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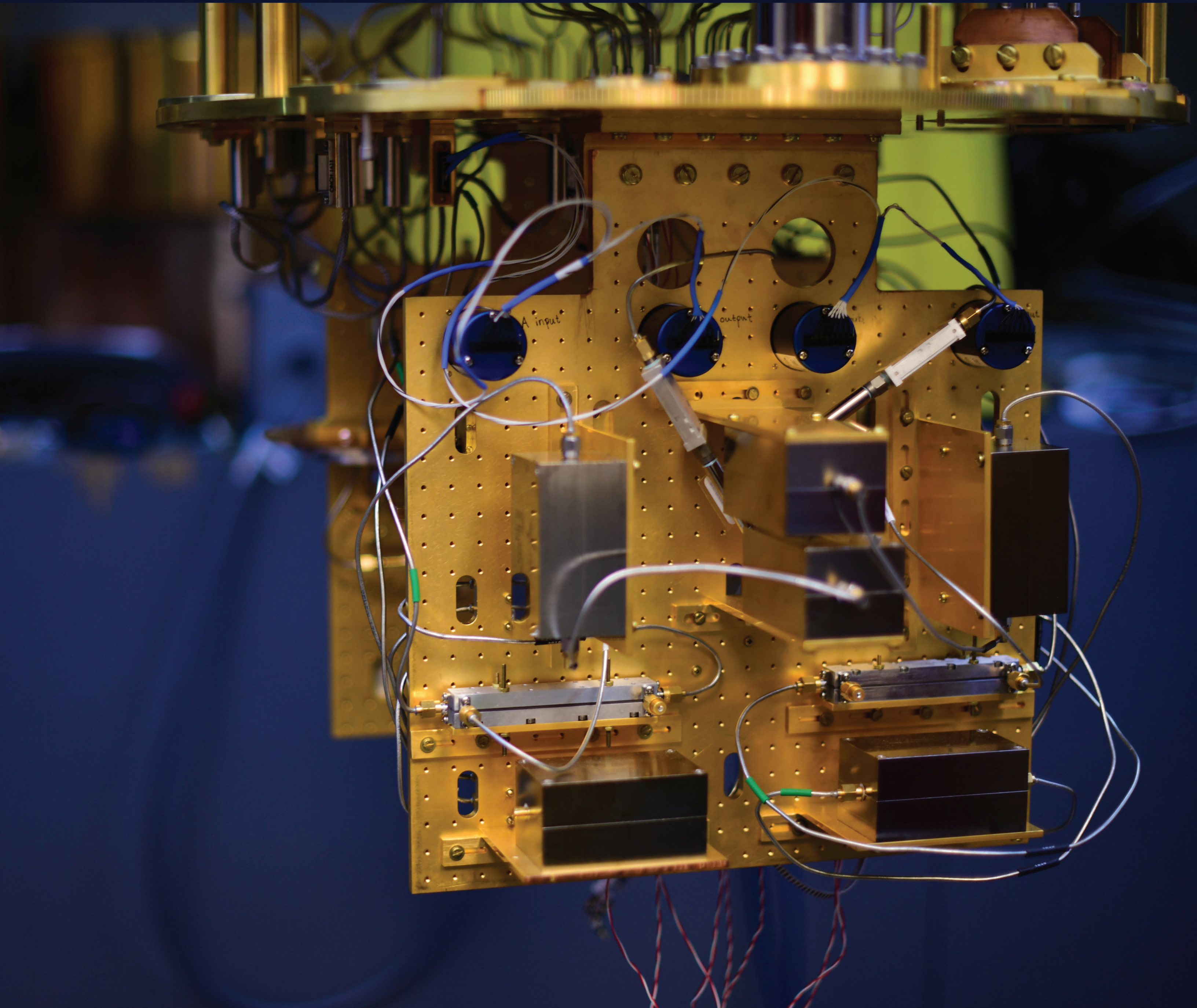
Proceedings



S1.01 Generalized flux qubit arrays as low-anharmonicity analogue quantum simulators

Ilan T. Rosen, Kasper Poulsen, Sarah Muschinske, William D. Oliver

Sponsorship: IC Postdoctoral Fellowship

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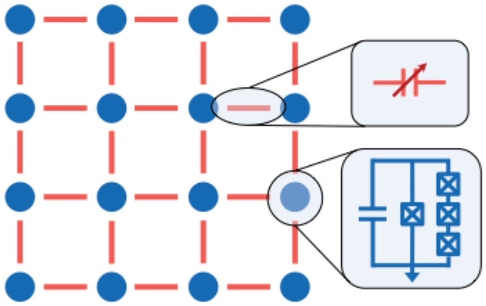
Interest in analogue quantum simulation with superconducting qubit arrays is flourishing due to their native realization of the Bose-Hubbard Hamiltonian, their wide range of accessible energy scales, and their capability for full- or partial-state tomographic measurement. Yet the large anharmonicity of conventional qubits restricts qubit array simulators from exploring weak-interaction physics. Generalized flux qubits (GFQs) offer similar coherence, control, and measurement characteristics as conventional qubits, but also feature tunable anharmonicity. Here, we propose arrays of superconducting generalized flux qubits (GFQs) as analogue quantum simulators of weakly interacting physics. We discuss how device-fabrication-based uncertainty constrains the disorder-to-self-energy and disorder-to-anharmonicity ratios in realistic GFQ arrays. We then numerically study condensed matter benchmark models, highlighting the regimes accessible with realistic GFQ array simulators.



S1.02 Coherent control of large superconducting quantum systems

M. S. Moreira, A. Greene, Y. Sung, Q. Ding, S. Muschinske, A. H. Karamlou, I. Rosen, J. Grover, W. D. Oliver

Sponsorship: Laboratory for Physical Sciences, Defense Advanced Research Projects Agency (DARPA), Intelligence Advanced Research Projects Activity (IARPA)

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Superconducting-qubit systems are a promising platform for the implementation of error-corrected, fault-tolerant quantum computers, for which the surface code is a prominent approach. However, such systems have suffered from a number of known error sources that threaten to compromise our ability to improve its logical performance by increasing the code size. In particular, major error sources were individuated to leakage, stray interactions, and crosstalk [1].

Focusing on problems arising from the need to scale large arrays of superconducting qubits while ensuring their coherent control, we propose methods to characterize and mitigate these three classes of errors, through the development of improved 2-qubit gate schemes and the optimization of package and lattice design parameters. Furthermore, we propose various methods for the enhancement of electronic, mechanical, and cryogenic infrastructure, required to further scale planar lattice designs.

[1] Google Quantum AI Team. “Suppressing Quantum Errors by Scaling a Surface Code Logical Qubit.”, 20 July 2022, e-Print: 2207.06431.

S1.03 A compact, coplanar architecture for fast readout of superconducting qubits using intrinsic Purcell filters

David Pahl, Patrick Harrington,, William D. Oliver

Sponsorship:

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Reading out a qubit by dispersively coupling it to a resonator is a central ingredient in almost all circuit quantum electrodynamics (QED) experiments. The induced resonator-mediated decay rate of the qubit is often suppressed by adding Purcell filters. Alternatively, recent experiments have achieved state-of-the-art readout speeds and fidelities simply by coupling the feedline to a 3D readout resonator close to the node of the dressed qubit mode. In contrast to previous work, we plan to realize this “intrinsic Purcell filter” using flux-tunable qubits in a coplanar and, therefore, more scalable architecture. Using flux tuning, we demonstrate the ability to optimally align the dressed qubit mode with the external coupling. This experiment showcases an alternative to current readout architectures, with smaller footprints and similar performance. This is especially interesting for quantum error correction experiments where readout speed is critical, but space is at a premium due to the density of qubit arrays.

S1.04 High-fidelity two-qubit gates using closed-loop feedback

Lukas Pahl, Jeffrey Grover, William D. Oliver

Sponsorship: MURI

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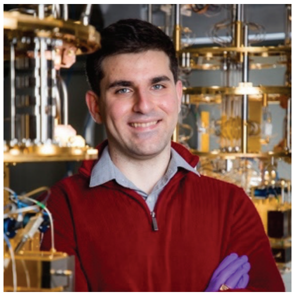
High-fidelity two-qubit gates are an essential resource for quantum information processors. In many cases, two-qubit gate fidelities are limited by the coherence times of qubits. Here, we experimentally apply closed-loop feedback to stabilize
the frequency fluctuations of different elements in a two-qubit gate. Specifically,
the architecture consists of a fixed-frequency and a flux-tunable qubit whose interactions are mediated by a tunable coupler. The T1-coherence time of the flux tunable qubit is optimized by operating away from the qubit flux-noise insensitive point while maintaining high T2-coherence due to closed-loop feedback. The coupler frequency is stabilized while the coupler is idling, which is crucial for the modulated flux pulse to drive the coupler correctly in and out of resonance with the qubits. Both strategies improve the gate fidelities of the two-qubit gate architecture, which have been previously measured to be around 99.8% on the same device. This work demonstrates how advanced control techniques can improve the fidelities of two-qubit interactions, a crucial ingredient for quantum simulation and gate-model quantum computation.

S1.05 Many-body quantum simulation using superconducting qubits



Amir H. Karamlou, Yariv Yanay, Agustin Di Paola, Cora Barrett, Ilan Rosen, Sarah Muschinske, Patrick Harrington, David K. Kim, Alexander Melville, Bethany M. Niedzielski, Jonilyn L. Yoder, Mollie E. Schwartz, Jeffrey Grover, Simon Gustavsson, William D. Oliver

Sponsorship: This research was funded in part by the National Science Foundation under grants PHY-1720311 and 1839197; and by the Under Secretary of Defense for Research and Engineering under Air Force Contract No. FA8702-15-D-0001.

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Four decades ago, quantum simulation was proposed as the first application for a quantum computer. Superconducting quantum processors hold great potential for simulating many-body quantum systems. However, experimental studies of such systems are challenging due to stringent coherence requirements and limitations in experimental control. In this work, we will discuss our work in controlling and calibrating a processor consisting of many qubits, and present our results on probing the dynamics and entanglement properties of many-body quantum systems.

S1.06 Optimizing quarton-based high-speed readout in the presence of noise

Jeremy Kline, Yufeng Ye, Alec Yen, Andres Lombo, Kevin P. O'Brien

Sponsorship: Alan L. McWhorter (1955) Fund Fellowship

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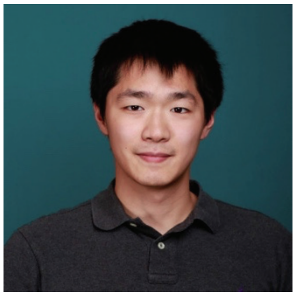
Superconducting circuits remain one of the most promising quantum computing platforms. In these devices, nonlinear coupling (used for two-qubit gates and qubit readout) is often obtained by a linear coupling between a qubit and far-detuned resonator. However, this mixes the qubit and resonator modes and only results in a weak nonlinear coupling, motivating a recent proposal to use a quarton as a purely nonlinear coupling element. The quantitative effects of common superconducting circuit noise sources on this scheme are unknown. Flux noise could result in spurious linear coupling and T1 loss in the transmon qubits, while the large (nonlinear) inductance of the quarton may reduce sensitivity to charge noise (allowing higher anharmonicity transmons). We consider the use of a quarton for high-speed readout and quantify the impact of common noise sources, analyzing tradeoffs between qubit coherence, measurement time, and readout fidelity. These results will inform the design of future quarton-based devices, which could enable faster two-qubit gates and readout.



S1.07 An Architecture for Robust, High-Fidelity Two-Qubit Fluxonium Gates with a Transmon Coupler

Leon Ding, Max Hays, Youngkyu Sung, Bharath Kannan, Junyoung An, Agustin Di Paolo, Thomas Hazard, Kate Azar, Bethany M. Niedzielski, Alexander Melville, Mollie E. Schwartz, Jonilyn L. Yoder, Devin Underwood, Terry P. Orlando, Simon Gustavsson, Jeffrey A. Grover, Kyle Serniak, William D. Oliver

Sponsorship: This research was funded in part by the U.S. Army Research Office Grant No. W911NF-14-1-0682, by the Assistant Secretary of Defense for Research \& Engineering under Air Force Contract No. FA8721-05-C-0002. L.D. gratefully acknowledges support from the IBM PhD Fellowship, M.H. gratefully acknowledges support from the IC Postdoctoral Research Fellowship, and Y.S. gratefully acknowledges support from the Korea Foundation for Advances Studies. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the U.S. Government.

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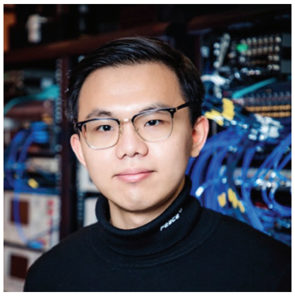
Qubit lifetimes and weak anharmonicities in superconducting transmon-based quantum computers are leading causes of gate infidelity. The fluxonium qubit is a promising alternative to transmons, with coherence times reaching milliseconds and anharmonicities of several gigahertz. In this work, we present an architecture consisting of fluxonium qubits coupled via a tunable-transmon coupler (FTF, for fluxonium-transmon-fluxonium). FTF provides two very important benefits: (1) it allows for stronger couplings for non-computational state gates, and (2) suppresses the static ZZ down the kHz levels without requiring strict parameter matching. This ZZ describes a continual entangling rate which is an unwanted byproduct of coupling superconducting qubits, and must be mitigated in multi-qubit systems. We take advantage of these strong couplings by performing a microwave-activated CZ gate, achieving high-fidelities with clear paths forward toward 99.9%. Furthermore, the frequency at which the gate is driven can be tuned over a large range, corresponding to the coupler spectrum. Altogether, we show that FTF is a promising alternative multi-qubit architecture in which both high-fidelity and robustness are simultaneously realized.



S1.08 Signal Processing Perspectives on Pulse Design for Two-Qubit Gates in Superconducting Circuits

Qi Ding, Alan V. Oppenheim, Petros T. Boufounos, Simon Gustavsson, Thomas A. Baran, William D. Oliver

Sponsorship: This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Quantum Systems Accelerator.

