Physics) (poster)
Measuring and predicting the performance of atomic-scale systems as quantum classifiers
Quantum machine learning (QML) is an exciting new field that investigates if quantum-mechanical systems, usually parametrized unitary gates acting on qubits, can be used for machine learning tasks. But quantum computers are expensive and scarce. An alternative proposed recently [arxiv:2303.12231] is to use the quantum dynamics of atomic systems interacting with shaped laser pulses to construct ultrafast quantum classifiers. Data and trainable weights can be encoded in the amplitudes and phases of the laser, the output of the model is given by observables in the final state of the atom. We investigate different optimization strategies to train the system and the influence of the parameters of the atomic system and the laser pulses on its ability to learn complicated maps on large input spaces by finding quantitative measures for this ability. Candidates for such measures are geometric quantities, e.g. the change in length of paths in input space after being propagated through the model.

P34 | **Tangyou Huang** (Chalmers University of Technology) (poster)
High-fidelity superconducting two-qubit gate with optimal control
The fidelity of qubit gates plays a pivotal role in quantum computing applications. In this context, we focus on optimizing the fidelity of superconducting two-qubit gates by employing quantum optimal control techniques. Our approach involves closed-loop optimization, wherein we utilize a classical optimizer in conjunction with experimental instrumentation to sequentially improve gate fidelity by adjusting the pulse envelope. Notably, we

employ gradient-based methods to prevent poor convergence, thus improving the efficiency of the optimization process. Instead of relying on standard quantum state tomography, our method acquires gradient information through floquet calibration, resulting in a reduced experimental burden. As a result, we successfully establish CZ/iSWAP operations with gate fidelity exceeding 99.5% in superconducting parametric gates. Our study is anticipated to facilitate experimental implementation with significantly reduced measurement and data burdens.

P35 | **Kapil Goswami** (Zentrum für Optische Quantentechnologien, University of Hamburg) (poster)
Solving optimization problems on quantum systems.
Solving industry-related optimization problems classically is challenging as they are NP-hard. Exploring resource-efficient encoding schemes for such problems in NISQ era can lead to practical quantum advantage. These problems are typically formulated either as a quadratic unconstrained binary optimization (QUBO) or integer programming (IP). Our first work provides a framework to solve QUBO problems such as Max-Cut and MIS by using locally controlled light shifts on Rydberg atoms platform. We establish a one-to-one mapping from the graph problems (MIS/Max-Cut) to a many-body interacting setup, providing a more favorable scaling of qubits with problem size compared to existing schemes. In our second work, an algorithm is introduced that directly solves an IP problem using multi-levels of a single atom and selectively transfer the population between the energy manifolds to find the optimal solution. Both of the quantum algorithms utilize quantum optimal control to reach the solution.

P36 | **Aviv Aroch** (Hebrew University of Jerusalem) (poster)
Mitigating controller noise in quantum gates using optimal control theory
All quantum systems are subject to noise from the environment or external controls. This noise is a major obstacle to the realization of quantum technology. For example, noise limits the fidelity of quantum gates. Employing optimal control theory, we study the generation of quantum single and two-qubit gates. Specifically, we explore a Markovian model of phase and amplitude noise, leading to the degradation of gate fidelity. We show that optimal control with such noise models generates control solutions to mitigate the loss of gate fidelity. The problem is formulated in Liouville space, employing a highly accurate numerical solver and the Krotov algorithm to solve optimal control equations.

May 22 (Wednesday)

Session 4

9:00 – 9:45 | **Daniel Egger** (IBM Quantum, Zürich) (invited talk)
Scaling quantum computing with dynamic circuits
Current quantum hardware is noisy, can only store information for a short time, and is limited to a few qubits, typically arranged in a planar connectivity. However, many applications of quantum computing require more connectivity than the planar lattice offered by the hardware on more qubits than is available on a single QPU. We overcome these limitations with error mitigated dynamic circuits and circuit-cutting to create quantum states with a periodic connectivity employing up to 142 qubits spanning multiple QPUs connected in real-time with a classical link. In a dynamic circuit, quantum gates can be classically controlled by the outcomes of mid-circuit measurements within a fraction of the coherence time of the qubits. Our real-time classical link allows us to apply a quantum gate on one QPU conditioned on the outcome of a measurement on another QPU. This error mitigated control-flow enhances qubit connectivity, enables a modular scaling, and broadens the QPU's instruction set.

