Coping with Errors in Scalable Quantum Computing Systems

778. WE-Heraeus-Seminar

08 Jan - 11 Jan 2023
at the Physikzentrum Bad Honnef/Germany

The WE-Heraeus Foundation supports research and education in science, especially in physics.
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Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 778. WE-Heraeus-Seminar:

Quantum computing is rapidly evolving from a basic science activity of university labs towards an enterprise with high-rising market projections, strongly increasing investments and with startups and large enterprises assessing quantum use-cases in their business sectors. In contrast to classical computers, however, quantum processors must cope with the errors that occur during computations, which limits the complexity of algorithms that can currently be run on these systems. There are two basic strategies to address this issue:

The first direction is to reduce the error rates by improving the fidelity of quantum gate operations at the hardware level by better qubit control, materials and processor packaging. In this area, impressive improvements have been made in the various quantum hardware platforms. The second option is to measure the impact of errors on quantum operations and directly correct them, with the ultimate goal of realizing a fully error-corrected universal quantum computer that can run arbitrary algorithms. In between these two extremes, the impact of errors on quantum applications can be mitigated without full error correction, which requires bringing together physical understanding of errors and algorithmic insights.

This WE-Heraeus Seminar addresses these crucial topics and brings together leading quantum scientists from academia and industry concentrating on four potentially scalable quantum architectures – ion traps, superconducting qubits, spin qubits in quantum dots and neutral atoms. The seminar will focus on recent improvements in gate fidelities and quantum control, error mitigation strategies, error detection, fast feedback and developments in error protection using error resilient encodings and stabilizer codes. Furthermore, the seminar aims to discuss advances in error correction algorithms that can be applied to currently available quantum hardware to connect theoretical predictions with experimental realization on the path towards universal quantum computing.

Scientific Organizers:

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Introduction

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Registration:

Martina Albert (WE-Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h)
and Monday (08:00 – 12:30 h)

Program

Program

Sunday, 8 January 2023

17:00 – 21:00	**Registration and mount Posters**	
From 18:30	*BUFFETT SUPPER / Informal get together*	
20:00	Organizers	**Kick-Off Scientific Program**
20:15	Daniel Gottesman	**Opportunities and Challenges in Fault-Tolerant Quantum Computation**
21:00	**Discussions at the Posters**	

Monday, 9 January 2023

07:30 – 08:45	*BREAKFAST*	
08:45 – 09:00	Organizers	**Organizational notes**

Ion Traps

09:00 – 09:45	Ciaran Ryan-Anderson	**Implementing Fault-tolerant Entangling Gates on the Five-qubit Code and the Color Code**
09:45 – 10:30	Tracy Northup	**Coping with errors in trapped-ion quantum networks**
10:30 – 11:00	*COFFEE BREAK*	

Spin Qubits

11:00 – 11:45	Seigo Tarucha	**High-fidelity quantum gates and quantum phase error correction in silicon**
11:45 – 12:30	Stefano Bosco	**Sweet spots for charge and hyperfine noise in hole spin qubits**
12:30 – 14:00	*LUNCH*	

Program

Monday, 9 January 2023

Error Correction and Error Mitigation – Theory and Algorithms

14:00 – 14:45	Barbara Terhal & Jorge Marques	**Hardware-Efficient Leakage Reduction For Superconducting Transmon Qubits**
14:45 – 15:30	Michael Hartmann	**Quantum Convolutional Neural Networks**
15:30 – 16:15	Abhinav Kandala	**Error mitigation for noisy quantum processors: a path to quantum advantage**
16:15 – 16:45	*COFFEE BREAK*	

Superconducting Qubits

16:45 – 17:30	James Robin Wootton	**Quantum Error Correction Experiments at IBM Quantum**
17:30 – 18:15	Simone Gasparinetti	**Coherent-state process tomography of continuous-variable quantum gates**
18:30	*HERAEUS DINNER at the Physikzentrum* *(cold and warm buffet, with complimentary drinks)*	

Program

Tuesday, 10 January 2023

07:30 – 08:30	*BREAKFAST*	

Superconducting Qubits

08:30 – 09:15	Kevin Satzinger	**Suppressing quantum errors by scaling a surface code logical qubit**
09:15 – 10:00	Andreas Wallraff	**A Distance-Three Surface Code Realized in Superconducting Circuits**
10:00 – 10:30	*COFFEE BREAK*	
10:30 – 11:15	Max Werninghaus	**Black box optimization of computational gates for superconducting qubits**

Ion Traps

11:15 – 12:30	Jonathan Home	**Quantum error correction with motional states of trapped ions**
12:30 – 14:00	*LUNCH*	
14:00 – 14:15	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**

Neutral Atoms

14:15 – 15:00	Alexandre Dareau	**Quantum Computing with Neutral Atoms: an Experimenter's Perspective**
15:00 – 15:45	Wenchao Xu	**Quantum science with Rydberg ensembles: from one to many**
15:45 – 16:00	*COFFEE BREAK*	

Program

Tuesday, 10 January 2023

16:00 – 17:00	**Podiumsdiskussion** **« Der Weg zum Quantenvorteil »**

- Braucht es die Quantenfehlerkorrektur für praxistaugliche Anwendungen von Quantencomputern?
- Wo sind die Grenzen bezüglich Verbesserungen in der Kohärenz von Qubits?
- Welche Anwendungen eignen sich für NISQ Systeme?
- Können wir mit NISQ Systemen einen praxistauglichen Quantenvorteil zeigen?
- Wie können wir die extrem kleinen Fehlerraten erreichen, welche gewisse Simulationsaufgaben benötigen?
- Wie steht Europa im Vergleich zu anderen Ländern auf dem Weg von NISQ Systemen zu universellen Quantenrechnern?

17:00 – 18:30	**Flash Poster Session**
18:30 – 19:30	*DINNER*
19:30	**Poster Session continued**

Program

Wednesday, 11 January 2023

07:30 – 08:30	*BREAKFAST*	

Spin Qubits

08:30 – 09:15	Natalia Ares	**Machine learning for tackling quantum device variability**
09:15 – 10:00	Menno Veldhorst	**Quantum computing with germanium**
10:00 – 10:30	*COFFEE BREAK*	
10:30 – 11:15	Yann-Michel Niquet	**Engineering sweet spots in hole spin qubits**

Error Correction and Error Mitigation – Theory and Algorithms

11:15 – 12:00	Markus Müller	**Fault-Tolerant QEC: From Disordered Spin Models to First Universal Logical Gates**
12:00 – 12:45	Guillermo García Perez	**Mitigating noise on and with informationally complete measurements**

12:45 – 14:15	*LUNCH*	
14:15 – 15:00	Balint Koczor	**Will (near-term) quantum computers deliver real advantage?**
15:00 – 15:30	Organizers	**Poster Award and Closing Session**

15:30 – 18:00	**Walk to local sight-seeing spot**
18:30	*DINNER*

Program

Thursday, 12 January 2023

07:30 – 08:30 *BREAKFAST*

End of seminar and departure

Abstracts of Lectures

(in alphabetical order)

Machine learning for tackling quantum device variability

N. Ares[1]

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Machine learning is proving to be essential in the tuning and characterization of quantum devices. The search for operation conditions, which often requires navigating large and complex parameter spaces, can now be fully automated, with performances superior to those achieved by human experts [1]. Now these machine learning approaches are not only enabling scalability by automating qubit control, but also by providing us with unprecedented insight into quantum device variability.

We can use these machine learning algorithms for automatic tuning across different semiconductor platforms [2]. This demonstrates not only the robustness of these algorithms against the differences in the characteristics of the material system and device architecture, but that they can provide a tool for their comparison and analysis.

I will show that by using a physics-aware machine learning algorithm we are able to infer the disorder potential affecting the operation of quantum dot devices, revealing a hidden characteristic of such devices, and thus narrowing the gap between simulation and reality [3].

References

[1] N. Ares. Machine learning as an enabler of qubit scalability. Comment - Nature Reviews Materials 6, 870 (2021)

[2] B. Severin, D. T. Lennon, L. C. Camenzind, F. Vigneau, F. Fedele, D. Jirovec, A. Ballabio, D. Chrastina, G. Isella, M. de Kruijf, M. J. Carballido, S. Svab, A. V. Kuhlmann, F. R. Braakman, S. Geyer, F. N. M. Froning, H. Moon, M. A. Osborne, D. Sejdinovic, G. Katsaros, D. M. Zumbühl, G. A. D. Briggs, N. Ares, Cross-architecture Tuning of Silicon and SiGe-based Quantum Devices Using Machine Learning. arXiv:2107.12975.

[3] D.L. Craig, H. Moon, F. Fedele, D.T. Lennon, B. Van Straaten, F. Vigneau, L.C. Camenzind, D.M. Zumbühl, G.A.D. Briggs, M.A. Osborne, D. Sejdinovic, N. Ares, Bridging the reality gap in quantum devices with physics-aware machine learning. arXiv:2111.11285.