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Although there has been tremendous progress towards achieving low error rates with superconducting qubits, error-prone two-qubit gates remain a bottleneck in realizing large-scale quantum computers. To boost the two-qubit gate fidelity to the highest attainable levels, given limited coherence times, it is essential to develop a systematic framework for optimizing pulse design. In this talk, we formulate the problem of pulse design for two-qubit gates in superconducting qubits within the context of classical signal processing. We take advantage of filter design techniques, including window functions and the Parks-McClellan algorithm to approach the problem. Our research indicates that pulse classes popular in signal processing applications – the Chebyshev pulses and pulses given by the Parks-McClellan algorithm – have the potential to outperform the Slepian pulse, which is currently widely used in quantum experiments.

Abstracts

S1.09 Reducing qubit decoherence in superconducting circuits using closed-loop feedback

Kevin Kiener, Simon Gustavsson, William D. Oliver

Sponsorship: QSA award - 6945631

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Quantum computers promise to outperform classical computers in various domains such as quantum chemistry, decryption, and machine learning. Superconducting circuits are one of the most promising approaches for building such a quantum computer, and multiple companies have already demonstrated superconducting quantum chips containing more than 100 qubits. Yet, all superconducting qubits are limited in their performance by flux noise.

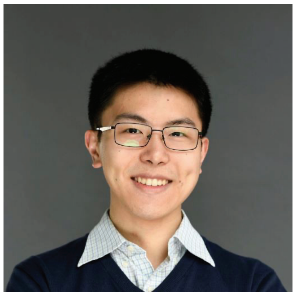
Flux noise is a decoherence mechanism present in all superconducting circuits, presumably originating from local magnetic spin impurities on the surface of the metal. The flux noise has a 1/f frequency spectrum, with dominant low-frequency components. This allows a closed-loop feedback system to be used to track and counteract the effects of the noise.

In this work, we present progress towards implementing such a noise-canceling feedback protocol on the Xilinx RF-system-on-chip (RFSoC) architecture. The RFSoC can generate and digitize waveforms up to a frequency of 7 GHz through direct digital synthesis, allowing it to be used as a cost-effective standalone system to directly control and read out superconducting qubits.

S1.10 Gradiometric quarton as a nonlinear coupler for superconducting qubits and resonators

Yufeng Ye

Sponsorship: AWS Center for Quantum Computing|MIT Center for Quantum Engineering, Laboratory for Physical Sciences (H98230-19-C-0292), IBM PhD fellowship, NSERC Postgraduate Scholarship



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Nonlinear couplings between superconducting qubits such as the cross-Kerr interaction are used for important operations including qubit readout and gates. Most nonlinear coupling schemes including the long-established dispersive shift have limited cross-Kerr strength and non-ideal interactions such as residual self-Kerr. We previously proposed quarton couplers as promising nonlinear couplers between qubits and resonators that can facilitate cross-Kerr magnitudes of the order of gigahertz.

Here, we present a device containing two transmon qubits coupled by a gradiometric quarton coupler. Through flux tuning the gradiometric quarton and transmon SQUID, we explore the potential of purely nonlinear coupling between the qubits and cancellation of qubit self-Kerr to linearize it into a resonator. We present experimental results on a device designed to operate in a parameter space that has large cross-Kerr couplings and large detuning to suppress other unwanted interactions. Large cross-Kerr between qubit and resonator is expected to enable applications including faster high fidelity qubit readout and gates.

S1.11 Bosonic quantum error correction using a bit-flip-protected control qubit

Shoumik Chowdhury*, Shantanu R. Jha*, Max Hays*, Miuko Tanaka, Agustin Di Paolo, Patrick M. Harrington, Jeff Knecht, Alexander Melville, Bethany Niedzielski, Mollie E. Schwartz, Jonilyn Yoder, Kyle Serniak, Jeffrey A. Grover, William D. Oliver

Sponsorship: This research was funded in part by the AWS Center for Quantum Computing. M. H. acknowledges funding from the IC Postdoctoral Fellowship. S. C. and S. R. J. acknowledge support from the National Science Foundation Graduate Research Fellowship under Grant No. 1745302. Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors(s) and do not necessarily reflect the views of the National Science Foundation.

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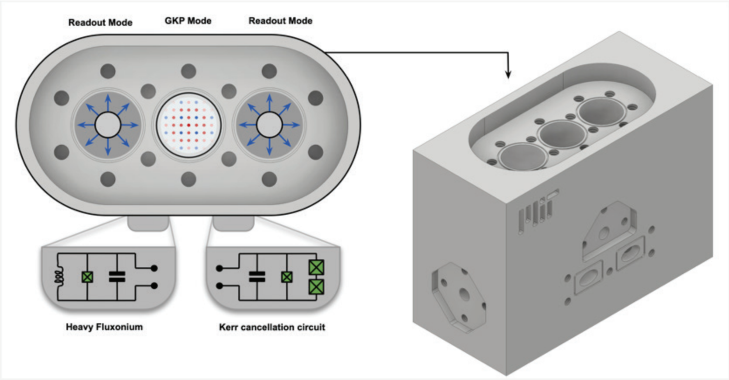
Bosonic quantum error correction (QEC) involves encoding information in the phase space of a quantum harmonic oscillator, and offers a hardware-efficient path towards fault-tolerant quantum information processing. In superconducting circuits, bosonic QEC has been demonstrated using 3D cavity resonators controlled via fixed-frequency transmon qubits. However, a major limitation in previous bosonic QEC realizations has come from bit-flip errors in the transmon control qubit, with typical T_1 lifetimes on the order of 100 microseconds. These errors propagate back onto the bosonic mode, and result in logical lifetimes that are upper-bounded by approximately ~$10T_1$. In this work, we propose replacing the transmon with a heavy-fluxonium qubit, which has recently been shown to possess T_1 lifetimes in excess of 1 millisecond. By embedding a fluxonium within a 3D cavity architecture, we can demonstrate bosonic QEC using the Gottesman-Kiteav-Preskill (GKP) encoding. Here, we report on progress towards this 3D cavity-fluxonium platform through extensive numerical simulations, device design, and initial experimental work. We also consider next steps, and propose a future design for extensible bosonic quantum error correction in 2D.



S1.12 Learning-based Calibration of Flux Crosstalk in a Transmon Qubit Array

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Cora N. Barrett, Amir H. Karamlou, Sarah E. Muschinske, Ilan T. Rosen, Alexander Melville, Bethany M. Niedzielski, Jonilyn L. Yoder, Mollie E. Schwartz, Jeffrey A. Grover, William D. Oliver

Sponsorship: C.N.B. acknowledges support from the STC Center for Integrated Quantum Materials, NSF Grant No. DMR-1231319.|This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Quantum Systems Accelerator.|This research was funded in part by the National Science Foundation under grants PHY-1720311 and 1839197; and by the Under Secretary of Defense for Research and Engineering under Air Force Contract No. FA8702-15-D-0001. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the U.S. Government.

Flux-tunable transmon qubit arrays are a promising platform for quantum computation and simulation. A challenge in scaling this platform, however, is the flux crosstalk in the system. In order to exercise precise control, we need to measure this flux crosstalk, and compensate for it. Brute force approaches to flux crosstalk calibration scale quadratically with the number of qubits in the array. As we strive towards chips with hundreds of qubits, we need an extensible approach. We propose an iterative learning-based procedure to calibrate flux crosstalk. Based on statistical tests on simulated data, we have demonstrated our calibration protocol to be accurate (less than 1 MHz mean frequency error for qubits with a maximum frequency of 5 GHz) and to scale approximately linearly with array size. We have experimentally implemented this calibration protocol on planar and 3D integrated flip-chip devices, enabling precise control of qubit frequencies with an approach that will extend naturally as we fabricate larger qubit arrays.

S1.13 Directional readout resonator with interference Purcell filter for scalable and modular qubit readout

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Alec Yen, Yufeng Ye, Kaidong Peng, Gregory Cunningham, Jennifer Wang, Kevin O’Brien

Sponsorship: This research was funded in part by an NSF Graduate Research Fellowship and by the MIT-IBM Watson AI

The presence of large and high-magnetic field circulators and isolators poses a significant challenge to quantum error correction, for which the number of superconducting qubits is expected to scale to thousands to millions. In transmission-based readout, a circulator or isolator is often needed to impedance match to the input of the amplifier. This is because a weakly-coupled port is typically used at the input of the readout bus to provide directionality close to unity for the readout microwave signal. In addition to requiring an extra non-reciprocal element, the weakly-coupled port also creates spatial dependence of the couplings to the readout resonators and limits the modularity of typical qubit readout design. In this work, we present a design for “directional readout”, which avoids using a weakly-coupled port while preserving near-unity directionality. We also include in our design an “interference Purcell filter,” a new form of bandstop Purcell suppression compatible with directional readout. We present progress towards an experimental implementation of directional readout designed to have near-unity directionality and high-fidelity readout of a transmon qubit. This design is expected to facilitate more scalable and modular qubit readout and design.

S1.14 Low-Loss Floquet Mode Josephson Traveling-Wave Parametric Amplifiers with Broadband Near-Ideal Intrinsic Quantum Efficiency

Kaidong Peng, Jennifer Wang, Mahdi Naghiloo, Jeffrey Knecht, Jack Y Qiu, Alec Yen, Yufeng Ye, Gregory D Cunningham, Katrina M Sliwa, Bethany M Niedzielski, Max Tan, Alicia J Zang, Kyle Serniak, Mollie E Schwartz, William D Oliver, and Kevin P O'Brien

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Sponsorship: This work was funded in part by the AWS Center for Quantum Computing and by the Massachusetts Institute of Technology (MIT) Research Support Committee from the NEC Corporation Fund for Research in Computers and Communications. This material is based upon work supported under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the U.S. Air Force.

Quantum limited amplifiers are a key measurement hardware for superconducting quantum computers. We experimentally demonstrate a low-loss, Floquet mode traveling-wave parametric amplifier (Floquet TWPA) using a superconducting qubit compatible aluminum process. With 20 dB gain and less than 1 dB of insertion loss over a several GHz bandwidth, our Floquet TWPAs are ideal for a wide range of information-critical applications such as multiplexed qubit readout. We present preliminary results on noise characterization and superconducting qubit measurements using a Floquet TWPA. With their large instantaneous bandwidth, low insertion loss, and near-ideal quantum efficiency, Floquet TWPAs can significantly reduce measurement hardware overhead and are therefore suitable for large-scale quantum computers.

S1.15 On-Demand Directional Microwave Photon Emission using Waveguide Quantum Electrodynamics

Aziza Almanakly, Bharath Kannan, Youngkyu Sung, Agustin Di Paolo, David A. Rower, Jochen Braumüller, Alexander Melville, Bethany Niedzielski, Amir Karamlou, Kyle Serniak, Antti Vepsäläinen, Mollie E. Schwartz, Jonilyn L. Yoder, Joel Wang, Terry P. Orlando, Simon Gustavsson, Jeffrey A. Grover, William D. Oliver

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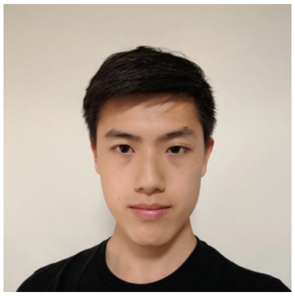
Sponsorship: This research was funded in part by the US Department of Energy, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division under contract no. DE-AC02-05-CH11231 within the High-Coherence Multilayer Superconducting Structures for Large Scale Qubit Integration and Photonic Transduction program (QISLBNL); and by the Under Secretary of Defense for Research and Engineering under Air Force Contract No. FA8702-15-D-0001. A.A. acknowledges support from the PD Soros Fellowship program. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the U.S. Government.

Routing quantum information between non-local computational nodes is a foundation for extensible networks of quantum processors. Quantum information transfer between arbitrary nodes is generally mediated either by photons that propagate between them, or by resonantly coupling nearby nodes. The utility is determined by the type of emitter, propagation channel, and receiver. Conventional approaches involving propagating microwave photons have limited fidelity due to photon loss and are often unidirectional, whereas architectures that use direct resonant coupling are bidirectional in principle, but can generally accommodate only a few local nodes. Here we demonstrate high fidelity, on-demand, directional, microwave photon emission. We do this using an artificial molecule comprising two superconducting qubits strongly coupled to a bidirectional waveguide, effectively creating a chiral microwave waveguide. Quantum interference between the photon emission pathways from the molecule generates single photons that selectively propagate in a chosen direction. This circuit will also be capable of photon absorption, making it suitable for building interconnects within extensible quantum networks.

S2.01 Cavity-enhanced spin-photon interface in diamond

Kevin C. Chen, Lorenzo de Santis, Linsen Li, Ian Christen, Eric Bersin, Madison Sutula, Dirk Englund

Sponsorship: National Science Foundation RAISE-TAQS (Grant No.1839155), MITRE Corporation Moonshot program



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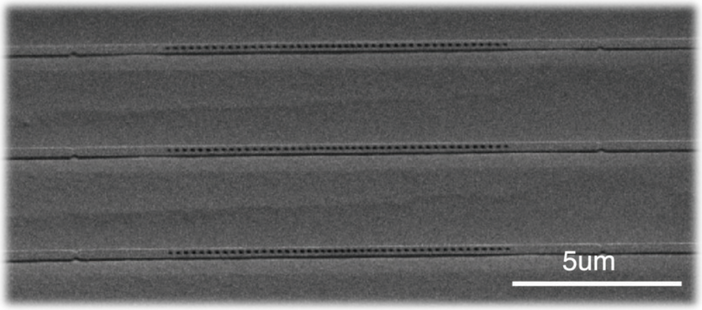
Constructing a quantum network has been a central goal in quantum information processing pertaining to communication, computation, and sensing. However, its realistic implementations have been stymied by the ability to efficiently distribute optical entanglement across distant nodes. One promising approach entails using photonic cavities that boost both the single photon generation probability and the entanglement fidelity, which are two figures of merit essential for practical quantum networks. Here, we experimentally demonstrate the elementary component of such a cavity-based architecture: a solid-state defect center coupled to a nanophotonic cavity. Specifically, we show Purcell enhancement of a diamond color center embedded inside a 1D photonic crystal cavity via lifetime measurements. The device is also contained in a state-of-the-art quantum micro-chiplet conducive to heterogeneous integration into scalable platforms such as photonic integrated circuits. Our work marks the first step towards building an extensible, high-efficiency, and high-fidelity quantum repeater network.