9:45 – 10:30 | **Michael Goerz** (United States Army Research Lab) (invited talk)
Modernizing the Quantum Control Stack with the QuantumControl.jl Framework
In recent years, there have been considerable advances in scientific computing that open new opportunities for the efficient numerical simulation of quantum systems and for optimal control. These include tools developed in the context of machine learning, like automatic differentiation or the use of GPUs. A new software framework, QuantumControl.jl, exploits the unique capabilities of the Julia language to incorporate these modern techniques while maintaining the highest numerical performance. I will discuss the conceptual advances realized in the framework, including a newly developed method of semi-automatic differentiation that allows to efficiently evaluate gradients for any computable functional without the usual prohibitive memory footprint associated with automatic differentiation. I will also discuss how these concepts support the solution of optimal control problems in quantum information and quantum metrology.

Session 5

11:00 – 11:20 | **Thomas Schulte-Herbrüggen** (Technical University of Munich) (contributed talk)
Symmetry Decides Observability in Quantum Dynamics
Among the questions arising in quantum engineering there is a practical yet fundamental one: given a controlled quantum dynamical system, for which observables (or more generally POVMs) can measurements give full information for system identification? In finite-dimensional closed systems, a unified (Lie) frame of quantum systems theory settles this observability problem—-as will be illustrated in paradigmatic n-qubit systems. Implications and generalisations will be outlined as well.

11:20 – 11:40 | **Eugenio Pozzoli** (University of Rennes) (contributed talk)
Time-zero controllability and Lie algebraic properties of infinite-dimensional closed quantum systems
What is the minimum time required to control a closed quantum system? Since the seminal works of Khaneja, Brockett, and Glaser on the time-optimal control of spin systems, Lie algebraic properties of the dynamical generators have proved to be useful tools for deriving explicit time-optimal control strategies, such as the pulse-drift-pulse strategy used for creating unitary gates in minimal time. In some cases, the min time can be pushed to zero. For finite-dimensional quantum systems, this fact is well understood in Lie algebraic terms. In this talk, I will report on recent developments in infinite dimension. This setting includes paradigmatic examples such as harmonic oscillators and rotors. In infinite dimension, new Lie algebraic properties furnish explicit time-zero control strategies, mysteriously similar to the pulse-drift-pulse strategy. In particular, I will present the first example of a time-zero globally controllable bilinear Schrödinger PDE.

11:40 – 12:25 | **Alfio Borzì** (University of Würzburg) (invited talk)
The Pontryagin Maximum Principle for Solving Quantum Optimal Control Problems with Sparsity Promoting Cost Functionals
This talk is devoted to the analysis and numerical solution of non-smooth quantum optimal control problems with continuous and discontinuous control costs that promote sparsity. Sparse optimal controls can be conveniently produced by laboratory pulse shapers. A representative class of these control problems is analysed in the framework of the Pontryagin maximum principle (PMP) and a PMP-based numerical optimisation scheme, called the SQH method, is presented and investigated. Results of numerical experiments with a quantum spin system are presented that demonstrate the effectiveness of the SQH method and for comparison with a semi-smooth Newton method. Joint works with T. Breitenbach and G. Ciaramella.
Refs:
T. Breitenbach and A. Borzì, J. Comput. Appl. Math., 369 (2020) 112583.
G. Ciaramella and A. Borzì, Num. Funct. Anal. Optim., 37 (2016), 938-965.