Sweet spots for charge and hyperfine noise in hole spin qubits

Stefano Bosco and Daniel Loss

University of Basel, Basel, Switzerland

Hole spin qubits in silicon and germanium quantum dots are promising platforms for quantum computing because of their large spin-orbit interactions, permitting efficient and ultrafast all-electric qubit control and strong spin-photon coupling. On the other hand, spin-orbit interactions also couple the qubit to charge noise, reducing its coherence time. I will discuss ways to engineer and tune the spin-orbit interaction in order to enable sweet spots where the charge noise can be completely removed [1,2,3].

We find that charge noise can be suppressed in silicon fin field effect transistors, one of the leading candidates for scalable semiconductor quantum computers. Interestingly, in these systems also the noise caused by hyperfine interactions with nuclear spins -another leading source of decoherence in spin qubits- can be suppressed at the sweet spots, greatly enhancing the coherence of these qubits, and reducing the need for expensive isotopically purified materials [4].

References

[1] Bosco, Hetényi, and Loss, *PRX Quantum* **2**, 010348 (2021)
[2] Bosco and Loss, *Phys. Rev. Applied* **18**, 044038 (2022)
[3] Adelsberger, Benito, Bosco, Klinovaja, and Loss, *PRB* **105**, 075308 (2022)
[4] Bosco and Loss, *Phys. Rev. Letters* **127**, 190501 (2021)

Quantum Computing with Neutral Atoms: an Experimenter's Perspective

A. Dareau[1]

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In the past few years, **neutral atoms** have entered the quantum computing race as serious contenders to long-established players such as superconducting- or ion-based platforms. Neutral-atom-based platforms build on an innovative technique pioneered by the group of A. Browaeys and T. Lahaye [1] to **trap individual atoms in a configurable, defect-free array**. Interactions between atoms can then be controlled by exciting them to a highly excited Rydberg state.

This platform has already demonstrated its versatility, especially in the field of **quantum simulation**, where it has recently allowed to simulate quantum many-body systems in **regimes that are out of reach with current classical approaches** [2]. In the context of quantum computing, applications have been proposed and demonstrated regarding **optimization problems solving** [3] or **gate implementation** [4]. Those successes have raised the attention of the quantum community, such that many academic groups worldwide have started to build and operate such platforms. More recently, **quantum startups such as PASQAL** have emerged, with the aim to harness the potential of this technology to deliver a neutral-atom based quantum processing platform [5].

In this talk, I will give an introduction to this platform, focusing on an experimental perspective. I will present the underlying physical ingredients and technological building blocks, as well as a short review of the main achievements that have paved its history. I will then present the main challenges this platform is currently facing, and the paths being explored to circumvent them.

PASQAL (www.pasqal.com) is a French startup designing and developing neutral-atom based QPUs, funded in 2019 as a spin-off of the Browaeys' group.

References

[1] A. Browaeys and T. Lahaye, Nature Physics **16**, 132–142 (2020).
[2] P. Scholl *et al.,* Nature **595**, 233–238 (2021).
[3] S. Ebadi *et al.*, Science **376**, 1209-1215 (2022).
[4] K. M. Maller *et al.,* Phys. Rev. A **92**, 022336 (2015).
[5] L. Henriet *et al.,* Quantum **4**, 327 (2020).

Mitigating noise on and with informationally complete measurements

Guillermo García-Pérez[1]

[1] *Algorithmiq Ltd, Helsinki, Finland*

Simulating many-body quantum physics is one of the most promising applications in near-term quantum computing. However, several challenges need to be tackled. In addition to the detrimental effects of noise, the algorithms that can be run on near-term devices suffer from efficiency issues that must be tackled too. In this talk, I will briefly explain how the use of informationally complete generalised measurements (IC POVM) can be exploited to speed up these methods, how IC POVM can be implemented on noisy hardware and, finally, how the use of IC data opens new avenues to mitigate errors in post-processing using tensor network methods.

References

[1] G. García-Pérez, M. A. C. Rossi, B. Sokolov, F. Tacchino, P. Kl. Barkoutsos, G. Mazzola, I. Tavernelli, S. Maniscalco, PRX Quantum **2**, 040342 (2021)

[2] A. Glos, A. Nykänen, E.-M. Borrelli, S. Maniscalco, M. A. C. Rossi, G. García-Pérez, arXiv:2208.07817 (2022)

[3] G. García-Pérez, E.-M. Borrelli, M. Leahy, J. Malmi, S. Maniscalco, M. A. C. Rossi, B. Sokolov, D. Cavalcanti, arXiv:2207.01360 (2022)

Coherent-state process tomography of continuous-variable quantum gates

M. Kervinen[1], M. Kudra[1], S. Ahmed[1], A. Eriksson[1], F. Quijandría[1], A. Frisk Kockum[1], P. Delsing[1], and S. Gasparinetti[1]

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A promising approach to quantum computing relies on encoding logical quantum information in harmonic oscillators. Choosing certain superpositions of Fock states as logical states provides protection against errors, but at the price of requiring more complex quantum gates that address multiple Fock states simultaneously. To accurately characterize these gates, quote their fidelity, and draw up a reliable error budget, remains a challenge. Here, we demonstrate the use of coherent-state process tomography to characterize quantum gates on bosonic encodings. Our method uses coherent states as input probes and direct Wigner tomography to reconstruct the process matrix of the gate under test. In contrast to other methods, the process matrix describes the action of the gate on the full Fock space in which the logical states are embedded. As an example, we characterize a logical X gate performed on a qubit encoded using the binomial encoding. The gate is performed using a sequence of SNAP gates and displacements [1]. Finally, we discuss different representations of the process matrix and how they can be used to learn about different types of error.

References

[1] M. Kudra *et al.*, Robust Preparation of Wigner-Negative States with Optimized SNAP-Displacement Sequences, PRX Quantum **3**, 030301 (2022)

Opportunities and Challenges in Fault-Tolerant Quantum Computation

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Abstract

I will give an overview of what I see as some of the most important future directions in the theory of fault-tolerant quantum computation. In particular, I will give a brief summary of the major problems that need to be solved in fault tolerance based on low-density parity check codes and in hardware-specific fault tolerance. I will then conclude with a discussion of a possible new paradigm for designing fault-tolerant protocols based on a space-time picture of quantum circuits.

Quantum Convolutional Neural Networks

Michael J. Hartmann

Friedrich-Alexander Universität Erlangen-Nürnberg

Quantum computing has made significant progress in recent years so that substantial gate sequences can now be run, and the output states become too complex to be fully analyzed by classical techniques. Here Quantum Convolutional Neural Networks, gate sequences that condense the relevant quantum information of the output state onto just a few qubits, can become a highly valuable tool. In this talk I will discuss how Quantum Convolutional Neural Networks can be used for recognizing a symmetry protected topological phase with a non-local order parameter by reading out just a single qubit on a superconducting quantum processor. In particular, I will focus on making Quantum Convolutional Neural Networks robust by reducing the number of quantum gates that they require and by equipping them with error tolerance mechanisms that allow to detect quantum phases despite imperfections in the prepared state.

Quantum error correction with motional states of trapped ions

J. P. Home[1]

[1]*Institute for Quantum Electronics, ETH Zürich*
Quantum Center, ETH Zürich

I will describe experimental progress aimed at realizing error-corrected quantum computing systems in the motional degree of freedom of trapped-atomic ions. We have realized many rounds of quantum error correction in GKP-encoded logical qubits, extending the logical qubit lifetime by more than a factor of 3 [1,2]. Critical to these experiments was the implementation of measurement and correction suited to experimentally accessible finite-energy states. I will present theoretical and experimental progress towards implementing multi-qubit gates in a radio-frequency trap. Furthermore, I will discuss possibilities to extend control of ions to microtrap arrays using micro-fabricated Penning traps [3], based on our recent first trapping and motional state control in such a setup.

References

[1] C. Flühmann et al., Nature 566, 513-517 (2019)
[2] B. DeNeeve et al. Nature Physics 18, 3, 296-300 (2022)
[3] S. Jain et al., PRX 10, 3, 031027 (2020)

Error mitigation for noisy quantum processors: a path to quantum advantage

Abhinav Kandala

IBM T J Watson Research Center, IBM Quantum, Yorktown Heights, USA

Quantum processors based on superconducting circuits have now reached a scale that is well beyond direct diagonalization. However, in the absence of fault tolerance, the central question is whether such noisy processors can provide useful computations. In this context, error mitigation techniques can provide access to noise-free observables even from today's noisy processors. I will introduce these techniques, discuss the current state of quantum hardware at IBM and recent experimental results, and chart out an immediately accessible path to quantum computational advantage.