S2.02 Building a quantum network with silicon-vacancy defects in diamond

M. Sutula, P.-J. Stas, Y. Q. Huan, C. M. Knaut, D. R. Assumpcao, Y.-C. Wei, E. N. Knall, A. Suleymanzade, S. W. Ding, B. Pingault, H. Park, M. Loncar, M. D. Lukin

Sponsorship: This work was supported by the NSF, CUA, DOE, AFOSR, the NSF Center for Quantum Networks, and the AWS Center for Quantum Networking. Devices were fabricated in the Harvard University Center for Nanoscale Systems (CNS), a member of the NNCI, NSF award no. 1541959. MS acknowledges funding from the NASA Space Technology Graduate Research Fellowship Program. YQH acknowledges support from the A*STAR NSS, and ENK and DA acknowledge support from the NSF GRFP.

Quantum networks enable a host of applications in quantum information processing, including distributed computing and quantum secure communications. Here, we present silicon-vacancy centers in diamond (SiVs) as a promising qubit platform. In particular, long electronic spin coherence times and access to nuclear ancilla qubits make SiVs an ideal candidate for use as memories in quantum networks. We report on the 29Si-isotope SiV as an integrated two-qubit register with high fidelity readout and a long-lived nuclear spin. Further, utilizing highly strained SiVs maintains spin coherence properties above dilution refrigerator temperatures. We leverage nanophotonic cavities to achieve an efficient spin-photon interface, enabling generation of heralded electron-photon and nuclear-photon Bell states with integrated error detection, representing an important step towards the realization of quantum repeaters based on solid state quantum emitters.

S2.03 Super-resolved Atomic Scale Quantum Emitter Arrays
Y. Duan, I. Christen, Y. Yu, K.C. Chen, M. Trusheim, D. Englund
Sponsorship: DoE, CIQM, MITRE

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Quantum emitters in diamond are promising for quantum networking applications due to their spin and optical properties. In particular, recent integration of group-IV emitters with diamond nanophotonic devices has enabled efficient spin-photon interfaces in high-cooperativity emitter-cavity structures. Optimizing emitter-cavity coupling, as well as scaling to high device number, requires precise and accurate positioning of quantum emitters. Previous studies have shown diamond emitter creation via direct focused-ion beam implantation (FIB), which promises nanometer-scale positioning precision and accuracy. To date, the achievable beam width of FIB processes has limited experimental realizations to implanted SiV emitters with a full width at half maximum (FWHM) spread of ~ 50 nm. Here we report on implantation of Si++ and Ge++ ions at implantation energies of 70 keV and dose swept from 60 to 150 ions/spot using a AuGeSi liquid metal alloy ion source, achieving a beam diameter of 6 nm (Raith Velion FIB). To ensure the implantation accuracy across a large (mm-scale) sample, we align to a series of global and local markers in situ. This combination of ultra-small beam diameter and high-accuracy marker registration promises precise and accurate emitter positioning. We then verify the emitter distribution with sub-nanometer precision using a cryogenic superresolution imaging technique. We address individual emitters through frequency-resolvable resonant optical transitions at 4 K, allowing for spatial localization of each emitter within a FIB-implanted spot. By reconstruction of the true emitter distribution, we reveal an emitter-emitter spacing with a mean below 10 nanometers. This method for generating arbitrary arrays of diamond quantum emitters will facilitate the development of scalable quantum networks and quantum sensors.

S3.01 Cavity-mediated neutral atom array platform for quantum information

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Sponsorship: NSF, NSF CUA, NASA, MURI, ONR

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Neutral atom arrays are a promising candidate for large-scale programmable quantum information systems. Current platforms have high gate fidelities (~99.9%), potential for scalability, and any-to-any qubit connectivity. However, they are limited by the slow (~ms) and destructive state readout done via fluorescence imaging which requires reinitializing the system each readout round. We propose a cavity-coupled platform for neutral atom arrays that will address these limitations. Atoms will be loaded into a 1D tweezer array from a Rb-87 MOT. Fast, nondestructive state readout (~μs) will be used to determine the number of atoms in the array and binary search will be used to diagnose errors by dynamically coupling the atoms to a high-finesse optical cavity. The efficiency of the error diagnosis will be checked through fluorescence imaging. Cavity-coupled neutral atom arrays introduce speed-up over existing quantum computing platforms.

S3.02 Preparing dark states in closely spaced atomic arrays

Oriol Rubies-Bigorda, Valentin Walther, Stefan Ostermann, Ana Asenjo-Garcia, Susanne Yelin

Sponsorship: Fundacio Bancaria “la Caixa”, Fundacion Mauricio y Carlota Botton, NSF - CUA PFC

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Ordered atomic arrays with subwavelength spacing have emerged as a versatile quantum optical platform that exhibits strong and directional coupling between light and matter. In this platform, collective interactions give rise to sets of super-and subradiant lattice states. While radiating states can be easily excited, subradiant modes do not couple to the radiative field and cannot be accessed by incoming light fields. In this poster, I will show that spatial modulations of the atomic detunings can be used to deterministically address such highly subradiant states, often called dark states. This access opens the door to novel schemes for few-photon storage, generation and control, which can be readily realized using arrays of cold atoms, excitons in two-dimensional semiconductors and superconducting qubits coupled to waveguides.

S3.03 Elastic and inelastic dipolar interactions in quantum gases

Pierre Barral, Michael Cantara, Li Du, Julius de Hond, Alan O. Jamison, Wolfgang Ketterle

Sponsorship: Vannevar Bush Faculty Fellowship, DURIP 2019 (AFOSR)

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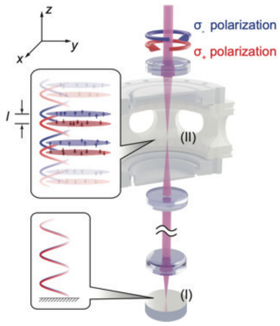
There has been a long-term effort in enhancing long-range interactions while reducing inelastic losses in quantum gases, from dipolar relaxation in spin mixtures to reactive collisions in molecules. Our work shows two approaches in this direction. For the first time, we show shielding between atoms via the dipolar interaction and strong confinement. This has been achieved with bosonic dysprosium and resulted in an order-of-magnitude suppression of dipolar relaxation. We also present a completely new method for trapping dysprosium atoms at a 60 nanometers scale and demonstrate the influence of dipole-dipole interaction at such a small distance. Theoretical and experimental aspects will be presented.



S3.04 Bosonic stimulation of atom-light scattering in an ultracold gas

Yu-Kun Lu, Yair Margalit, Wolfgang Ketterle

Sponsorship: National Science Foundation, Vannevar-Bush Faculty Fellowship

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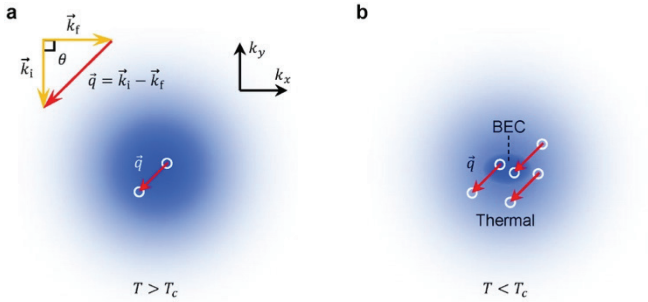
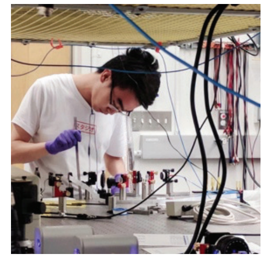
For bosons, the transition rate into an already occupied quantum state is enhanced by its occupation number. This effect — bosonic stimulation — has been predicted more than 30 years ago but has proven elusive to direct observation. Here we investigate this effect in an ultracold gas of bosons. We show that the bosonic enhancement factor for an harmonically trapped gas is bounded by a universal constant above the phase transition to a Bose-Einstein condensate and depends linearly on the condensate fraction just below the phase transition. We observe bosonic enhanced light scattering both above and below the phase transition, and we show how interactions can alter bosonic stimulation and optical properties of the gas. Lastly, we demonstrate that for a multi-level system prepared in a single internal state, bosonic enhancement is reduced because bosonic stimulation occurs only for Rayleigh scattering, but not for Raman scattering.



S3.05 Ablation loading of barium ions into a surface-electrode trap

Xiaoyang Shi, Susanna L Todaro, Karen Lei, Gabriel Mintzer, Felix W Knollmann, Kyle DeBry, Trevor McCourt, Colin D Bruzewicz, John Chiaverini, Isaac L Chuang

Sponsorship: U.S. Army Research Office through grant W911NF-20-1-0037, SLT was supported by an Intelligence Community Post-Doctoral Research Fellowship, KD was supported by the LPS-CQE Doc Bedard Fellowship



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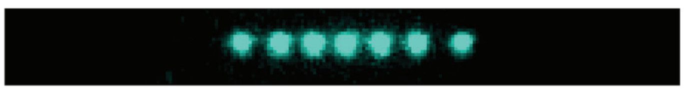
Trapped-ion quantum information processing can benefit from qubits encoded in isotopes that are practically available in only small quantities, e.g. due to low natural abundance or radioactivity. Laser ablation provides a method of controllably liberating neutral atoms or ions from low-volume targets, but energetic ablation products can be difficult to confine in the low-depth, micron-scale, microfabricated traps amenable to high-speed, high-fidelity manipulation of ion arrays. Here we investigate ablation-based ion loading into surface-electrode traps (SETs) of different sizes to test a model describing ion loading probability as a function of effective trap volume and other trap parameters. The results guide our demonstration of Ba+ ablation production and loading, and co-trapping of Sr+ and Ba+, in SETs in a cryogenic vacuum system; these techniques are generally applicable to limited-quantity species of interest for quantum computing, simulation, and sensing. We also demonstrate progress toward coherent control of the Ba+ optical qubit.



S3.06 Integrated Photonics for Advanced Cooling of Trapped-Ion Quantum Systems

S. Corsetti*, A. Hattori*, T. Sneh, M. Notaros, R. Swint, P. T. Callahan, C. D. Bruzewicz, F. Knollmann, R. McConnell, J. Chiaverini, J. Notaros

Sponsorship: NSF QLCI HQAN (2016136)|NSF QLCI Q-SEnSE (2016244), MIT CQE (H98230-19-C-0292), NSF GRFP (Grant No. 1122374), MIT Cronin Fellowship, MIT Locher Fellowship

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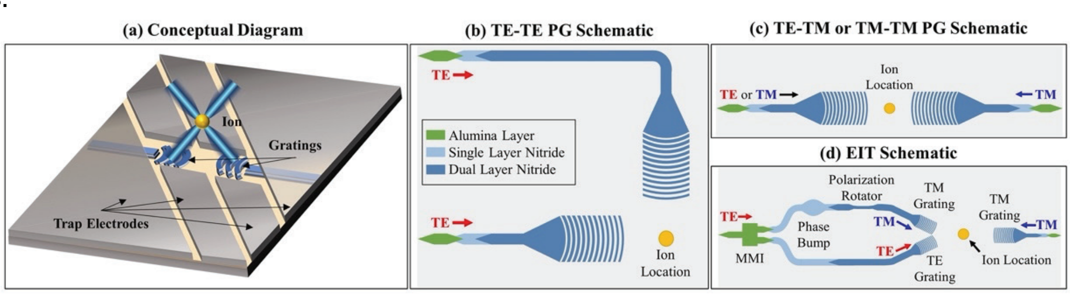
Trapped ion systems are a promising modality for quantum information processing due to their long coherence times and strong ion-ion interactions, which enable high-fidelity two-qubit gates. However, most current implementations are comprised of complex free-space optical systems, whose large size and susceptibility to vibrations and drift can limit fidelity and addressability of ion arrays, hindering scaling. Integrated-photonics-based solutions offer a potential avenue to address many of these challenges. Motional state cooling is a key optical function in trapped-ion systems. However, to date, integrated-photonics-based demonstrations have been limited to Doppler and resolved-sideband cooling. In this work, we develop integrated-photonics-based system architectures and the design of key integrated devices for two advanced cooling schemes, polarization gradient (PG) and electromagnetically-induced-transparency (EIT), enabling better cooling performance for multi-ion systems.