Session 6

16:30 – 16:50 | **N. Anders Petersson** (Lawrence Livermore National Laboratory) (contributed talk)
Mitigating scaling barriers through time-parallel multiple shooting method
Significant progress has been made in the development of numerical methods and computational tools to optimally design control pulses for small quantum systems. However, current methods face the challenge of scalability barriers due to rapidly increasing computational costs, as well as more complicated optimization landscapes, when applied to larger quantum systems. In recent efforts, we have improved the scalability of quantum optimal control by employing a time-parallel multiple-shooting optimization algorithm. Here, intermediate quantum states are introduced as additional optimization variables while continuity of the state evolution is enforced through equality constraints. This allows the time-evolution to be decoupled into multiple time windows that can be evolved independently, and concurrently in time, using many compute cores. Since the state evolution only becomes continuous upon convergence, the approach potentially allows for shortcuts through the optimization landscape.

16:50 – 17:10 | **Reinhold Schneider** (Technical University of Berlin) (contributed talk)
Compositional Tensor Networks
We consider deep networks built by the composition of function tensor networks with tree structure (HT/TT), but focusing function tensor trains. Compositional sparsity, coined by W. Dahmen, has been inspired by Deep Neural Networks. The individual neural network layers are replaced by tree-based tensor networks (HT/TT). The key is that we use the composition of non-linear functions as a numerical tool for approximation building deep tensor networks. As a particular example we consider flow-driven deep tensor networks and its relation to

optimal control, optimal transport and variational mean filed games. By a variational Monte Carlo approach we derive an optimization procedure for the computation (training) of the tensors.

17:10 – 17:55 | **Ugo Boscain** (CNRS, LJLL, Sorbonne Université, Inria Paris) (invited talk)
Ensemble controllability for n-level quantum systems
A two level quantum system driven by one external field is usually controlled by using chirped pulses that are obtained using the rotating wave approximation and the adiabatic approximation "in cascade". This is done in particular when the resonance frequency is not known precisely (hence when results of ensemble controllability are needed). Unfortunately, the two approximations (which both need a long time) cannot be done independently since the two time scales interact. We study how the cascade of the two approximations can be justified, while preserving the robustness of the adiabatic strategy. We also quantify the uncertainty interval of the resonance frequency for which the population inversion works. As a by-product, we prove controllability of an ensemble of spin systems by a single real-valued control, providing an extension of a celebrated result with two controls by Khaneja, Li, Beauchard, Coron, Rouchon. Extensions to n-level systems are provided.

May 23 (Thursday)

Session 7

9:00 – 9:45 | **Tommaso Calarco** (Forschungszentrum Jülich) (invited talk)
Quantum firmware: optimal control for quantum computers and quantum simulators
Quantum optimal control is well known to improve the performance of quantum technology devices up to their limits in terms e.g. of system size and speed of operation. This talk will present our recent results with a variety of quantum technology platforms, focusing in particular on ultracold atoms, and introduce our newly developed software for automatic calibration of quantum operations - the fundamental building block of next-generation quantum firmware.

9:45 – 10:30 | **Ilya Kuprov** (University of Southampton) (invited talk)
Simulation and design of shaped pulses beyond the piecewise-constant approximation
Response functions of resonant circuits create ringing artefacts if their input changes rapidly. When physical limits of electromagnetic spectroscopies are explored, this creates two types of problems. Firstly, simulation: the system must be propagated accurately through every response transient, this may be computationally expensive. Secondly, optimal control: circuit response must be taken into account, it may be advantageous to design pulses that are resilient to such distortions. At the root of both problems is the popular piecewise-constant approximation for control sequences in the rotating frame. In magnetic resonance it has persisted since the earliest days and has become entrenched in the commercially available hardware. In this paper, we report an implementation and benchmarks of recent Lie-group methods that can efficiently simulate and optimise smooth control sequences.

Session 8

11:00 – 11:20 | **Dominique Sugny** (Laboratoire Interdisciplinaire Carnot de Bourgogne) (contributed talk)
Quantum optimal control of a Bose-Einstein Condensate in an optical lattice
We apply innovative tools coming from quantum optimal control theory to improve theoretical and experimental techniques in quantum technologies. This approach allows us to explore and to experimentally reach the physical limits of the corresponding dynamics in the presence of typical experimental imperfections and limitations. After an introduction to these techniques, different applications to the control of a Bose Einstein Condensate in an optical lattice are presented. The experimental implementation of optimal control protocols is described, both for two-level and many-level cases, with the current constraints and limitations of such platforms.