Will (near-term) quantum computers deliver real advantage?

B. Koczor[1]

[1]*University of Oxford, Oxford, UK*

Quantum computers are becoming a reality and current generations of machines are already well beyond the 50-qubit frontier. However, hardware imperfections still overwhelm these devices and it is generally believed the fault-tolerant, error-corrected systems will not be within reach in the near term: a single logical qubit needs to be encoded into potentially thousands of physical qubits which is prohibitive. It is thus a very exciting challenge in the near term to achieve practical value with noisy intermediate-scale quantum (NISQ) devices.

Due to limited resources, in the near term, we need to resort to quantum error mitigation techniques. I will explain the basic concepts and then discuss recent breakthrough results on exponentially effective error mitigation [1], including an architecture of multiple quantum processors that perform the same quantum computation in parallel [2]; using their outputs to verify each other results in an exponential suppression of errors. In the second part of my talk, I will explain that the most promising candidates for achieving value in the NISQ era are variational quantum circuits. These have the potential to solve real-world problems---including optimisation or ground-state search---but their main drawback is they rely on a non-trivial optimisation (training). I will explain a recent development that uses extremely powerful classical shadows to accelerate training in a way previously thought impossible [3]. I will finally identify the most likely areas where quantum computers may deliver a true advantage in the near term.

References

[1] B. Koczor: *Exponential Error Suppression for Near-Term Quantum Devices* Physical Review X **11**, 031057 (2021)
[2] H. Jnane, B. Undseth, Z. Cai, S. C. Benjamin, B. Koczor: *Multicore Quantum Computing,* Physical Review Applied **18**, 044064 (2022)
[3] G. Boyd, B. Koczor: Physical Review X **12**, 041022 (2022)

Fault-Tolerant QEC: From Disordered Spin Models to First Universal Logical Gates

Markus Müller
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Abstract

To date, the construction of scalable fault-tolerant quantum computers remains a fundamental scientific and technological challenge, due to the influence of unavoidable noise. Quantum error correction codes allow one to protect quantum information during storage and processing. We will present strategies to detect and fight various sources of errors, including the loss of qubits, and we will present new connections between quantum error correction and classical statistical mechanics models, in the context of fundamental error thresholds for circuit noise [1]. When manipulating logical quantum states, it is imperative that errors caused by imperfect operations do not spread uncontrollably through the quantum register, requiring fault-tolerant quantum circuit designs. Here, I will discuss recent theory work and collaborative experimental breakthroughs towards fault-tolerant quantum error correction, with a focus on trapped ions. This includes the first realisation of a universal and fault-tolerant logical gate set [2] and the deterministic correction of qubit loss [3]. Furthermore, I will briefly comment on complementary explorative approaches towards robust quantum processors, based e.g. on quantum machine-learning based concepts such as recently proposed quantum autoencoders for quantum error correction [4].

[1] D. Vodola *et al.*, Fundamental thresholds of realistic quantum error correction circuits from classical spin models, Quantum 6, 618 (2022)
[2] L. Postler *et al.*, Demonstration of fault-tolerant universal quantum gate operations, Nature 605, 675 (2022)
[3] R. Stricker *et al.*, Deterministic correction of qubit loss, Nature 585, 207 (2020)
[4] D. Locher *et al.*, Quantum error correction with quantum autoencoders, arXiv:2202.00555 (2022)

Engineering sweet spots in hole spin qubits

N. Piot[1], B. Brun[1], V. Schmitt[1], S. Zihlmann[1], V. P. Michal[2], A. Apra[1], J. C. Abadillo-Uriel[2], X. Jehl[1], B. Bertrand[3], H. Niebojewski[3], L. Hutin[3], M. Vinet[3], M. Urdampilleta[4], T. Meunier[4], Y.-M. Niquet[2], R. Maurand[1], S. De Franceschi[1]

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Hole spin qubits in semiconductor quantum dots afford the unique advantage of an efficient electrical control. This control is enabled by the strong spin-orbit interaction in the valence band of semiconductors, which couples the spin to the real-space motion of the hole. Rabi frequencies in the tens of MHz range are thus routinely achieved in hole spin qubit devices. This electrical spin susceptibility, however, comes at the expense of a stronger sensitivity to charge noise and disorder.

Here, we demonstrate the existence of operations sweet spots where dephasing due to charge noise is minimized while electrical spin control is still possible. We report on a spin-orbit qubit consisting of a single hole electrostatically confined in a natural silicon metal-oxide-semiconductor device [1]. We vary the magnetic field orientation, and highlight specific directions where the Larmor frequency becomes almost independent on the gate voltage fluctuations. We correspondingly observe an extension of the Hahn-echo coherence time up to 88 µs, exceeding by an order of magnitude the best values reported for hole-spin qubits to date, and approaching the state-of-the-art for electron spin qubits with synthetic spin-orbit coupling in isotopically-purified silicon.

Detailed microscopic modeling reveals the fingerprints of residual disorder (surface roughness and charge traps) in the device. It also shows how sweet spots can be further engineered in order to achieve more resilient spin qubits. These findings enhance the prospects of silicon-based hole spin qubits for scalable quantum information processing.

References

[1] N. Piot, B. Brun *et al.*, Nature Nanotechnology **17**, 1072–1077 (2022).

Coping with errors in trapped-ion quantum networks

T. E. Northup[1]

[1]*Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Austria*

Trapped-ion quantum networks offer a route to distributed quantum computing, interconnected quantum sensors, and secure communication. However, state-of-the-art networks currently consist of just two nodes, with one or two ions per node [1, 2, 3]. Furthermore, the best fidelities for remote entanglement are still well below what has been achieved for local entanglement within a trapped-ion processor. Thus, the question of how to cope with errors looks quite different in a network setting than for a local quantum computer; while we will focus here on a trapped-ion setting, this statement holds generally across platforms.

We will first examine the state of the art for distributing quantum states faithfully between remote nodes of a quantum network. We will then investigate what limits current fidelities for remote entanglement and what some promising strategies are — both in the short term and intermediate term — to mitigate errors while still targeting high entanglement rates.

References

[1] D. Hucul, I. V. Inlek, G. Vittorini, C. Crocker, S. Debnath, S. M. Clark, and C. Monroe, Nat. Phys. **11**, 37 (2015)

[2] L. J. Stephenson, D. P. Nadlinger, B. C. Nichol, S. An, P. Drmota, T. G. Ballance, K. Thirumalai, J. F. Goodwin, D. M. Lucas, and C. J. Balance, Phys. Rev. Lett. **124**, 110501 (2020)

[3] V. Krutyanskiy, M. Galli, V. Krcmarsky, S. Baier, D. A. Fioretto, Y. Pu, A. Mazloom, P. Sekatski, M. Canteri, M. Teller, J. Schupp, J. Bate, M. Meraner, N. Sangouard, B. P. Lanyon, T. E. Northup, arXiv:2208.14907 (2022)

Implementing Fault-tolerant Entangling Gates on the Five-qubit Code and the Color Code

C. Ryan-Anderson[1], N. C. Brown[1], M. S. Allman[1], B. Arkin[1], G. Asa-Attuah[2], C. Baldwin[1], J. Berg[1], J. G. Bohnet[1], S. Braxton[1], N. Burdick[2], J. P. Campora[1], A. Chernoguzov[1], J. Esposito[1], B. Evans[1], D. Francois[1], J. P. Gaebler[1], T. M. Gatterman[1], J. Gerber1, K. Gilmore[1], D. Gresh[1], A. Hall[1], A. Hankin[1], J. Hostetter[2], D. Lucchetti[1], K. Mayer[1], J. Myers[2], B. Neyenhuis[1], J. Santiago[2], J. Sedlacek[2], T. Skripka[1], A. Slattery[2], R. P. Stutz[1], J. Tait[2], R. Tobey[1], G. Vittorini[2], J. Walker[1], and D. Hayes[1]

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We compare two different implementations of fault-tolerant entangling gates on logical qubits. In one instance, a twelve-qubit trapped-ion quantum computer is used to implement a non-transversal logical CNOT gate between two five qubit codes. The operation is evaluated with varying degrees of fault tolerance, which are provided by including quantum error correction circuit primitives known as flagging and pieceable fault tolerance. In the second instance, a twenty-qubit trapped-ion quantum computer is used to implement a transversal logical CNOT gate on two [[7,1,3]] color codes. The two codes were implemented on different but similar devices, and in both instances, all of the quantum error correction primitives, including the determination of corrections via decoding, are implemented during runtime using a classical compute environment that is tightly integrated with the quantum processor. For different combinations of the primitives, logical state fidelity measurements are made after applying the gate to different input states, providing bounds on the process fidelity. We find the highest fidelity operations with the color code, with the fault-tolerant SPAM operation achieving fidelities of 0.99939(15) and 0.99959(13) when preparing eigenstates of the logical X and Z operators, which is higher than the average physical qubit SPAM fidelities of 0.9968(2) and 0.9970(1) for the physical X and Z bases, respectively. When combined with a logical transversal CNOT gate, we find the color code to perform the sequence--state preparation, CNOT, measure out--with an average fidelity bounded by [0.9957,0.9963]. The logical fidelity bounds are higher than the analogous physical-level fidelity bounds, which we find to be [0.9850,0.9903], reflecting multiple physical noise sources such as SPAM errors for two qubits, several single-qubit gates, a two-qubit gate and some amount of memory error.