S3.07 Efficient algorithms to solve atom reconfiguration problems: the redistribution-reconfiguration (red-rec) algorithm

Marc Bacvanski, Barry Cimring, Remy El Sabeh, Stephanie Maaz, Izzat El Hajj, Naomi Nishimura, Amer E. Mouawad, Alexandre Cooper

Sponsorship: Canada First Research Excellence Fund (CFREF)

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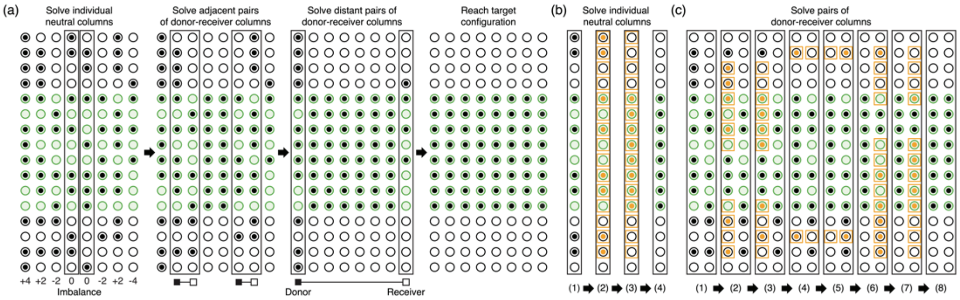
To scale neutral atom quantum computers to thousands of qubits, it is essential to reliably and quickly assemble large numbers of optical traps using moving optical tweezers. We propose the redistribution-reconfiguration (red-rec) algorithm for computing control operations for configuring compact arrangements of atoms optical trap arrays. The red-rec algorithm efficiently redistributes atoms among columns and reconfigures each column minimizing displacements, harnessing parallel control operations to reduce execution times. We use simulations to compare the red-rec algorithm against approaches with guaranteed optimality bounds, and with realistic physical parameters for atom loss, we show that the red-rec algorithm demonstrates a path to successfully preparing arrays of several thousand atoms in different sizes of static arrays and target configurations. Finally, we use these results to identify and quantify the challenges of scaling to tens of thousands of atoms: number of traps, field of view, and trap loading efficiency. The red-rec algorithm will be useful for preparing large configurations of atoms, creating opportunities for engineering quantum many-body systems with larger dynamic connectivity graphs, and designing and benchmarking improved reconfiguration algorithms.



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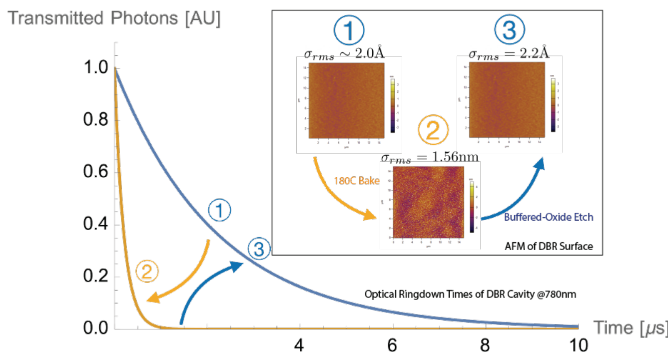
S4.01 SiO2 Crystal Growth Mechanism for Vacuum Degradation of Distributed Bragg Reflector Mirrors

Alyssa Rudelis, Vladan Vuletic

Sponsorship: NSF, NSF CUA, NASA, MURI through ONR

On the way to fault-tolerance, neutral atom quantum computing will reach a critical point in system size. As qubit number increases, sufficient laser power, optical access, and fast multi-qubit gates will not be achievable. To address these challenges, we must shift to modular cavity-coupled architectures. However, high-finesse distributed Bragg reflector (DBR) mirrors can degrade in ultra-high vacuum (UHV) conditions, making the upgrade to cavity-coupled atom arrays risky. We propose a kinetics explanation for the degradation of high-finesse DBR optical cavity mirrors post UHV anneal and make recommendations for prevention. Based on post-mortem atomic force microscopy (AFM), X-ray fluorescence (XRF), selective wet etching, and optical measurements, we find the degradation is explained by oxidation reduction in Ta_2O_5 followed by penetrative diffusive growth of SiO_2 crystals through a top layer of Ta_2O_5. We discuss the dependence of mirror losses on surface roughness and recover the original low-loss state of the mirror by etching away the SiO_2 crystals. Future studies can avoid these vacuum-induced losses by depositing a SiO_2 cap on the DBR surface, allowing quicker adoption of cavity-coupled atom qubit arrays and a path toward scalable quantum computing architectures.



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S4.02 Preparing dark states in closely spaced atomic arrays

Haowei Xu, Guoqing Wang, Changhao Li, Hua Wang, Hao Tang, Ariel Rebekah Barr, Paola Cappellaro, Ju Li

Sponsorship: Office of Naval Research, MURI (#N00014-17-1-2661), Honda Research Institute USA, Inc. (#031807-00001), DTRA Interaction of Ionizing Radiation with Matter (IIRM) University Research Alliance (URA) (#HDTRA1-20-2-0002)

The initialization of nuclear spin to its ground state is challenging due to its small energy scale compared with thermal energy, even at cryogenic temperature. In this work, we propose an opto-nuclear quadrupolar effect, whereby two-color optical photons can efficiently interact with nuclear spins. Leveraging such an optical interface, we demonstrate that nuclear magnons, the collective excitations of nuclear spin ensemble, can be cooled down optically. Under feasible experimental conditions, laser cooling can suppress the population and entropy of nuclear magnons by more than two orders of magnitude, which could facilitate the application of nuclear spins in quantum information science.

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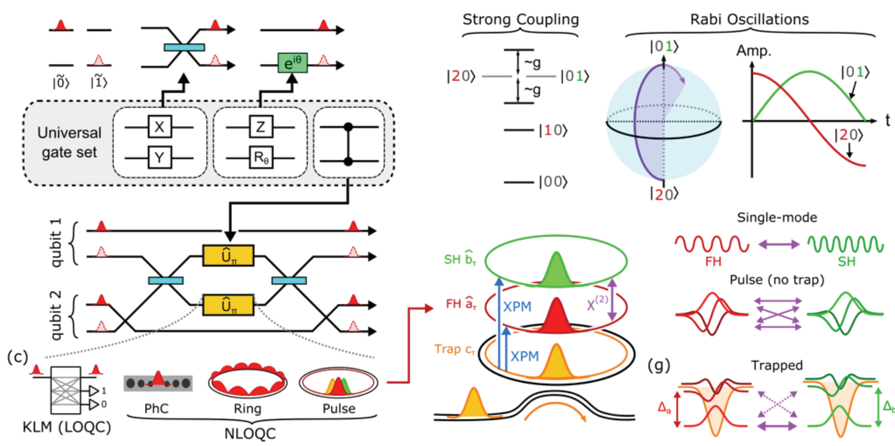
S4.03 Temporal Trapping of Ultrashort Pulses Enables Deterministic Optical Quantum Computation

Ryan Hamerly, Ryotatsu Yanagimoto, Marc Jankowski, Edwin Ng, Hideo Mabuchi

Sponsorship: NTT Research (R.H., H.M.), Stanford Q-FARM, Masason Foundation (R.Y.), ARO, NSF (H.M.)

The realization of deterministic photon-photon gates is a central goal in quantum optics. A longstanding challenge is that optical nonlinearities in scalable, room-temperature material platforms are too weak to achieve the required strong coupling, due to the critical loss-confinement tradeoff in existing photonic structures. We propose a novel confinement method, dispersion-engineered temporal trapping, to circumvent the tradeoff, paving a route to all-optical strong coupling. Temporal confinement is imposed by an auxiliary trap pulse via cross-phase modulation, which, combined with the spatial confinement of a waveguide, creates a "flying cavity" that enhances the nonlinear interaction strength by orders of magnitude. Simulations confirm that temporal trapping confines the dynamics to a single-mode subspace, enabling high-fidelity quantum gate operations. With realistic dispersion engineering and loss figures, we show that trapped ultrashort pulses can achieve strong coupling on near-term nonlinear nanophotonic platforms. Our results highlight the potential of ultrafast nonlinear optics to become the first scalable, high-bandwidth, and room-temperature platform that achieves a strong coupling, opening a new path to quantum computing, simulation, and light sources.



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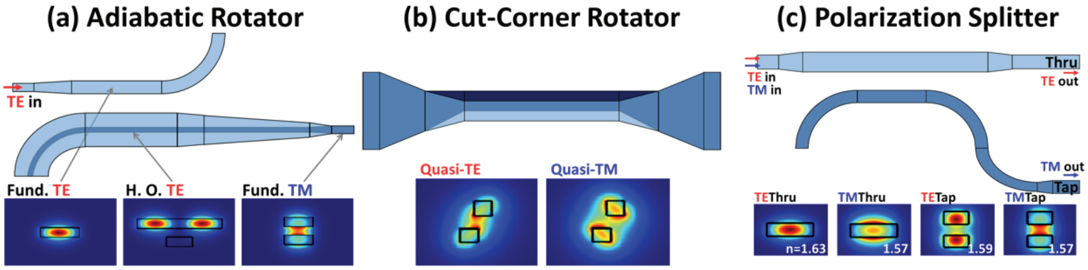
S4.04 Integrated Visible-Light Polarization-Control Devices for Atomic Quantum Technologies

Ashton Hattori*, Tal Sneh*, Milica Notaros, Sabrina Corsetti, and Jelena Notaros

Sponsorship: NSF QLCI HQAN (2016136), NSF QLCI Q-SEnSE (2016244), MIT Center for Quantum Engineering (H98230-19-C-0292), National Science Foundation (NSF) Graduate Research Fellowship Program (Grant No. 1122374), MIT Frederick (1953) and Barbara Cronin Fellowship, MIT Rolf G. Locher Endowed Fellowship

Trapped-ion-based and neutral-atom-based systems are two promising modalities for quantum information processing. However, most current implementations of these atomic technologies utilize complex free-space optical systems, whose large size and susceptibility to vibrations and drift can limit fidelity and addressability, hindering scaling. Integrated-photonics-based solutions offer a potential avenue to address many of these challenges for both modalities. Advanced polarization control for near-UV to infrared wavelengths plays a vital role in state preparation, control, and readout for these atomic systems. While mature integrated polarization-control devices at infrared wavelengths have been demonstrated, advanced integrated polarization control at visible wavelengths has yet to be developed, given the challenges resulting from scaling of device dimensions with wavelength. In this work, we demonstrate the design of the first integrated polarization rotators and splitters operating at visible wavelengths. Specifically, we show an adiabatic polarization rotator, a compact off-axis polarization rotator, and a mode-coupling polarization splitter all operating at a wavelength of 422nm, allowing for advanced on-chip polarization control for high fidelity, scalable atomic systems.



S4.05 Quantum Limit on Noise in Feedback Oscillators

Hudson Loughlin and Vivishek Sudhir

Sponsorship: National Science Foundation (NSF), California Institute of Technology (Caltech), PI Startup Funds (MIT)

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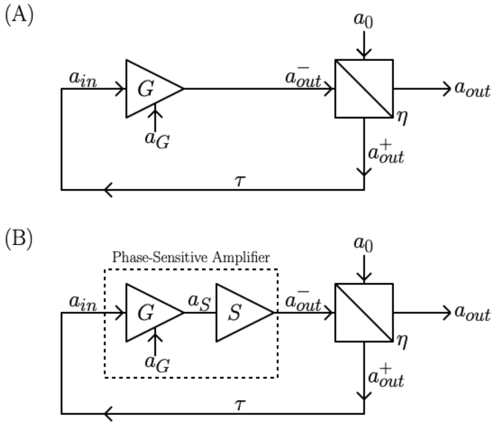
Frequency stabilized lasers are used in precision metrology schemes from interferometers to atomic clocks. It has been established that the Schawlow-Townes limit provides a fundamental limit to laser frequency stability, but the exact origins of this limit have remained constrained to specific models of laser noise. Here, we study an abstract model of an oscillator realized by an amplifier embedded in a positive feedback loop. Such a model applies to lasers, but also to a broader class of feedback oscillators. We show that there exists a quantum limit to the power and frequency stability of such an oscillator that is related to quantum noise added by two elements in the loop: the amplifier, and the out-coupler. This result relates the Schawlow-Townes result for the linewidth of a laser to the Haus-Caves quantum noise limit for a linear amplifier, while identifying the role of quantum noise added at the out-coupler. Through this quantum noise approach, we see that the Schawlow-Townes limit is a standard quantum limit on the phase quadrature spectrum of a feedback oscillator, and we reveal several mechanisms to systematically evade this limit.



S4.06 Design of Quantum Dot Lasers using Plasmonic Nanocavities

Jun Guan and Vladimir Bulovic

Sponsorship:

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Colloidal quantum dots (QDs) are promising materials for next-generation display technologies because of their high photoluminescence quantum yields, tunable emission colors, and solution processibility. To engineer emission characteristics of QDs, plasmonic lattice structures can provide subwavelength light confinement and suppress radiative loss. In this work, we investigate the coupling of indium phosphide QDs with aluminum nanoparticle lattices to achieve controlled light-emitting properties. We found that conformal coating of QD films on plasmonic lattices can result in hybrid waveguide-lattice modes. By varying the lattice periodicity or the thickness of the QD film, the QD emission wavelength and intensity can be manipulated. Our studies of QD-plasmon interactions open prospects for commercial QD laser devices and quantum-optical technologies.

S5.01 QuantumNAT: Quantum Noise-Aware Training with Noise Injection, Quantization and Normalization

Hanrui Wang, Jiaqi Gu, Yongshan Ding, Zirui Li, Frederic T. Chong, David Z. Pan, Song Han

Sponsorship: MIT-IBM Watson AI Lab, NSF CAREER Award, Qualcomm Innovation Fellowship

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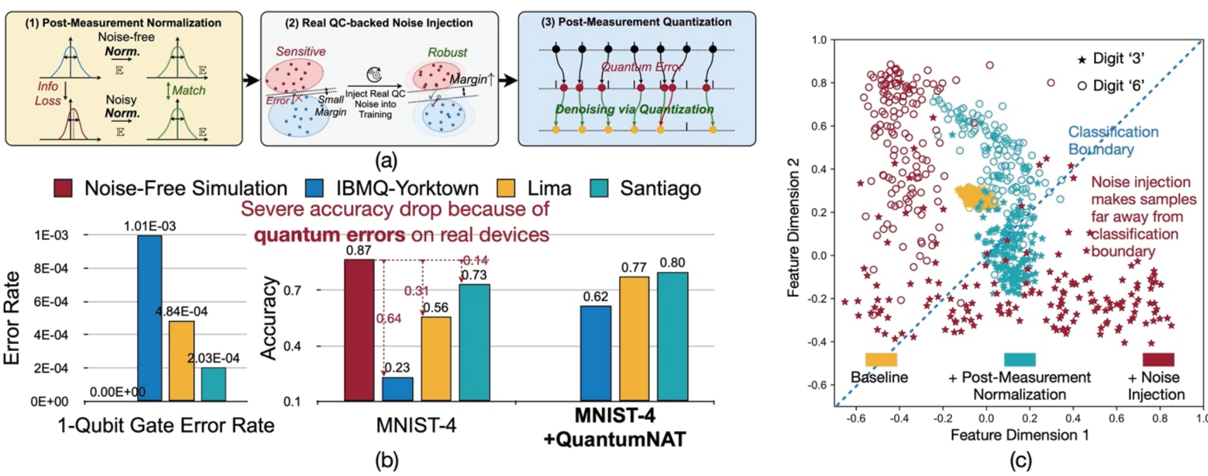
Parameterized Quantum Circuits (PQC) are promising towards quantum advantage on near-term hardware. However, due to the large quantum noises, the performance of PQC has a severe degradation on real quantum devices. We present QuantumNAT to perform noise-aware optimizations in both training and inference stages to improve robustness. We observe that quantum noise effect to measurement outcome is a linear map from noise-free outcome with a scaling and a shift factor. Therefore, we propose post-measurement normalization to mitigate the feature distribution differences between noise-free and noisy scenarios. Further, we propose noise injection by inserting quantum error gates to PQC according to realistic noise models of quantum hardware. Finally, quantization is introduced to quantize the measurement outcomes to discrete values, achieving the denoising effect. Extensive experiments on 8 classification tasks using 6 quantum devices demonstrate that QuantumNAT improves accuracy by up to 43%, and achieves over 94% 2-class, 80% 4-class accuracy.