11:20 – 11:40 | **Eloisa Cuestas** (Forschungszentrum Jülich) (contributed talk)
A quantum engine in the BEC-BCS crossover
We present a new class of many-body quantum engine that we termed Pauli engine. Our engine exploits genuine nonclassical forms of energy different from heat that have not been used until now for work production in cyclic engines. In the Pauli engine the energy input is not related to the temperature of an external bath, instead, our machine is fueled by the energy associated with the change of the statistical behavior of the

working medium from bosonic to fermionic and back. This mechanism is of purely quantum origin and has no equivalent in the classical regime. We experimentally realized the Pauli cycle by driving a trapped ultracold two-component Fermi gas of 6Li atoms between a Bose-Einstein condensate of bosonic molecules and a unitary Fermi gas. Such experiments result in an efficiency of up to 25%. Our findings establish quantum statistics as a useful thermodynamic resource for work production in a new class of emergent quantum engines.

11:40 – 12:25 | **Carrie Weidner** (Quantum Engineering Technology Laboratories, Bristol) (invited talk)
Controlling ultracold atoms in optical lattices: theory and practice (but mostly practice)
Quantum optimal control is a fantastic means of manipulating quantum systems for the purposes of quantum technology. In this realm, my specific interests for the past decade have centered around the (largely experimental) quantum control of very cold atoms in the sinusoidal potentials offered by optical lattice potentials. This talk will thus overview how one can use these systems to implement various forms of quantum technologies, e.g., sensing, simulation, information, networking, then providing an experimentalist's insight into how we approach the quantum optimal control of interesting systems. This will also highlight the various limitations that we must keep in mind during the design, simulation, and ultimate experimental manifestation of these systems.

Session 9

16:30 – 16:50 | **Fernando Gago Encinas** (Free University of Berlin) (contributed talk)
Testing systems for universal quantum computing: a controllability test using parametric quantum circuits
Universal quantum computing requires a quantum system that is operator-controllable. However, the number of resources required for controllability in complex systems is not obvious. Assessing this property on the systems themselves is also a difficult task to achieve in practice. Here we present a hybrid quantum-classical algorithm, uniting quantum measurements and classical calculations. The key to our approach is the design of a parametrized quantum circuit (PQC), which can be run on the original system with some auxiliary qubits. By applying dimensional expressivity analysis we are able to count the number of independent parameters in the PQC. This represents the dimensional expressivity of the PQC, which is then traced back to the controllability of the initial system. This connection between controllability and PQCs opens a new route to use quantum algorithms to explore other properties of the system, e.g. the quantum speed limit or the controllability of some subsystems.

16:50 – 17:10 | **David Edward Bruschi** (Forschunsgzentrum Jülich) (contributed talk)
Towards exact factorization of quantum dynamics via Lie algebras
Determining exactly the dynamics of a physical system is the paramount goal of any branch of physics. Quantum dynamics are characterized by the non-commutativity of operators, which implies that the dynamics usually can rarely be tackled analytically. A priori knowledge on the ability to obtain exact results would be of great advantage for many tasks of modern interest, such as quantum computing and quantum control. We initiate an approach to determine the dimensionality of a Hamiltonian Lie algebra by characterizing its generators. This requires us to develop a new tool to construct sequences of operators that determine the dimension of the algebra itself. Our work is exact and fully general, therefore providing statements on the ultimate ability to exactly control the dynamics or simulate specific classes of physical systems. This work has important implications for theoretical physics, and it aids our understanding of the structure of the Hilbert space, as well as Lie algebras.