Suppressing quantum errors by scaling a surface code logical qubit

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Quantum error correction offers a path to algorithmically-relevant error rates by encoding logical qubits within many physical qubits, where increasing the number of physical qubits enhances protection against physical errors. However, introducing more qubits also increases the number of error sources, so the density of errors must be sufficiently low in order for logical performance to improve with increasing code size. In this talk, we report the measurement of logical qubit performance on distance-3 and distance-5 surface codes on a Sycamore superconducting processor, and demonstrate that our code has sufficient performance to overcome the additional errors from increasing qubit number [1].

References

[1] Suppressing quantum errors by scaling a surface code logical qubit, Google Quantum AI, arXiv:2207.06431 (2022)

High-fidelity quantum gates and quantum phase error correction in silicon

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Silicon is a promising platform for making spin qubits in quantum computing, because of the long intrinsic coherence time and compatibility with advanced semiconductor manufacturing technology. Taking these advantages high-fidelity quantum operations have been achieved and industrial approaches have been employed to fabricate multi-qubit devices. In this talk I will review updated development of high control fidelities of single- and two-qubit gates [1, 2]. Based on the results of the quantum gate experiments we have developed three qubit operations for implementing quantum error correction, including generation of a three-spin entangled state [3] and a Toffoli gate, and finally achieved the three qubit phase error correction [4]. Lastly I will discuss the charge noise effects to influence the qubit fidelity in multi-qubit devices. We observe an apparent noise correlation between qubits, which may influence the performance of multi-qubit entanglement as well as quantum error correction.

[1] J. Yoneda et al., Nature Nanotechnol. 13, 102 (2018).
[2] A. Noiri et al., Nature 601, 338 (2022).
[3] K. Takeda et al. Nature Nanotechnol. 16, 965 (2021).
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Hardware-Efficient Leakage Reduction For Superconducting Transmon Qubits

Barbara Terhal & Jorge Ferreira Marques
(QuTech & Delft University of Technology)

Leakage outside of the qubit computational subspace poses a challenge to quantum error correction. We propose a leakage-reduction unit (LRU) mitigating this issue, with the purpose of running a transmon-based surface code, without requiring additional overhead in terms of hardware or QEC-cycle time. We report on the experimental success of realizing the LRU, and demonstrate its performance in a repeated 2-qubit parity check.

Quantum computing with germanium

M. Veldhorst[1]

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Delft, The Netherlands*

Semiconductor qubits have long been considered as a promising platform for quantum computing. Recently, germanium emerged as an excellent material with unique properties for qubit driving and a low-noise environment for long quantum coherence. In this talk I will present our efforts on scaling germanium quantum technology. Highlights include single qubit operation with fidelity F=99.99%, a record for semiconductor qubits, and the simultaneous operation of multiple qubits. Together with two-qubit, three-qubit and four-qubit gates, this enables to operate quantum circuits such as four-qubit entangling circuits and phase-flip codes for rudimentary error correction. Moving forward, we have operated two-dimensional quantum dot arrays hosting up to 16 quantum dots, performed coherent shuttling through quantum dot arrays, and defined new methods to obtain uniform potential landscapes. Together these results give prospects to scale semiconductor quantum technology.

A Distance-Three Surface Code Realized in Superconducting Circuits*

Andreas Wallraff [1]
[1] *Department of Physics, ETH Zurich, Switzerland*

Superconducting electronic circuits are ideally suited for studying quantum physics and its applications. Since complex circuits containing hundreds or thousands of elements can be designed, fabricated, and operated with relative ease, they are one of the prime contenders for realizing quantum computers. Currently, both academic and industrial labs vigorously pursue the realization of universal fault-tolerant quantum computers. However, building systems which can address commercially relevant computational problems continues to require significant conceptual and technological progress. For fault-tolerant operation quantum computers must correct errors occurring due to unavoidable decoherence and limited control accuracy. Here, we demonstrate quantum error correction using the surface code, which is known for its exceptionally high tolerance to errors. Using 17 physical qubits in a superconducting circuit we encode quantum information in a distance-three logical qubit building up on our distance-two error detection experiments [1]. In an error correction cycle taking only 1.1 µs, we demonstrate the preservation of four cardinal states of the logical qubit. Repeatedly executing the cycle, we measure and decode both bit- and phase-flip error syndromes using a minimum-weight perfect-matching algorithm in an error-model-free approach and apply corrections in postprocessing. We find a low logical error probability of 3 % per cycle [2]. The measured characteristics of our device agree well with a numerical model. Our demonstration of repeated, fast, and high-performance quantum error correction cycles, together with recent advances in ion traps, support our understanding that fault-tolerant quantum computation will be practically realizable.

[1] C. Kraglund Andersen et al., Nature Physics 16, 875–880 (2020)
[2] S. Krinner, N. Lacroix et al., Nature 605, 669–674 (2022)

*This work was done in collaboration with Sebastian Krinner, Nathan Lacroix, Ants Remm, Agustin Di Paolo, Elie Genois, Catherine Leroux, Christoph Hellings, Stefania Lazar, Francois Swiadek, Johannes Herrmann, Graham J. Norris, Christian Kraglund Andersen, Markus Müller, Alexandre Blais, Christopher Eichler, and Andreas Wallraff.

Black box optimization of computational gates for superconducting qubits.

Max Werninghaus[1] and S. Filipp[2]

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The optimization of quantum operations on superconducting qubits is crucial to allow for the accurate execution of quantum circuits. As experimental systems are subject to drifts, it is required to frequently re-optimize complex control shapes to maintain high fidelity operations. Here, I will report on our research on simultaneous optimization procedures of large parameter sets for such control shapes, and discuss the time budget requirements to maximize the uptime of superconducting qubit based quantum computers.

Quantum Error Correction Experiments at IBM Quantum

J. R. Wootton

IBM Quantum, IBM Research Europe - Zurich

We give an overview of recent quantum error correction experiments at IBM Quantum. In particular, the distance 2 code presented in [1], and the distance 3 code of [3]. We will also introduce Qiskit-QEC [3], a new software framework for quantum error correction. In particular, we will look at how this can be used to run experiments to benchmark progress towards fault-tolerance on current quantum hardware.

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[1] E. Chen, et al., Phys. Rev. Lett. **128**, 110504 (2022)
[2] N. Sundaresan et al., arXiv: 2203.07205 (2021)
[3] https://github.com/qiskit/qiskit-qec

Quantum science with Rydberg ensembles: from one to many

Wenchao Xu

ETH Zurich, Physics, Zurich, Switzerland

Quantum science promises great potential to revolutionize our current technologies such as quantum simulation and computation. Arrays of individual atoms trapped in optical tweezers has emerged as an attractive architecture for implementing quantum technologies. Rydberg states of atoms are often used to facilitate two-qubit gate operations and to simulate quantum many-body systems. However, for most schemes, readout of a Rydberg qubit is a destructive process that precludes its reuse and the application of many quantum error-correcting protocols.

To address these challenges, we take an alternative approach based on arrays of atomic ensembles. By harnessing the collective optical response of the atomic ensemble, we demonstrate a rapid preparation, manipulation, and non-demolish readout of a single Rydberg qubit embedded in an atomic ensemble. Scaling up the system towards large arrays of atomic ensembles have been achieved with apparatus upgrade, and preliminary results have demonstrated fast, parallel qubit readout.
If time allows, at the end of this talk, I will outline my proposed research at ETH Zurich.