(a) Three techniques proposed in QuantumNAT. (b) QuantumNAT improves the accuracy on real device. (c) Visualization of the feature space of 2-classification, the proposed techniques separate the features and improve accuracy.

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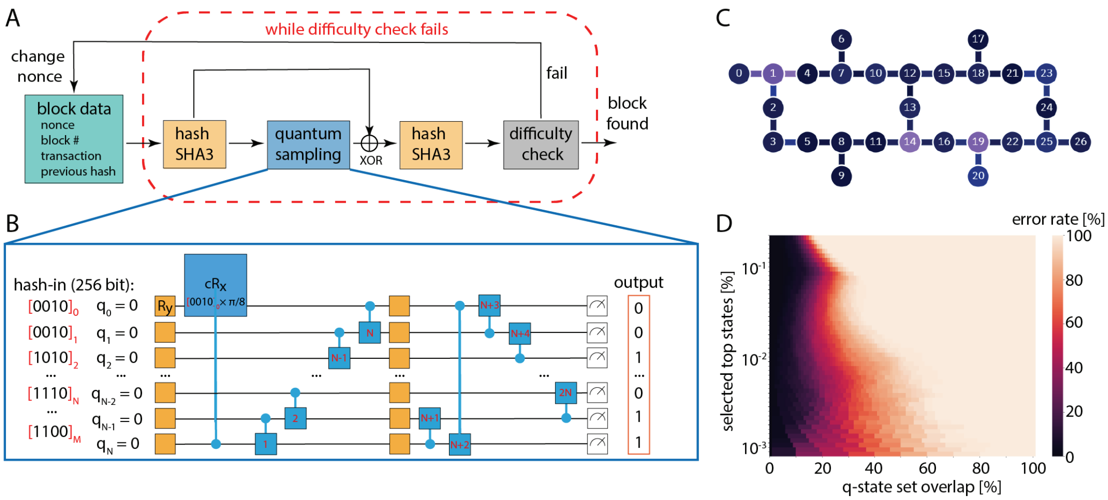
S5.02 Quantum Proof of Work with Parametrized Quantum Circuits

Maximus Liu, Khadijeh Najafi, Michael Dubrovsky, Mikhail Shalaginov
Sponsorship: M. Liu has been supported by the scholarship from AARD.

Recently quantum computers (QCs) have started to rival the existing classical supercomputers in completing computationally hard tasks. Despite a handful of demos, available noisy intermediate scale QCs are looking for practical applications. Here we explore the possibility of using the QCs in cryptocurrency mining. We propose a scheme for quantum-computer compatible Proof of Work (qPoW) protocol (Fig. A), which is an expanded version of traditional Bitcoin mining algorithm capitalizing on hash functions. The quantum circuit (Fig. B) encodes a pre-hashed bit string into parametrized gates and after 20,000 shots returns a probabilistic q-state distribution. Then, a few most probable q-states are written as a bit string and pushed through the rest of the qPoW. If the post-hashed bit string satisfies the difficulty condition and recorded q-state sets obtained by quantum and classical computers partially overlap, then a block is claimed to be mined and verified. We adopted the qPoW to be computed on superconducting IBM Q 27-qubit processors, e.g., ibm_peekskill (Fig. C). We have studied the qPoW mining success rates and found suitable ranges of hyperparameters for its deployment on IBM hardware (Fig. D).



Abstracts

S5.03 Koopman Operator learning for Accelerating Quantum Optimization and Machine Learning

Di Luo

Sponsorship: NSF AI Institute for Artificial Intelligence and Fundamental Interactions(IAIFI), Co-Design Center for Quantum Advantage (C2QA), Fermilab Theory Consortium "Intersections of QIS and Theoretical Particle Physics"

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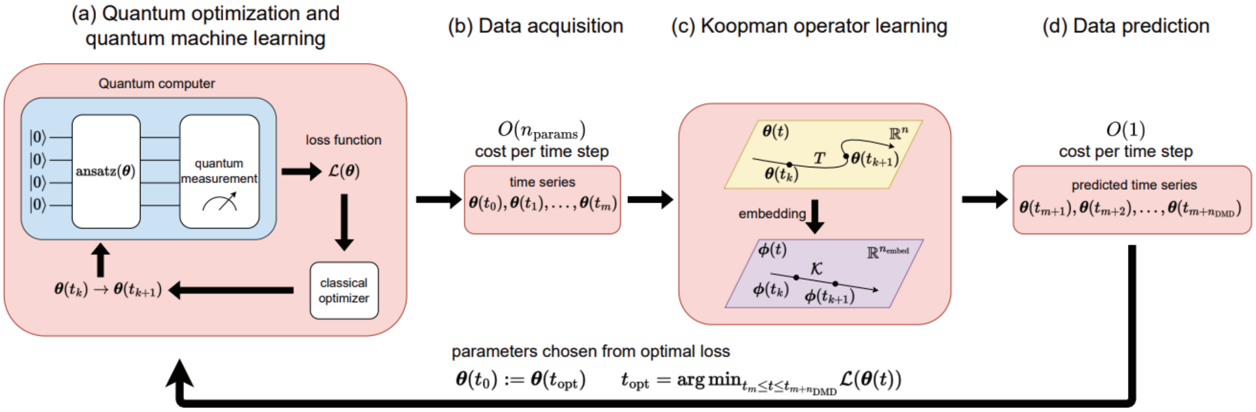
Finding efficient optimization methods plays an important role for quantum optimization and quantum machine learning on near-term quantum computers. While backpropagation on classical computers is computationally efficient, obtaining gradients on quantum computers is not, because the computational complexity scales linearly with the number of parameters and measurements. In this paper, we connect Koopman operator theory, which has been successful in predicting nonlinear dynamics, with natural gradient methods in quantum optimization. We propose a data-driven approach using Koopman operator learning to accelerate quantum optimization and quantum machine learning. We develop two new families of methods: the sliding window dynamic mode decomposition (DMD) and the neural DMD for efficiently updating parameters on quantum computers. We show that our methods can predict gradient dynamics on quantum computers and accelerate the variational quantum eigensolver used in quantum optimization, as well as quantum machine learning. We further implement our Koopman operator learning algorithm on a real IBM quantum computer and demonstrate their practical effectiveness.



S5.04 Equivalence of Coupled Parametric Oscillator Dynamics to Lagrange Multiplier Primal-Dual Optimization

Sri Krishna Vadlamani, Tianyao Patrick Xiao, Eli Yablonovitch

Sponsorship: National Science Foundation Award ECCS-0939514, Office of Naval Research Grant N00014-14-1-0505

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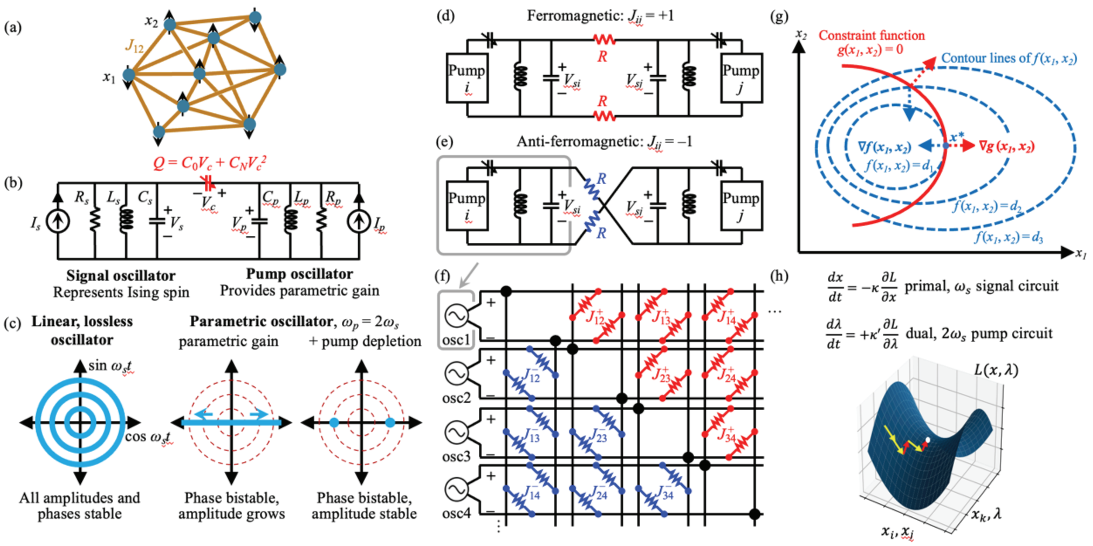
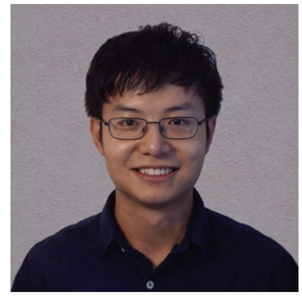
The maximization or minimization principles that are built into physics can be exploited to build machines that solve optimization problems. We present an approximate dynamical solver for the NP-hard Ising problem that is comprised of a network of coupled bistable parametric oscillators and show that it implements Lagrange multiplier constrained optimization. We show that the 2w pump depletion effect, which is intrinsic to parametric oscillators, automatically enforces the binary Ising constraints. This enables the system's continuous analog variables to converge to high-quality binary solutions to the optimization problem. Moreover, we establish an exact correspondence between the equations of motion for the coupled oscillators and the update rules in the primal-dual method of Lagrange multipliers. In particular, the w signal part of the circuit implements the primal step while the 2w pump part performs the dual step of the Lagrange multiplier method. Though our analysis is performed using electrical LC oscillators, it can be generalized to any system of coupled parametric oscillators. We simulate the dynamics of the coupled oscillator system on benchmark problems and demonstrate that its performance is comparable to the best-known results.



S5.05 Bootstrap Embedding of Quantum Chemistry on Quantum Computers

Yuan Liu, Zachary Chin, Oinam Meitei, Arkopal Dutt, Max Tao, Isaac Chuang, Troy Van Voorhis

Sponsorship: Department of Energy, Co-Design Center for Quantum Advantage (C2QA)



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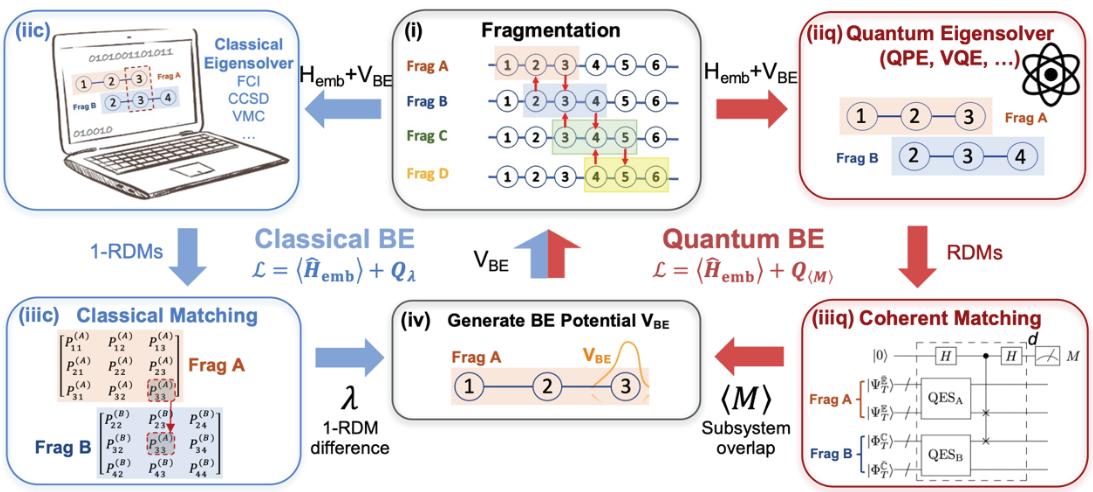
An outstanding challenge spanning the fields of quantum chemistry, materials science, and condensed matter physics is to determine the ground state of large-scale interacting fermionic systems. However, numerically solving the time-independent Schrodinger equation of a practical many-electron system accurately remains a daunting task because the dimension of the underlying Hilbert space grows exponentially with the number of electrons, and the computational resources required to perform calculations over such a large space can quickly exceed the capacity of current classical hardware. We present a quantum bootstrap embedding theory that formulates the electronic structure problem of the total system as a constraint optimization problem for a composite Lagrangian where the constraint is constructed from matching conditions on the qubit reduced density matrices. We then design an iterative hybrid quantum-classical algorithm to solve the optimization problem using quantum eigensolvers. An adaptive sampling scheduling and a quantum coherent matching algorithm are designed to dramatically improve the efficiency of the algorithm. Current quantum computers are small, but quantum bootstrap embedding proves a potentially generalizable strategy for harnessing such small machines.