17:10 – 17:30 | **Francesco Petiziol** (Technical University of Berlin) (contributed talk)
Optimized Floquet engineering of many-body interactions
We present a scheme for the accurate quantum simulation of Hamiltonians featuring many-spin interactions beyond pairwise coupling, with the example of Kitaev's toric code. The hybrid continuous-digital approach developed, combined with numerical optimization, achieves strong effective three- and four-spin interactions in a nonperturbative way. We further design an optimal protocol to prepare topologically ordered ground states with high fidelity. Our scheme finds a natural implementation in lattices of superconducting qubits where individual control and tuneable couplings are accessible.

May 24 (Friday)

Session 10

9:00 – 9:45 | **Christian Arenz** (Arizona State University) (invited talk)
Approximating Riemannian gradient flows on quantum computers for ground state problems
Adaptive quantum algorithms have been proposed to overcome challenges of existing hybrid quantum-classical algorithms related to ansatz selection and the optimization landscape structure. Instead of fixing an ansatz, in these approaches a quantum circuit is successively grown informed by measurement data. In this talk, I describe adaptive quantum algorithms as approximations of Riemannian gradient flows on the unitary group, an optimization framework where one directly optimizes over quantum circuits rather than gate or control pulse parameters. I show that despite the existence of saddle points, the full gradient flow converges to the ground state for almost all initial states. While the full gradient flow is in general not efficiently implementable on quantum devices, I go on to discuss several approximation schemes that exhibit similar convergence behavior but require only a polynomial overhead when it comes to device implementations.

9:45 – 10:30 | **Anja Metelmann** (Karlsruhe Institute of Technology) (invited talk)
High-Purity Entanglement of Hot Propagating Modes Using Nonreciprocity
Distributed quantum information processing and communication protocols demand the ability to generate entanglement among propagating modes. However, thermal fluctuations can severely limit the fidelity and purity of propagating entangled states, especially for low-frequency modes relevant for radio-frequency (RF) signals. We propose nonreciprocity as a resource here to render continuous-variable entanglement of propagating modes robust against thermal fluctuations. By utilising a cold-engineered reservoir we break the symmetry of reciprocity in a standard two-mode squeezing interaction between a low- and a high-frequency mode, and show that the rerouting of thermal fluctuations allows the generation of flying entangled states with high purity. Our approach requires only pairwise Gaussian interactions and is thus ideal for parametric circuit QED implementations.

Session 11

11:00 – 11:20 | **Dionisis Stefanatos** (University of Patras) (contributed talk)
Fast charging of an Ising spin pair quantum battery using optimal control
We consider the problem of fast charging a quantum battery composed of a pair of spins with Ising coupling, from the initial spin down state to the target spin up state, using transverse field control with bounded amplitude. Using optimal control theory we show that, although a single bang pulse can quickly achieve considerable charging levels for relatively large maximum control amplitude, complete charging is accomplished in minimum time by a bang-singular-bang pulse-sequence, where the intermediate singular pulse is an off pulse. If the control is restricted between zero and a maximum amplitude, the initial and final bang pulses attain the maximum value, while if it is restricted between symmetric negative and positive boundaries, the bang pulses have the same duration but opposite boundary values. For both cases we provide transcendental equations from which the durations of the individual pulses in the optimal pulse-sequence can be calculated.

11:20 – 11:40 | **Anthony Kiely** (University College Dublin) (contributed talk)
Universally Robust Quantum Control
We study the robustness of the evolution of a quantum system against small uncontrolled variations in parameters in the Hamiltonian. We show that the fidelity susceptibility, which quantifies the perturbative error to leading order, can be expressed in superoperator form and use this to derive control pulses which are robust to any class of systematic unknown errors. The proposed optimal control protocol is equivalent to searching for a sequence of unitaries that mimics the first-order moments of the Haar distribution, i.e. it constitutes a 1-design. We highlight the power of our results for error resistant single- and two-qubit gates.

11:40 – 12:25 | **Sophie Shermer** (Swansea University) (invited talk)
Robust Quantum Control
The talk will cover what robust control is and why we need it, a brief overview of classical robust control and why it is not applicable to most quantum control problems, tools available to assess robustness in quantum control — from statistical measures such Wasserstein distance to bounds based on differential sensitivity measures, as well as their limitations and obstacles to developing a general theory of robust quantum control.