Posters

Posters

Kiran Adhikari	**Quantum Cryptographic protocols from Random Circuit Sampling**
Ben Barber	**Post-selection-free preparation of high-quality physical qubits**
Jonas Bylander	**Extensive characterization and implementation of a family of three-qubit gates**
Alessandro Ciani	**Microwave-activated gates between a fluxonium and a transmon qubit**
Ish Dhand	**Designing logical qubits via easy-to-use and featured simulation software**
Carlos Alberto Diaz Lopez	**Considering spatial correlations within the circuit noise model to calculate weights on a decoder graph**
Daniel Egger	**Well-conditioned multi-product formulas for hardware-friendly Hamiltonian simulation**
Anders Enevold Dahl Karsten Flensberg Morten Kjaergaard Svend Krøjer	**Overcoming barriers: Fast universal control of a qubit with variable protection**
Francisco Fernandes Pereira	**Entanglement-assisted Quantum Codes from Cyclic Codes**
Regina Finsterhoelzl	**Error correcting codes on near-term devices of quasi-linear and central-spin-like connectivity**
Uwe R. Fischer	**Implementation-independent sufficient condition of the Knill-Laflamme type for the autonomous protection of logical qudits by strong engineered**

Posters

Niklas Glaser	**Tunable-coupler mediated multi-qubit controlled-phase gates with superconducting qubits**
Mats Granath	**From maximum likelihood to machine learning based decoding of topological stabilizer codes**
Bence Hetényi	**Anomalous zero-field splitting for hole spin qubits in Si and Ge quantum dots [1]**
Sascha Heußen	**Strategies for practical advantage of fault-tolerant circuit design in noisy trapped-ion quantum computers**
Joris Kattemölle	**Error correlations can improve the performance of variational quantum algorithms**
Andreas Ketterer	**Quantum gate-error and crosstalk characterization on superconducting transmon processors**
Berend Klaver	**Error correction for universal parity computing**
Kathrin König	**New techniques to improve zero-noise extrapolation on superconducting qubits**
Nathan Lacroix	**Realizing Repeated Quantum Error Correction in a Distance-Three Surface Code**
Yanan Liu	**Greedy versus Map-based Optimized Adaptive Algorithms for random-telegraph-noise mitigation by spectator qubits**
Bohan Lu	**Improved decoding of quantum LDPC codes using neural-network enhanced belief propagation**

Posters

Nathan McMahon	**Renormalisation Through The Lens of Quantum Convolutional Neural Networks (QCNNs)**
Julius Mildenberger	**Implementing Lattice Gauge Theories in Digital Quantum Simulators**
Jayshankar Nath	**A co-design superconducting quantum circuit for quantum simulations**
Josias Old	**Generalized Belief Propagation Algorithms for Decoding of Surface Codes**
Marita Oliv	**The Effect of Noise on the Performance of the Variational Quantum Eigensolver**
Kimin Park	**Slowing quantum decoherence of oscillators by hybrid processing**
Manuel Rispler	**Statistical-mechanics mappings for decoding QEC codes under circuit-level**
Ivan Rojkov	**Characterization and mitigation of coherent errors of near-term quantum devices**
Federico Roy	**Implementation of Fractional State Transfer on a Superconducting Qubit Chain**
Felix Rupprecht	**A simple error mitigation strategy for variational quantum algorithms**
Krishnakumar Sabapathy	**Holi codes and how to find them!**
Roberto Sailer	**Towards a repetitive simple quantum error correction in a nitrogen-vacancy spin system**

Posters

Gian Salis	**Reflectometric readout of quantum devices: microwave sideband interferometer and tank circuits with superconducting inductors**
Simon Schnake	**Impact of Quantum Noise on QGAN Training**
Alexander Simm	**Two qubits in one transmon - QEC without ancilla hardware**
Vanita Srinivasa	**Scalable approach for enhanced-range entanglement of electron spin qubits**
Basudha Srivastava	**Efficient decoding schemes for the XYZ2 hexagonal stabilizer code**
Jonathan Steinberg	**Optimizing shadow tomography with generalized measurements**
Tobias Stollenwerk	**Selective error mitigation for hard constraints in approximate quantum optimization algorithms**
Konstantin Tiurev	**The domain wall color code**
Sabine Tornow	**Measurement induced quantum walks on an IBM Quantum Computer**
Valle Varo	**Precise Quantum Angle Generator Designed for Noisy Quantum Devices**
Martin Wagener	**Towards entangling gates between bosonic qubits in trapped ions**
Lena Wagner	**Quantum Algorithms for the One-Dimensional Poisson Equation**
Christopher Warren	**Generating highly entangled states using a single-shot three-qubit gate**

Posters

Nicolas Wittler	**Co-design for quantum computing devices with optimal control**
Petr Zapletal	**Error-tolerant quantum convolutional neural networks for the recognition of symmetry-protected topological phases**

Abstracts of Posters

(in alphabetical order)

Quantum Cryptographic protocols from Random Circuit Sampling

K.Adhikari[1] and C.Deppe[1]

[1] *Institute for Communications Engineering, Technical University of Munich*

In an ongoing quest for Quantum Advantage, much focus is being given to quantum random circuit sampling tasks relevant to NISQ Era Quantum Supremacy experiments. One weakness of such NISQ Era Experiments is their limited applications. In this regard, we propose an application of random circuit experiments for quantum cryptographic protocols called Quantum Secret Sharing. Quantum Secret Sharing is a well-studied cryptographic protocol where a dealer shares an unknown quantum state to a set of players with the condition that only an authorized subgroup can recover it. Quantum Information scrambling, which describes properties of random circuit sampling, is a phenomenon in many body systems, where local disturbances get increasingly delocalized as time evolves. We study the equivalence between these two phenomena from the perspective of quantum error correction, decoupling theorems, and information theory based arguments. Further applications of this equivalence are discussed

Post-selection-free preparation of high-quality physical qubits

<u>Ben Barber</u>[1], Neil I. Gillespie[1] and J. M. Taylor[1]

[1] *Riverlane, Cambridge, UK*

Preparation and measurement of qubits could become a dominant source of error as gate fidelities improve. Preparation can be improved using auxiliary qubits and post-selection, but post-selection greatly complicates the scheduling of processes like syndrome extraction in a machine targeting fault-tolerance.

We present a family of quantum circuits that prepare high-quality $|0\rangle$ states without post-selection, instead using CNOT and Toffoli gates to non-linearly permute the computational basis. We find meaningful performance enhancements when two-qubit gate fidelities errors go below 0.2%, and even better performance when native Toffoli gates are available.

References

[1] Ben Barber, Neil I. Gillespie and J. M. Taylor, arXiv:2209.05391

Extensive characterization and implementation of a family of three-qubit gates

**C. W. Warren, J. Fernández-Pendás, S. Ahmed, T. Abad,
A. Bengtsson, J. Biznárová, A. Fadavi Roudsari, X. Gu, C. Križan,
A. Osman, P. Delsing, G. Johansson, A. Frisk Kockum, G. Tancredi,
and J. Bylander**

Chalmers University of Technology, Gothenburg, Sweden

While all quantum algorithms can be expressed in terms of single-qubit and two-qubit gates, more expressive gate sets can help reduce the algorithmic depth. This is important in the presence of gate errors, especially those due to decoherence. Using superconducting qubits, we have implemented a three-qubit gate by simultaneously applying two-qubit operations, thereby realizing a three-body interaction. This method straightforwardly extends to other quantum hardware architectures, requires only a "firmware" upgrade to implement, and is faster than its constituent two-qubit gates. The three-qubit gate represents an entire family of operations, creating flexibility in quantum-circuit compilation. We demonstrate a process fidelity of 97.90%, which is near the coherence limit of our device. We then generate two classes of entangled states, the GHZ and W states, by applying the new gate only once; in comparison, decompositions into the standard gate set would have a two-qubit gate depth of two and three, respectively. Finally, we combine characterization methods and analyze the experimental and statistical errors on the fidelity of the gates and of the target states.

Reference

C. W. Warren et al. arXiv:2207.02938 (2022)

Microwave-activated gates between a fluxonium and a transmon qubit

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We propose and analyze two types of microwave-activated gates between a fluxonium and a transmon qubit, namely a cross-resonance (CR) and a CPHASE gate. For a medium-frequency fluxonium qubit, the transmon-fluxonium system allows for a cross-resonance effect mediated by the higher levels of the fluxonium over a wide range of transmon frequencies. This allows one to realize the cross-resonance gate by driving the fluxonium at the transmon frequency, mitigating typical problems of the cross-resonance gate in transmon-transmon chips related to frequency targeting and residual ZZ coupling. However, when the fundamental frequency of the fluxonium enters the low-frequency regime below 100 MHz, the cross-resonance effect decreases leading to long gate times. For this range of parameters, a fast microwave CPHASE gate can be implemented using the higher levels of the fluxonium. In both cases, we perform numerical simulations of the gate showing that a gate fidelity above 99% can be obtained with gate times between 100 and 300 ns. Next to a detailed gate analysis, we perform a study of chip yield for a surface code lattice of fluxonia and transmons interacting via the proposed cross-resonance gate. We find a much better yield as compared to a transmon-only architecture with the cross-resonance gate as native two-qubit gate.