S5.06 Guaranteed bounds on achievable performance in quantum control

Flemming Holtorf

Sponsorship: This material is based upon work supported by the National Science Foundation OAC-1835443, SII-2029670, ECCS-2029670, OAC-2103804, and PHY-2021825; the Advanced Research Projects Agency-Energy DE-AR0001211 and DE-AR0001222; the Defense Advanced Research Projects Agency (DARPA) HR00112290091; the United States Artificial Intelligence Accelerator FA8750-19-2-1000.

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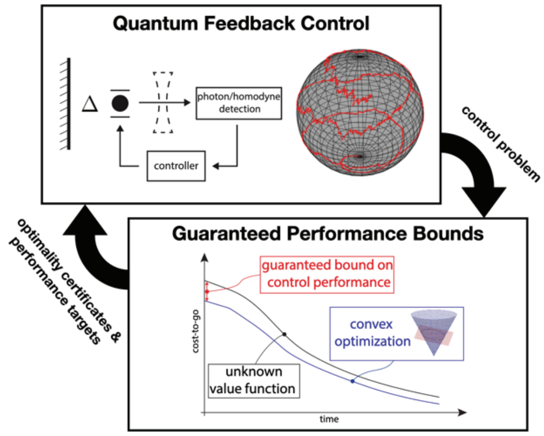
Optimal feedback control of quantum systems plays an important role in quantum sensing and information processing. Despite this relevance, however, all but the simplest quantum control problems have no known analytical solutions and even rigorous numerical approximations are usually inaccessible. This can be attributed to the complex dynamics associated with quantum systems subject to continuous measurements, such as photon counting or homodyne detection setups, which are generally described by nonlinear jump-diffusion processes.

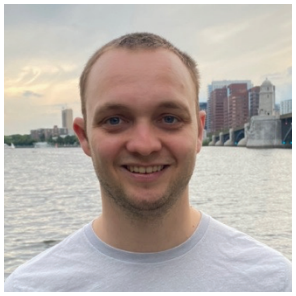
As a consequence, the use of heuristics, often based on reinforcement learning or expert intuition, is common practice for the design of quantum control policies. But while these heuristics often perform remarkably well in practice, they seldom come with a mechanism to evaluate the degree of suboptimality they introduce, leaving it purely to intuition when to terminate the controller design process. To address this issue, we present a convex optimization based framework for the computation of informative bounds on the best possible control performance via sum-of-squares programming. We demonstrate the utility of the approach by constructing certifiably near optimal control policies for qubit systems with photon counting and homodyne detection setups.



S5.07 Control of Stochastic Quantum Dynamics by Differentiable Programming

Frank Schäfer, Flemming Holtorf, Julian Arnold, Pavel Sekatski, Martin Koppenhöfer, Niels Lörch, Michal Kloc, Christoph Bruder, Chris Rackauckas, Alan Edelman

Sponsorship: This material is based upon work supported by the Swiss National Science Foundation 51NF40-185902, the National Science Foundation OAC-1835443, SII-2029670, ECCS-2029670, OAC-2103804, and PHY-2021825; the Advanced Research Projects Agency-Energy DE-AR0001211 and DE-AR0001222; the Defense Advanced Research Projects Agency (DARPA) HR00112290091; and the United States Artificial Intelligence Accelerator FA8750-19-2-1000.



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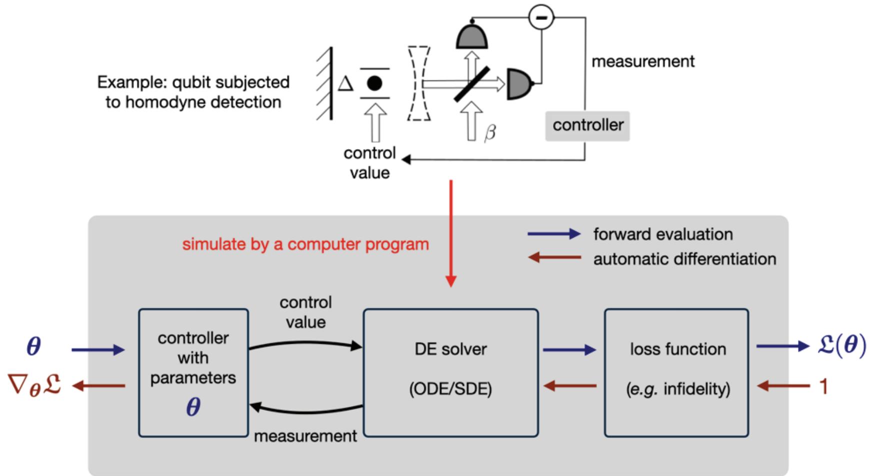
Conceptually, it is straightforward to determine the time evolution of a quantum system for a fixed initial state given its (time-dependent) Hamiltonian or Lindbladian. Depending on the physical context, the dynamics is described by an ordinary or stochastic differential equation. Controlling the (stochastic) dynamics of a quantum system is indispensable in fields such as quantum information processing. However, solving this inverse problem by deriving a performant control scheme is generally hard. Here, we propose a framework for the automated design of closed-loop control schemes based on differentiable programming.

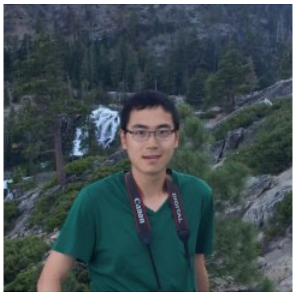
Specifically, we employ a controller in form of a neural network that predicts a control value to be applied in the next time step based on the current state of the quantum system or the observed measurement record. A relevant example of such a measurement record is a homodyne detection signal which contains only very limited information on the actual state of the system, masked by unavoidable photon-number fluctuations. The parameters of the neural network are tuned based on gradient information computed by (adjoint) sensitivity methods. We verify the robustness of our framework in different scenarios.



S5.08 Tower: Data Structures in Quantum Superposition

Charles Yuan, Michael Carbin

Sponsorship:



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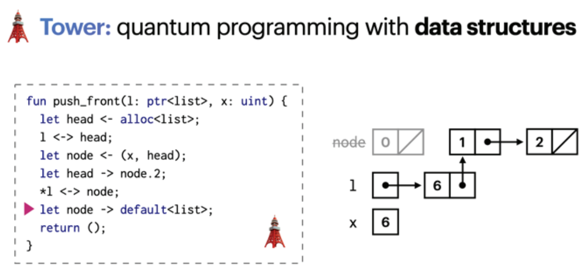
Emerging quantum algorithms for problems such as element distinctness, subset sum, and closest pair demonstrate computational advantages by relying on abstract data structures. Practically realizing such an algorithm as a program for a quantum computer requires an efficient implementation of the data structure whose operations correspond to unitary operators that manipulate quantum superpositions of data.
To correctly operate in superposition, an implementation must satisfy three properties -- reversibility, history independence, and bounded-time execution. Standard implementations, such as the representation of an abstract set as a hash table, fail these properties, calling for tools to develop specialized implementations.
In this work, we present Tower, a language for quantum programming with recursively defined data structures. We also present Boson, the first memory allocator that supports reversible, history-independent, and constant-time dynamic memory allocation in quantum superposition. Using Tower, we implement Ground, the first quantum library of data structures, including lists, stacks, queues, strings, and sets.



S5.09 Quantum algorithms for group convolution, cross-correlation, and equivariant transformations

Grecia Castelazo, Quynh T. Nguyen, Giacomo De Palma, Dirk Englund Seth Lloyd, and Bobak T. Kiani

Sponsorship: This work was supported by the NSF, IARPA, DOE, and DARPA.

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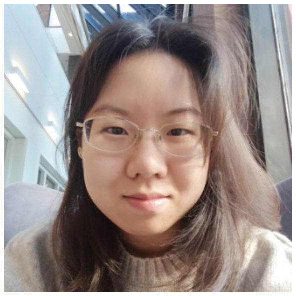
Group convolutions and cross-correlations, which are equivariant to the actions of group elements, are commonly used to analyze or take advantage of symmetries inherent in a given problem setting.
Here, we provide efficient quantum algorithms for performing linear group convolutions and cross-correlations on data stored as quantum states. Runtimes for our algorithms are poly-logarithmic in the dimension of the group and the desired error of the operation. Motivated by the rich literature on quantum algorithms for solving algebraic problems, our theoretical framework opens a path for quantizing many algorithms in machine learning and numerical methods that employ group operations.



S6.01 K band Josephson traveling wave parametric amplifiers for neutrino mass measurement

Jennifer Wang, Kaidong Peng, Wouter Van De Pontseele, Katrina Sliwa, Patrick Harrington, Yanjie Qiu, Kyle Serniak, Joseph A. Formaggio, William D. Oliver, Kevin P. O'Brien

Sponsorship: This work is supported by the MIT-CQE Doc Bedard Fellowship, the US DOE Office of Nuclear Physics (DE-FOA-0002110), the US NSF, the PRISMA+ Cluster of Excellence at the University of Mainz, and internal investments at all institutions.

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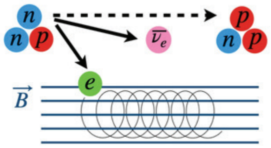
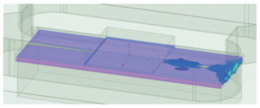
Josephson traveling wave parametric amplifier (JTWPAs) are high-gain, broadband, and low-noise quantum amplifiers that are crucial for superconducting qubit readout, and hold great promise in advancing quantum sensing capabilities for many fields. In collaboration with Project 8, a next-generation neutrino mass experiment which measures the electron cyclotron frequency from tritium beta decay to infer the neutrino mass, we are developing high frequency JTWPAs centered at 25 GHz. These JTPWAs are predicted to attain 20 dB of gain over a few GHz of bandwidth with approximately 85% quantum efficiency relative to an ideal phase-preserving amplifier, which is an order of magnitude better noise performance than that of off-the-shelf HEMT amplifiers. This talk presents simulations of the frequency response and parasitics of high-frequency JTWPA chip designs, as well as how to optimize packaging to minimize extraneous modes and impedance mismatches. We also present experimental progress towards utilizing the JTWPA in the Project 8 measurement chain to detect electromagnetic signals below the femtowatt level, and highlight that the high frequency JTWPA bandwidth can be tailored to a wide range of applications, such as quantum information processing, dark matter searches, and fundamental physics





S6.02 Characterizing the Interaction Graph of a Multi-Spin Network in Diamond

Alex Ungar, Won Kyu Calvin Sun, Paola Cappellaro

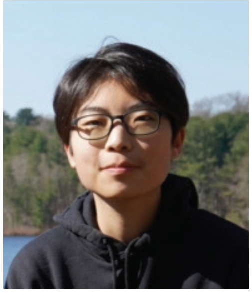
Sponsorship: NSF Graduate Research Fellowship Grant No. 1745302

Optically dark electronic spins in diamond surrounding optically addressable nitrogen vacancy (NV) centers can act as qubits in a multi-spin quantum register to help realize more powerful quantum devices. While recent experiments have shown initialization and control of electronic spins near a NV center, the system size has been limited to spins directly coupled to it. In this work we demonstrate our ability to further scale up a quantum register of electronic spins in diamond by harnessing spins beyond the coherence limit of the central NV center. We map out an unknown graph of interacting spins in the environment of a single NV center, and we achieve complete characterization of a four-spin network within a finite frequency range and above a practical coupling strength threshold. This will enable us to polarize a dark spin that is beyond the practical control limit of the central NV center, which could be used for sensing of distant electronic spins. The control tools we develop and our results provide a roadmap to engineer larger solid-state quantum registers, and further advance their capabilities for quantum sensing, device characterization, and simulation.

S6.03 Transition-edge Sensors in Bolometric Detectors of the Ricochet Experiment

Jiatong Yang, Wouter Van De Pontseele, Joseph Formaggio, on behalf of the Ricochet Collaboration

Sponsorship: National Science Foundation



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A transition-edge sensor (TES) is a superconducting thin film operating close to its transition temperature. Designed to have a sharp transition, the TES is sensitive to small changes in temperature. Thus, it has been widely used in sensitive cryogenic calorimeters for particle physics experiments. Ricochet is an experiment that measures the neutrino spectrum of Coherent Elastic Neutrino-Nuclear Scattering at low energies. In the experiment, recoil energy deposited in a superconducting absorber is transferred to a TES that converts temperature changes into changes in current, which then gets amplified and read out.

We modeled and characterized the TES's designed by Northwestern University and fabricated at Argonne National Laboratory. We measured the IV curves and impedance curves of the TES and observed pulses originating from events within the TES and the absorber. From those measurements, we obtained important parameters of the TES, including its transition temperature, its sensitivity to temperature and current, and its thermal time constant. These parameters enable us to model and understand the current and temperature response of the devices.

S6.04 Frequency Multiplexing of Cryogenic Sensors for the Ricochet Experiment

W. Van De Pontseele, J. Yang, P. M. Harrington, S. Henderson, W. D. Oliver, F. Formaggio

Sponsorship: DOE QuantISED award DE-SC0020181 and Heising-Simons Foundation

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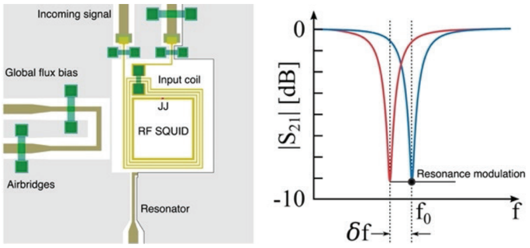
Readout of low-intensity microwave signals over a wide bandwidth has become increasingly important for fundamental science. The high frequency allows high information transfer, which is ideal for multiplexing detectors and reducing low-frequency noise.

One specific experiment in need of frequency multiplexing is Ricochet. Ricochet aims to measure coherent neutrino scattering to search for new fundamental physics. It consists of superconducting crystals that function as bolometers and are read out using transition-edge sensors.