References

[1] A. Ciani, B. Varbanov, N. Jolly, C. K. Andersen, Phys. Rev. Research 4, 043127 (2022)

Designing logical qubits via easy-to-use and featured simulation software

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Designing fault-tolerant quantum computers using inevitably noisy devices is challenging because of the lack of analytical methods for studying thresholds and overheads. Current simulation tools are not suitable for the demanding requirements of today, where numerous industry and academic groups are experimentally realizing first logical qubits and also developing and showcasing blueprints towards fault-tolerance in the presence of many different hardware imperfections. The requirements boil down to (i.) fast simulations of thousands of qubits as necessary for fault-tolerance (ii.) high-performance decoding algorithms and implementations (iii.) a broad database of noise models present in realistic hardware of different platforms and (iv.) the ability to easily visualize different aspects of fault-tolerance and logical qubit performance.

We present a software that meets these requirements. The software enables non-experts in fault-tolerance design logical qubit experiments with ease through minimal code and FT-tailored visualization tools. For experts in fault tolerance, we provide broad functionality including (i.) a fast tableau simulator (ii.) a vast array of error models including Pauli errors, measurements, qubit loss, fabrication errors and more, (iii.) high-performance matching-based and union-find decoders. We expect that this end-to-end simulation software, owing to its ease of use and state-of-the-art functionality will be an invaluable tool for industry and academic groups in quantum computing. All participants of the workshop will be provided access to a free trial of the software.

Considering spatial correlations within the circuit noise model to calculate weights on a decoder graph

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Achieving fault tolerance requires access to not only the highest quality of quantum hardware but also accurate and fast decoders to find and correct errors. Accuracy of decoders can be increased without a loss in speed by specifying weights to the syndrome graph based on the probabilities of errors that occur on the qubits and gates. Specifying weights is relatively straightforward in the so-called phenomenological error model, i.e., with single errors acting on data qubits and measurement outcomes, because there is a direct relation between error probabilities and weights on the edges of the syndrome graph [1]. However, for demanding real-world applications, it is preferable to exploit a so-called circuit noise error model, which includes a detailed description of all the errors that occur during the implementation of a quantum error correcting circuit. Decoder weights can be calculated from the circuit noise error model via a calculation of the effective phenomenological error model. This calculation is nontrivial because errors that occur on ancilla qubits or entangling gates can spread to multiple qubits in the course of the error-correction cycle. Previous works have calculated these single error and correlated error probabilities for a variety of codes [2, 3, 4]. Although the event of errors propagating through the entangling gates has been considered, the probabilities provided cannot be used to straightforwardly obtain an effective phenomenological error model. This is because the probability distributions of single errors and correlated errors are obtained separately, and the latter cannot be processed as weights on a decoder graph. Here, we propose and elaborate on an algorithmic approach to calculate these probabilities and decoder weight in a general way that is not subject to the structure of the error correction code and is suitable for a broad class of errors. We compare the performance of different decoders using the weights thus calculated with earlier methods.

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Well-conditioned multi-product formulas for hardware-friendly Hamiltonian simulation

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Simulating the time-evolution of a Hamiltonian is one of the most promising applications of quantum computers. Multi-Product Formulas (MPFs) are well suited to replace standard product formulas since they scale better with respect to time and approximation errors. Hamiltonian simulation with MPFs was first proposed in a fully quantum setting using a linear combination of unitaries. Here, we analyze and demonstrate a hybrid quantum-classical approach to MPFs that classically combines expectation values evaluated with a quantum computer. This has the same approximation bounds as the fully quantum MPFs, but, in contrast, requires no additional qubits, no controlled operations, and is not probabilistic. We show how to design MPFs that do not amplify the hardware and sampling errors, and demonstrate their performance. In particular, we illustrate the potential of our work by theoretically analyzing the benefits when applied to a classically intractable spin-boson model, and by computing the dynamics of the transverse field Ising model using a classical simulator as well as quantum hardware. We observe an error reduction of up to an order of magnitude when compared to a product formula approach by suppressing hardware noise with Pauli Twirling, pulse efficient transpilation, and a novel zero-noise extrapolation based on scaled cross-resonance pulses. The MPF methodology reduces the circuit depth and may therefore represent an important step towards quantum advantage for Hamiltonian simulation on noisy hardware.

Overcoming barriers: Fast universal control of a qubit with variable protection

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Morten Kjaergaard[1] and **Karsten Flensberg**[1]

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Fast, high fidelity control of protected superconducting qubits is fundamentally challenging due to their inherent insensitivity. To achieve high coherence and fast control simultaneously, we propose to use qubits with a variable level of T1-protection. In this way, fast gates can be performed using traditional microwave pulse techniques in the unprotected regime while the qubits enjoy extended relaxation times when idling in the protected regime. To test the performance of such a scheme, we propose a simple T1-protected qubit design, the double-shunted flux qubit (DSFQ), a variation of the capacitively shunted flux qubit where the level of protection is controlled through a single tunable junction. We show numerically that the overhead due to tuning in and out of protection is minimal and that both single- and two-qubit gates can be performed with high fidelity without occupying the low coherence, non-computational states.

Entanglement-assisted Quantum Codes from Cyclic Codes

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IQM, Algorithm and Applications, Munich, Germany

Entanglement-assisted quantum error-correcting (EAQEC) codes are quantum codes which use entanglement as a resource. These codes can provide error correction capability higher than the (entanglement unassisted) codes derived from the traditional stabilizer formalism. In this work, we provide a general method to construct EAQEC codes from cyclic codes. Afterward, the method is applied to Reed-Solomon, BCH, and general cyclic codes. We use the Euclidean and Hermitian construction of EAQEC codes. Three families have been created; two families of EAQEC codes are maximal distance separable (MDS), and one is almost MDS or almost near MDS. The comparison of the codes in this paper is mainly based on the quantum Singleton bound.

Error correcting codes on near-term devices of quasi-linear and central-spin-like connectivity

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We evaluate the performance of small error-correcting codes which we implement on hardware platforms of very different connectivity and coherence: On a superconducting processor and on a spintronic quantum register consisting of a colour centre in diamond. Taking the hardware-specific errors and connectivity into account, we investigate the dependence of the resulting logical error rate on the platform features such as the native gates, the native connectivity, gate times and coherence times. We investigate different recovery schemes for the encoded quantum state based upon the classical information obtained by the measurement outcome. Using an error model parametrized for the given hardware, we simulate the performance and benchmark these predictions with experimental results when running the code on the superconducting processor. The results indicate that for small, low-weight parity check codes, the hexagonal, quasi-linear layout proves advantageous, yet for codes relying on controlled multi-qubit operations with high-weight stabilizers, the CSS-like connectivity and native Toffoli gate of the colour centre enables a favourable transpilation [1].

References

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Implementation-independent sufficient condition of the Knill-Laflamme type for the autonomous protection of logical qudits by strong engineered dissipation

Jae-Mo Lihm, Kyungjoo Noh, and Uwe R. Fischer

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Autonomous quantum error correction utilizes the engineered coupling of a quantum system to a dissipative ancilla to protect quantum logical states from decoherence. We show that the Knill-Laflamme condition, stating that the environmental error operators should act trivially on a subspace, which then becomes the code subspace, is sufficient for logical qudits to be protected against Markovian noise. It is proven that the error caused by the total Lindbladian evolution in the code subspace can be suppressed up to very long times in the limit of large engineered dissipation, by explicitly deriving how the error scales with both time and engineered dissipation strength. To demonstrate the potential of our approach for applications, we implement our general theory with binomial codes, a class of bosonic error-correcting codes, and outline how they can be implemented in a fully autonomous manner to protect against photon loss in a microwave cavity.

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Jae-Mo Lihm, Kyungjoo Noh, and Uwe R. Fischer, Phys. Rev. A **98**, 012317 (2018).

Tunable-coupler mediated multi-qubit controlled-phase gates with superconducting qubits

Niklas J. Glaser[1,2], **Federico Roy**[1,3] **and Stefan Filipp**[1,2]

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Applications for noisy intermediate scale quantum computing devices rely on the efficient entanglement of many qubits to reach a potential quantum advantage. Entanglement is typically generated using two-qubit gates, with the qubits arranged on a square grid with pair-wise qubit-qubit couplers. Tuning the frequency of the coupler by adiabatic flux pulses enables us to control the conditional energy shifts between the qubits and to realize controlled-phase gates. We investigate optimal pulse shapes parametrizations, for decoherence limited CPHASE gates. The direct control of strong multi-qubit interactions can improve the efficiency of large-scale entanglement. We thus extend the scheme to a system of three superconducting transmon-type qubits coupled via a single flux-tunable coupler, which enables the direct implementation of the full family of pairwise controlled-phase (CPHASE) and controlled-controlled-phase (CCPHASE) gates. To accurately adjust the resulting controlled relative phases, we use a gate protocol involving refocusing pulses in combination with adjustable interaction times. Numerical simulations result in CCPHASE fidelities around 99% using currently achievable system parameters and decoherence rates.

From maximum likelihood to machine learning based decoding of topological stabilizer codes

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Topological stabilizer codes may hold the key to fault tolerant quantum computing. One of many challenges with implementing such codes relates to the decoder, which should map a set of stabilizer measurements to the correction least likely to cause a logical failure. In designing a decoder algorithm there is a trade-off between accuracy, speed and versatility, reflected in the range from computationally demanding, but near optimal, maximum likelihood (MLD) decoders, to fast heuristic decoders. I will present our work on a Monte Carlo based MLD [1] and machine learning (ML) based decoders using deep reinforcement learning (RL) [2,3] as well as graph neural networks (GNN) [4] and compare these to the minimum weight perfect matching (MWPM) algorithm. The MLD explicitly counts unique error configurations to identify the most likely equivalence class of errors, thus considering the multiplicity of errors, as required for optimal decoding. The RL based decoders are trained to suggest a correction operator with the lowest probability weight, outperforming MWPM for depolarizing noise. The GNN decoder can be described as a trained message passing algorithm that propagates information between the nodes of a syndrome graph. It operates as a graph classifier, syndrome to most likely error class, and is trained using a continuously populated data set of random syndromes. An interesting feature of the ML based decoders is that they can potentially be implemented model free, without knowledge of single qubit error rates, trained only with experimental data of syndrome and final state measurements. In addition, even though the training of a neural network is computationally demanding the forward pass evaluation is very fast, as required for real time decoding.

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Anomalous zero-field splitting for hole spin qubits in Si and Ge quantum dots [1]

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An anomalous energy splitting of spin triplet states at zero magnetic field has recently been measured in germanium quantum dots. This zero-field splitting could crucially alter the coupling between tunnel-coupled quantum dots, the basic building blocks of state-of-the-art spin-based quantum processors, with profound implications for semiconducting quantum computers. We develop an analytical model linking the zero-field splitting to spin-orbit interactions that are cubic in momentum. Such interactions naturally emerge in hole nanostructures, where they can also be tuned by external electric fields, and we find them to be particularly large in silicon and germanium, resulting in a significant zero-field splitting in the μeV range. We confirm our analytical theory by numerical simulations of different quantum dots, also including other possible sources of zero-field splitting. Our findings are applicable to a broad range of current architectures encoding spin qubits and provide a deeper understanding of these materials, paving the way towards the next generation of semiconducting quantum processors.

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Strategies for practical advantage of fault-tolerant circuit design in noisy trapped-ion quantum computers

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Fault-tolerant quantum error correction provides a strategy to protect information stored or processed by a quantum computer against noise which would otherwise corrupt the data. A fault-tolerant quantum computer must implement a universal gate set on the logical level in order to perform arbitrary calculations to in principle unlimited precision. In this manuscript, we characterize the recent demonstration of a fault-tolerant universal gate set in a trapped ion quantum computer [1] and explore pathways to improve the design of experimental setups in order to reach advantage of logical over physical qubit operation. Various break-even points for fault-tolerant quantum operations are shown to be within reach for near-term improvements of ion trap quantum computing capabilities. Furthermore, we analyze the influence of crosstalk noise in entangling gates for logical state preparation circuits. These can be designed to respect fault-tolerance for specific microscopic noise models. We find that an experimentally informed depolarizing noise model captures the essential noise dynamics of the fault-tolerant experiment, and the infidelity introduced by crosstalk is negligible in the currently accessible regime of physical error rates. Additionally, we show that for the current and anticipated future regime of physical error rates non-deterministic state preparation schemes perform favorably over their deterministic counterparts. For the latter, we provide a fault-tolerant unitary logical qubit initialization circuit which can be realized without in-sequence measurement and feed-forward of classical information. Our results offer guidance on improvements of physical qubit operations in order to design practical quantum computers and validate numerical simulations as a tool to predict logical failure rates in quantum computing architectures based on trapped ions.

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Error correlations can improve the performance of variational quantum algorithms

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The effects of uncorrelated noise on variational quantum algorithms such the Quantum Approximate Optimization Algorithm (QAOA) have been studied intensively. Recent experimental results, however, show that the errors impacting Noisy Intermediate-Scale Quantum (NISQ) devices are significantly correlated. We introduce a model for both spatially and temporally (non-Markovian) correlated errors based on classical environmental fluctuators [Fig. 1]. The model allows for the independent variation of the marginalized spacetime-local error rates and the correlation strength. Using this model, we study the effects of correlated stochastic noise on QAOA. We find evidence that the performance of QAOA improves as the correlation time or correlation length of the noise is increased at fixed local error rates. This shows that noise correlations in themselves need not be detrimental for NISQ algorithms such as QAOA.

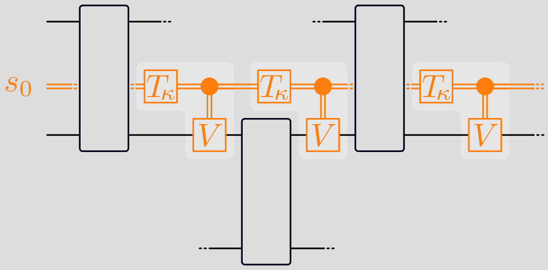

Figure 1. The fluctuator model for temporally correlated errors. Every qubit interacts with an independent, classical two-level fluctuator (double line, only one fluctuator shown). The fluctuator is initially excited with probability p, as described by the classical ensemble s_0. The operation T_κ resets the fluctuator to s_0 with probability $1-\kappa$. A unitary V is applied to the qubit if and only if the fluctuator is excited, leading to a model for temporally correlated errors with tunable correlation time $0 \leq \tau = -1/\log\kappa < \infty$. The spacetime local, marginalised error rate of this model equals p, fully independent of τ.

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Quantum gate-error and crosstalk characterization on superconducting transmon processors

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Currently available quantum computing hardware based on superconducting transmon architectures realizes networks of hundreds of qubits with the possibility of controlled nearest-neighbor interactions. However, the inherent noise and decoherence effects of such quantum chips considerably alter basic gate operations and lead to imperfect outputs of the targeted quantum computation. We show how to characterize such quantum gate errors in detail using a combination of quantum process and gate set tomography in order to estimate a complete set of single- and two-qubit gate operations. Key ingredients of our approach are the efficient characterization of a universal single qubit gate set via gate-set tomography and the subsequent reconstruction of one additional two-qubit entangling gate using a long-sequence version of quantum process tomography.

Furthermore, we focus on the characterization of crosstalk effects which manifest themselves in correlations between simultaneously executed quantum gates on neighboring qubits. In particular, we show how to efficiently and systematically characterize the magnitude of such crosstalk effects on an entire quantum chip using the randomized benchmarking protocol and demonstrate this procedure on real quantum hardware provided by IBM. Lastly, we use the gained information in order to propose novel and more accurate means to simulate noisy quantum hardware by devising an appropriate crosstalk-aware noise model.

Error correction for universal parity computing

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Recently Fellner et. al. proposed a universal parity quantum computing framework, which provides a universal gate set for quantum computing with all-to-all connectivity and intrinsic robustness to bit-flip errors based on parity encoding [1]. We benchmark the performance of various schemes to correct bit-flip errors within the universal parity quantum computing framework. These error correction techniques include minimum-weight decoding, spanning-tree decoding, belief propagation and perfect weight minimum matching. Furthermore, we discuss recent progress towards extending the perfect weight minimum matching decoder to modular parity architectures containing three and four-qubit stabilizers as described by Ender et al. [2].

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New techniques to improve zero-noise extrapolation on superconducting qubits

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Currently available quantum computing hardware suffers from errors due to environmental influences, nearest-neighbor interactions and imperfect gate operations. To achieve robust quantum computing, there are techniques like error mitigation by zero-noise extrapolation [1]. We propose a method for estimating the strength of the error occurring in a given quantum circuit in order to improve the result of this extrapolation. Furthermore, the impact of gate errors on observable expectation values can be reduced by noise tailoring, which converts arbitrary errors into stochastic Pauli errors [2]. Using these techniques, we elaborate on the implementation of error mitigation on a superconducting quantum computer and its impact on the computation of expectation values.

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Realizing Repeated Quantum Error Correction in a Distance-Three Surface Code

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Quantum computers hold the promise of solving computational problems that are intractable using conventional methods. For fault-tolerant operation, quantum computers must correct errors occurring owing to unavoidable decoherence and limited control accuracy. Here we demonstrate quantum error correction using the surface code, which is known for its exceptionally high tolerance to errors. Using 17 physical qubits in a superconducting circuit, we encode quantum information in a distance-three logical qubit, building on recent distance-two error-detection experiments [1-3]. In an error-correction cycle taking only 1.1 μs, we demonstrate the preservation of four cardinal states of the logical qubit. Repeatedly executing the cycle, we measure and decode both bit-flip and phase-flip error syndromes using a minimum-weight perfect-matching algorithm in an error-model-free approach and apply corrections in post-processing. We find a low logical error probability of 3% per cycle when rejecting experimental runs in which leakage is detected. The measured characteristics of our device agree well with a numerical model. Our demonstration of repeated, fast and high-performance quantum error-correction cycles, together with recent advances in ion traps [4], support our understanding that fault-tolerant quantum computation will be practically realizable.