Together with Lincoln Laboratory, we designed, fabricated and characterised devices for frequency multiplexing in 6 and 18 channels configurations. The signals inductively couple into RF SQUIDS that modulate the resonant frequency of aluminium resonators. These high-Q resonators connect to a single common RF feedline, simplifying cabling and reducing heat loads. The low-frequency signals are recovered using SLAC Microresonator Radio Frequency (SMuRF) electronics for the readout of frequency-division-multiplexed cryogenic sensors.



S6.05 Observations of Muon-induced Qubit Errors

Mingyu Li, Patrick M. Harrington, Wouter Van De Pontseele, Max Hays, Daniel Mayer, David K. Kim, Bethany M. Niedzielski, Alexander Melville, Jeffrey A. Grover, Kyle Serniak, Joseph A. Formaggio, William D. Oliver

Sponsorship: This research was supported by an appointment to the Intelligence Community Postdoctoral Research Fellowship Program at MIT, administered by Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and the Office of the Director of National Intelligence. This research was funded by the Under Secretary of Defense for Research and Engineering under Air Force Contract No. FA8702-15-D-0001. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the USDR&E, USAF, ODNI, or DOE.

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An outstanding challenge spanning the fields of quantum chemistry, materials science, and condensed State-of-the-art superconducting transmon qubits have O(100μs) energy relaxation times T1 and decoherence times T2. However, correlated errors resulting from nonequilibrium quasiparticles generated by environmental ionizing radiation and cosmic rays presents a significant challenge to quantum error correction schemes. which is exacerbated by environmental ionizing radiations and cosmic rays. In this work, we quantify the impact of cosmogenic muons that traverse the chip substrate. The deposited energy in the substrate increases the quasiparticle density and causes simultaneous relaxation errors for an array of qubits. We use the coincidence between multiple-qubit errors and signals from scintillating muon detectors to determine the likelihood of a radiative impact resulting in correlated qubit errors. Our coincidence model provides a fitted likelihood of observing correlated qubit errors given that a muon traverses the chip. We measure the rate of muon-induced errors to be on the order of 0.1 s−1 cm−2. These measurements quantify the sensitivity of the qubits to natural ionizing radiation, and they have implications for quantum error correction protocols.

S6.06 Defect Identification in 2-terminal Superconducting Devices using Time Domain Reflectometry

Torque (Tareq) El Dandachi, Emma Batson, Reed Foster, Marco Colangelo, Karl Berggren

Sponsorship: CQN

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Defects that occur in superconducting nanowires during fabrication suppress the critical current of the device and change the overall behavior. Being able to debug superconducting devices and locate these defects is a valuable tool for scaling devices and achieving better performance. By locating these defects we can not only improve our fabrication process but it also allows us to go back and repair them in the device. Time Domain Reflectometry (TDR) is a technique used on transmission lines to detect defects based on the reflections of pulses sent in. We apply a similar technique on superconducting transmission lines that takes advantage of the non-linearity and switching behavior of the wire. We show that by timing two pulses sent from either end of the wire, we can locally measure the switching current of the device at every segment and use that to infer the location of defects.

S6.07 Evolution of 1/f Magnetic Flux Noise in Superconducting Qubits with Weak Magnetic Fields

David Rower, Lamia Ateshian, Lauren H. Li, Max Hays, Dolev Bluvstein, Leon Ding, Bharath Kannan, Aziza Almanakly, Jochen Braumueller, David K. Kim, Alexander Melville, Bethany M. Niedzielski, Mollie E. Schwartz, Jonilyn L. Yoder, Terry P. Orlando, Joel I-Jan Wang, Simon Gustavsson, Jeffrey A. Grover, Kyle Serniak, Riccardo Comin, William D. Oliver

Sponsorship: National Science Foundation Graduate Research Fellowship, Under Secretary of Defense for Research and Engineering, U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Co-design Center for Quantum Advantage

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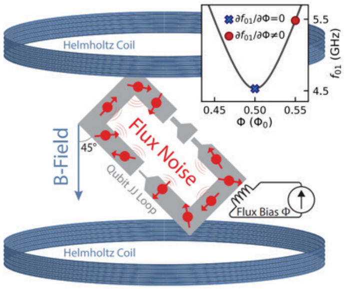
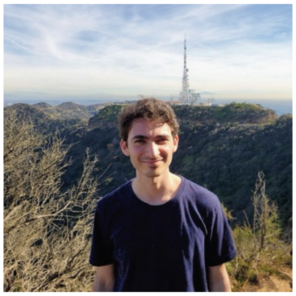
The microscopic origin of 1/f magnetic flux noise in superconducting circuits has remained an open question for decades, despite extensive experimental and theoretical investigation. Recent progress in superconducting devices for quantum information has renewed interest in this noise, as it commonly limits qubit coherence. The response of flux noise to external magnetic fields - which may shed light on its underlying microscopic physics - has yet to be studied. Here we apply weak in-plane magnetic fields to a flux qubit (where the Zeeman splitting of surface spins lies below the device temperature) and study the flux-noise-limited qubit dephasing. We observe an enhancement (suppression) of the spin-echo (Ramsey) pure dephasing time in fields up to B = 100 G. We also measure the flux-noise spectrum and observe a distinct transition in the low-frequency (< 10 Hz) spectral shape together with a reduction of the high-frequency (> 1 MHz) noise power with increasing magnetic field. We offer an interpretation of this behavior as being qualitatively consistent with increasing spin cluster sizes with applied field. These results provide new experimental constraints that should help to inform a complete microscopic theory of 1/f flux noise in superconducting circuits.





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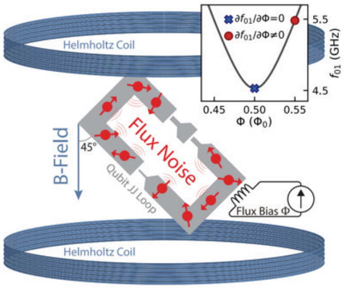
S6.08 Evolution of 1/f Magnetic Flux Noise in Superconducting Qubits with Weak Magnetic Fields

David Rower, Lamia Ateshian, Lauren H. Li, Max Hays, Dolev Bluvstein, Leon Ding, Bharath Kannan, Aziza Almanakly, Jochen Braumueller, David K. Kim, Alexander Melville, Bethany M. Niedzielski, Mollie E. Schwartz, Jonilyn L. Yoder, Terry P. Orlando, Joel I-Jan Wang, Simon Gustavsson, Jeffrey A. Grover, Kyle Serniak, Riccardo Comin, William D. Oliver

Sponsorship: NSF Graduate Research Fellowship under Grant No. 1745302, Under Secretary of Defense for Research and Engineering under Air Force Contract No. FA8702-15-D-0001, NSF award DMR-1747426

The microscopic origin of 1/f magnetic flux noise in superconducting circuits has remained an open question for decades, despite extensive experimental and theoretical investigation. Recent progress in superconducting devices for quantum information has renewed interest in this noise, as it commonly limits qubit coherence. The response of flux noise to external magnetic fields - which may shed light on its underlying microscopic physics - has yet to be studied. Here we apply weak in-plane magnetic fields to a flux qubit (where the Zeeman splitting of surface spins lies below the device temperature) and study the flux-noise-limited qubit dephasing. We observe an enhancement (suppression) of the spin-echo (Ramsey) pure dephasing time in fields up to B = 100 G. We also measure the flux-noise spectrum and observe a distinct transition in the low-frequency (< 10 Hz) spectral shape together with a reduction of the high-frequency (> 1 MHz) noise power with increasing magnetic field. We offer an interpretation of this behavior as being qualitatively consistent with increasing spin cluster sizes with applied field. These results provide new experimental constraints that should help to inform a complete microscopic theory of 1/f flux noise in superconducting circuits.



S6.09 Quantum Advantage in Continuous Variable Displacement Sensing

Jasmine Sinanan-Singh, Gabriel Mintzer, Yuan Liu, Isaac L Chuang

Sponsorship: C2QE

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Quantum systems of infinite-dimension such as bosonic oscillators provide vast resources for quantum sensing. Yet, a general theory on how to manipulate such bosonic modes for sensing is unknown. We present a general framework for algorithmic quantum sensing at the fundamental limits of quantum mechanics, i.e. the Heisenberg sensing limit. We manipulate the bosonic system by performing arbitrary polynomial transformations on the bosonic phase space using quantum signal processing (QSP) in a qubit+oscillator system. We use our bosonic QSP sensing framework to make binary decisions about signals affecting the oscillator. The sensing accuracy of a single shot qubit measurement can outperform the Heisenberg scaling as one bit of information may encode our yes/no question without violating any physical laws. Furthermore, we present a binary search algorithm that estimates an arbitrary displacement channel bit by bit.

S6.10 Diagnosis and Mitigation of Correlated Errors in Superconducting Qubits from Ionizing Radiation

Patrick M. Harrington, Mingyu Li, Wouter van de Pontseele, Daniel Mayer, David K. Kim, Bethany M. Niedzielski, Alexander Melville, Mollie E. Schwartz, Jonilyn L. Yoder, Jeffrey A. Grover, Kyle Serniak, Joseph Formaggio, William D. Oliver

Sponsorship: This research was funded by the Under Secretary of Defense for Research and Engineering under Air Force Contract No. FA8702-15-D-0001. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the USDR&E, USAF, ODNI, or DOE.

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Ionizing radiation causes momentary events of spatially-correlated superconducting qubit errors. We present the detection of multi-qubit correlated relaxation events in coincidence with cosmic ray secondary particles using scintillating detectors. These measurements identify the overall proportion of qubit errors caused by cosmic ray secondary particles versus all other sources of relaxation errors. The in-situ detection of radiation informs the sensitivity of each qubit to cosmic rays that penetrate the device substrate. Our findings reveal qubit device architectures that are less susceptible to the quasiparticles created by radiation absorption. The results of this cosmic ray coincidence measurement informs strategies that reduce the impact of ionizing radiation on quantum error correction schemes.

S7.01 Improvement on crystallinity of large scale MoTe2 thin film and electrical property of transistors by using high pressure annealing

Wen-His Lee, Lun-Wei Chen, Shih Syun Chen

Sponsorship: National Science and Technology Council

The transition metal dichalcogenides (TMDs) family of 2D materials exhibits multiple phases. Among them, MoTe2, which is particularly concerned in phase engineering applications, exhibits three phases, Td phase is a type-II Weyl semimetals, 2H phase is a semiconductor, 1T’ phase is a semimetal. With the small free energy difference between the semiconducting 2H phase and the metallic 1T' phase, the two phases of MoTe2 can naturally coexist. This 1T'−2H MoTe2 heterophase homojunction provides an elegant solution for ohmic contacts in 2D semiconductors.
In this work, we reveal that by a high pressure annealing (HPA) before post-tellurization, molybdenum or molybdenum oxide are able to form high-quality and highly crystalline MoTe2 2D films. And it shows a high switching ratio (104) and a good mobility (11 cm2V-1s-1), which will be helpful for the development of two-dimensional semiconductor logic elements. In addition, HPA process can effectively control the phase transition by using different kinds of gas atmosphere. The 2H-MoTe2 and can be obtained by tellurizing an oxygen HPA – Mo film, and the 1T’-MoTe2 can be obtained by using nitrogen during the HPA process. This work provides a process approach for ohmic contacts in low-dimensional large-area integrated circuits.

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S7.02 Multiplication of III-V Membranes by In-Situ Graphene Growth

Ne Myo Han, Hyunseok Kim, Yunpeng Liu, Kuangye Lu, Celesta Chang, Jeehwan Kim

Sponsorship: AFRL (FA9453-18-2-0017 and FA9453-21-C-0717), DARPA (029584-00001), DOE (DE-EE0008558)

Single-crystal III-V compound semiconductors are important building blocks for functional devices due to their high electron mobilities, wide range of bandgaps, and excellent optoelectronic properties. However, current methods to produce their freestanding membranes for heterointegration suffer from slow processes or poor material quality. Here, we demonstrate an approach to grow and harvest multiple wafer-scale single-crystal membranes by introducing weak van der Waals interfaces between epitaxial layers. This is achieved by directly growing graphene on III-V semiconductors in the MOCVD, which enables alternating growth of graphene and III-V semiconductor epilayers in a single run. Each epilayer in the multi-stack structure is then sequentially harvested by mechanical exfoliation, producing multiple freestanding single-crystal membranes with extremely high throughput from a single wafer, primed for integration in mixed-dimensional heterostructures.

S7.03 Observation of a U(1) Prethermal Time Crystal

Andrew Stasiuk, Paola Cappellaro

Sponsorship: This work was supported in part by the National Science Foundation under Grants No. PHY1915218.

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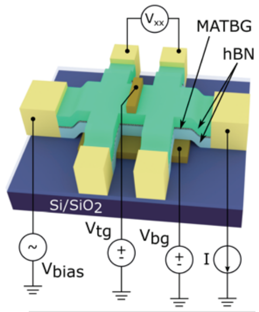
A time crystal is a novel state of periodically driven matter which breaks discrete time translation symmetry. Time crystals have been demonstrated experimentally in various programmable quantum simulators and exemplify how non-equilibrium, driven quantum systems can exhibit intriguing and robust properties absent in systems at equilibrium. These states are often stabilized by prethermalization, in which a periodically driven quantum system heats to infinite temperature exponentially slowly in the driving frequency. Recent theoretical work has developed the notion of prethermalization without temperature in order to explain time crystalline observations at (or near) infinite temperature. In this work, we utilize prethermalization without temperature to conclusively verify the emergence of a prethermal U(1) time crystalline state at infinite temperature. Here we show the existence of a long-lived prethermal regime whose lifetime is significantly enhanced by strengthening an emergent U(1) conservation law. In our solid-state NMR quantum simulator, we measure this enhancement through the global magnetization, and utilize on-site disorder to measure local observables and rule out the possibility of many-body localization.



S7.04 Highly tunable junctions and non-local Josephson effect in magic-angle graphene tunnelling devices

Daniel Rodan-Legrain, Yuan Cao, Jeong Min Park, Sergio C. de la Barrera, Mallika T. Randeria, Kenji Watanabe, Takashi Taniguchi & Pablo Jarillo-Herrero

Sponsorship: National Science Foundation, US Department of Energy, US Army Research Office, Fundación Bancaria 'la Caixa', Gordon and Betty Moore Foundation, Fundación Ramón Areces

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Magic-angle twisted bilayer graphene (MATBG) has recently emerged as a highly tunable two-dimensional material platform exhibiting a wide range of phases, such as metal, insulator, and superconductor states. Local electrostatic control over these phases may enable the creation of versatile quantum devices that were previously not achievable in other single-material platforms. Here, we exploit the electrical tunability of MATBG to engineer Josephson junctions and tunneling transistors all within one material, defined solely by electrostatic gates. Our multi-gated device geometry offers complete control over the Josephson junction, with the ability to independently tune the weak link, barriers, and tunneling electrodes. Utilizing the intrinsic bandgaps of MATBG, we also demonstrate edge tunneling spectroscopy within the same MATBG devices and measure the energy spectrum of MATBG in the superconducting phase. Furthermore, by inducing a double barrier geometry, the devices can be operated as a single-electron transistor. These MATBG tunneling devices, with versatile functionality encompassed within a single material, may find applications in tunable superconducting qubits, on-chip superconducting circuits, and electromagnetic sensing in next-generation quantum nanoelectronics.

S7.05 Assessing the Impact of Fabrication Variations on Josephson Traveling Wave Devices

A. E. Lombo, K. Peng, J. Wang, K. P. O'Brien

Sponsorship: AWS Centre for Quantum Computing

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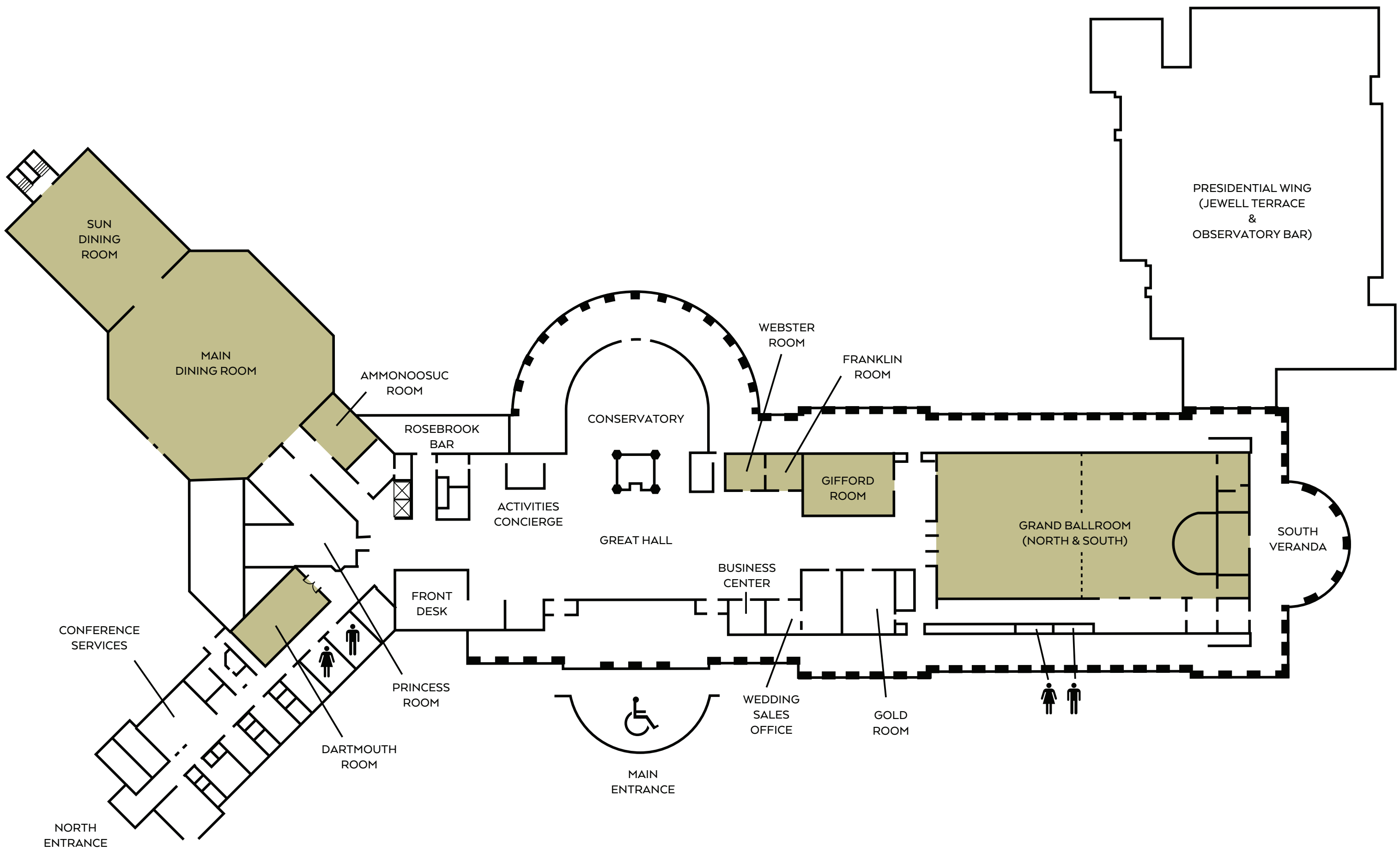
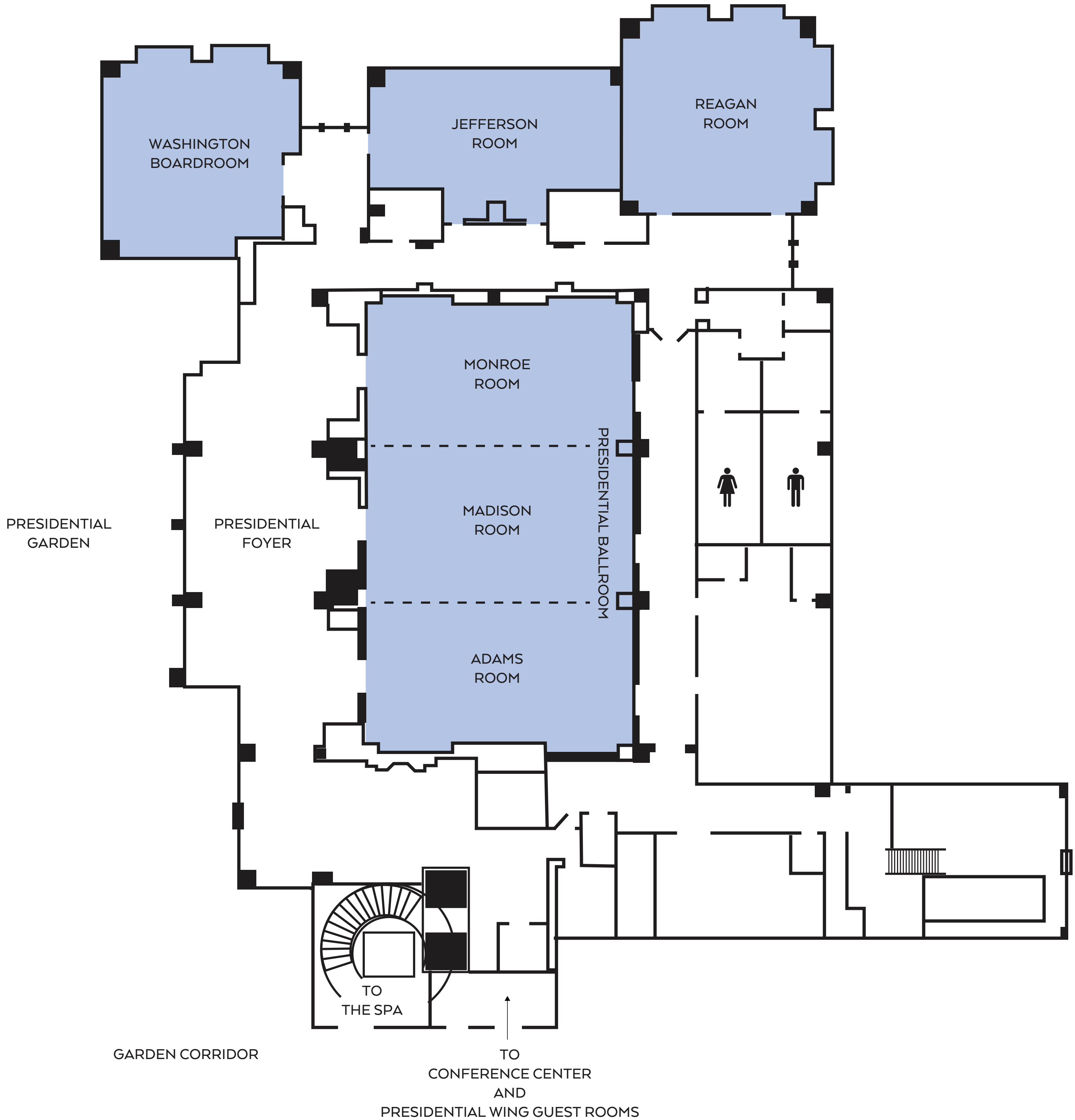
Josephson junction-based travelling wave parametric amplifiers (JTWPA) are widely used in cQED experiments for high-fidelity readout of superconducting qubits over a large bandwidth. The bandwidth results from a transmission line configuration with thousands of Josephson junctions. However, achieving high gain in such a device necessitates multi-layer structures over a large footprint. As a result, the performance can be impacted by the non-uniformity inherent in the fabrication process. In this work, we analyze the superconducting circuit performance in the presence of fabrication variations to predict the process constraints needed to enable the high reproducibility of micro and nanostructured components in the JTWPA in a planar configuration. We model cell-to-cell variations of circuit parameters and evaluate the impact of non-uniformity on the gain, quantum efficiency, return loss, and insertion loss through Monte Carlo simulations.

Maps



GREAT HALL LEVEL



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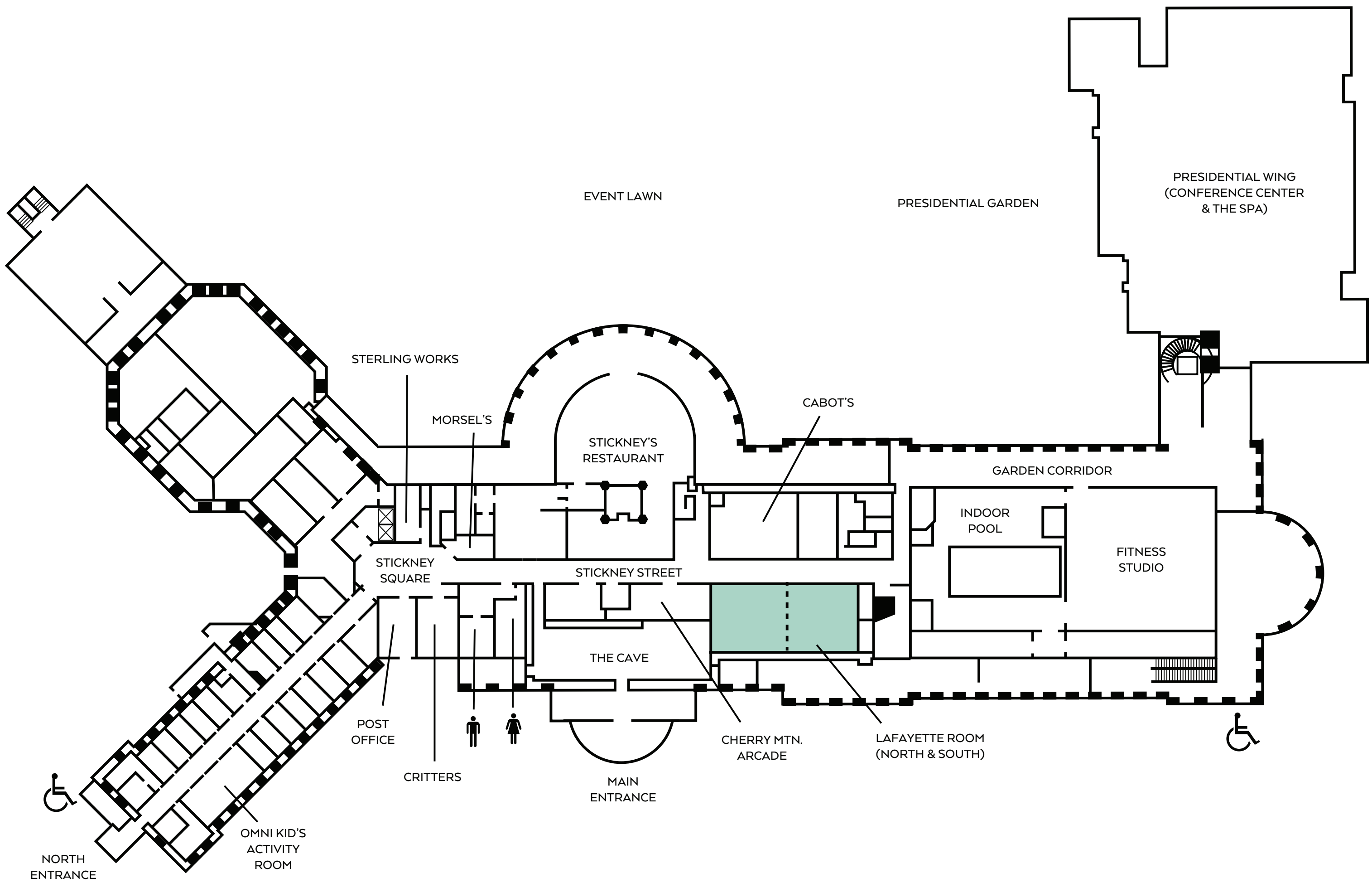

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