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Greedy versus Map-based Optimized Adaptive Algorithms for random-telegraph-noise mitigation by spectator qubits

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Qubit decoherence from environmental noises is one of the major obstacles to building useful largescale quantum computers [4, 3, 1, 2]. Noise mitigation technologies including quantum error correction (QEC), dynamical decoupling (DD) have proposed to prolong the coherence time of computational qubits. However, both QEC and DD approaches require direct controls or measurement on the qubits of interest, which could in turn create more sources of noises. In a scenario where data-storage qubits are kept in isolation as far as possible, with minimal measurements and controls, noise mitigation can still be done using additional noise probes, with corrections applied only when needed.

Motivated by the case of solid-state qubits, we consider dephasing noise arising from a two-state fluctuator, described by random telegraph process, and a noise probe which is also a qubit, a so-called spectator qubit (SQ). The SQ are qubit-type probes that are assumed to be much sensitive to target noise than data qubits and can be easily measured.

We construct the theoretical model assuming projective measurements on the SQ, and derive the performance of different measurement and control strategies in the regime where the noise mitigation works well. We first formulate a Bayesian map, which will be used to calculate the expected coherence function. We then start from the Greedy algorithm; that is, the strategy that always maximizes the data qubit coherence in the immediate future. We show numerically that this algorithm works very well, and find that its adaptive strategy can be well approximated by a simpler algorithm with just a few parameters. Based on this, and an analytical construction using Bayesian maps, we design a one-parameter (Θ) family of algorithms. In the asymptotic regime of high noise-sensitivity of the SQ, we show analytically that this Θ-family of algorithms reduces the data qubit decoherence rate by a divisor scaling as the square of this sensitivity.

We also numerically find an optimal $\Theta\star$, which yields the Map-based Optimized Adaptive Algorithm for Asymptotic Regime (MOAAAR). This MOAAAR is shown to outperforms the Greedy algorithem analytically. Furthermore we numerically show that this MOAAAR $\Theta\star$ is a plausibly optimal measurement strategy. With these results, we consider the case with some experimental imperfections such as readout time in measuring SQ. The results show that when the measurement time is inversely proportional to the sensitivity of SQ, our MOAAAR still can mitigate the dephasing to the same order as the ideal case.

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Title: Improved decoding of quantum LDPC codes using neural-network enhanced belief propagation

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Abstract: Belief propagation (BP) is a ubiquitous tool in decoding classical low-density parity-check codes (LDPC). The specific strengths of BP are its linear runtime scaling relative to the block length of the code and the ease with which it can be ported to dedicated decoding hardware. Unfortunately, classical BP algorithms are not well suited to decoding quantum LDPC codes due to cyclic dependencies arising from degenerate quantum errors. As such, quantum variants of BP are typically combined with post-processing routines such as ordered statistic decoding that can considerably impact the algorithm's runtime. Kuo and Lai proposed memory belief propagation (MBP) [1], in which they introduced a parameter α that modifies belief propagation, allowing the decoder to converge to one of the degenerate errors quickly. In this work, we build upon results from [2] and develop methods for improving the MBP decoder using neural network optimization. Our methods systematically locate the heuristically defined α parameter and further generalize the MBP decoder to a more expressive parametrization while maintaining scalability in training.

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Renormalisation Through The Lens of Quantum Convolutional Neural Networks (QCNNs)

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The cluster-Ising model is an example of a quantum model with a symmetry protected topological (SPT) phase. For this model, the efficiency of performing phase recognition has recently been improved over measuring string order parameter (SOP) by the use of a particular quantum convolutional neural network (QCNN), which was motivated by renormalisation theory [1].

Unlike most neural networks, the function of the QCNN used here is relatively straightforward to explain. First, each layer of the QCNN performs a process analogous to both renormalisation and quantum error correction. Then second, the remainder of the circuit simply determines if we are in the ground state of a stabiliser Hamiltonian. If the energy is sufficiently low we consider the input state to be in the target phase.

This QCNN also has a second feature, it is exactly equivalent to a constant depth quantum circuit + post-processing while still providing an exponential speed up in certain domains [2]. Beyond just providing a cheaper circuit, this also points to the generalisation of phase recognising QCNNs beyond the cluster-ising model. Combining these with the fidelity view of quantum phases, I will discuss the potential of QCNNs as a quantum information theory construction of renormalisation.

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Implementing Lattice Gauge Theories in Digital Quantum Simulators

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Digital quantum simulators provide a table-top platform for addressing salient questions in particle and condensed-matter physics. A particularly rewarding target is given by lattice gauge theories (LGTs). Their constituents, e.g., charged matter and the electric gauge field, are governed by local gauge constraints, which are highly challenging to engineer and which lead to intriguing yet not fully understood features. In recent work [1], we simulate a 1+1d Z2 LGT on a superconducting quantum chip. Our experiments have been performed remotely within the Early Access Program of Google Quantum AI. Efficiently synthesizing the three-body charge--gauge-field interaction renders single Trotter steps only 8 native two-qubit gates deep, enabling us to reach simulation times of up to 25 Trotter steps. We observe how tuning a term that couples only to the electric field confines the charges, a manifestation of the tight bond that the local gauge constraint generates between both. Moreover, we study a different mechanism based on previous work [2], where a modification of the gauge constraint from a Z2 to a U(1) symmetry freezes the system dynamics. To address and mitigate hardware errors, we, i.a., employ Floquet calibration, insert spin echo sequences, choose qubits and couplers starting from calibration data, and average over qubit assignments. Our work showcases the dramatic restriction that the underlying gauge constraint imposes on the dynamics of an LGT, it illustrates how gauge constraints can be modified and protected, and it promotes the study of other models governed by many-body interactions.

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A co-design superconducting quantum circuit for quantum simulations

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The co-design concept, where the algorithm and hardware are optimized in combination, is a viable strategy for reaching quantum advantage with NISQ quantum computational devices. For efficiently simulating a problem with all-to-all interactions, a star-architecture has been identified as requiring the minimal number of SWAP operations needed for mapping the physical qubit connections to the algorithm connectivity [1]. At IQM, we designed and fabricated a superconducting quantum circuit with such star-architecture where a distributed resonator is used as the central computational component to increase its capability for coupling more outer qubits. To operate the central resonator as an effective qubit, we developed two types of qubit-resonator operations: a swap operation for moving excitations and a CZ gate for algorithmic execution. We will present the experimental progress on operating the circuit for digitally simulating a nanoscale NMR system to demonstrate the process of hyperpolarizing the nuclear spins around nitrogen-vacancy (NV) color centers in diamond.

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Generalized Belief Propagation Algorithms for Decoding of Surface Codes

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Belief propagation (BP) is well-known as a low complexity decoding algorithm with a strong performance for important classes of quantum error correcting codes, e.g. notably for the quantum low-density parity check (LDPC) code class of random expander codes. However, it is also well-known that the performance of BP breaks down when facing topological codes such as the surface code, where naive BP fails entirely to reach a below-threshold regime, i.e. the regime where error correction becomes useful. Previous works have shown, that this can be remedied by resorting to post-processing decoders outside the frame- work of BP. In this work, we present a generalized belief propagation method with an outer re-initialization loop that successfully decodes surface codes, i.e. opposed to naive BP it re- covers the sub-threshold regime known from decoders tailored to the surface code and from statistical-mechanical mappings. We report a threshold of 17% under independent bit-and phase-flip data noise (to be compared to the ideal threshold of 20.6%) and a threshold value of 14% under depolarizing data noise (compared to the ideal threshold of 18.9%), which are on par with thresholds achieved by non- BP post-processing methods.

The Effect of Noise on the Performance of the Variational Quantum Eigensolver

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The Variational Quantum Eigensolver (VQE) [1] is considered as one of the most promising algorithms for near-term applications on Noisy Intermediate-Scale Quantum (NISQ) devices. It is a hybrid algorithm which uses the variational Rayleigh-Ritz principle to find the ground state energy of a quantum mechanical system and is expected to be useful for a broad range of problems in various fields, ranging from condensed matter physics over quantum chemistry to optimization [2,3,4]. Although VQE has shown some resilience to noise from quantum hardware [2], noise is one of the main obstacles on the way to its application in practical use cases.

We focus on a systematic investigation of the effect noise has on the performance of the VQE on the example of the H2 molecule for superconducting IBM devices. A thorough understanding will help to enable reasoned decisions on the choice of error mitigation methods and for potential improvements of them as well as for formulating hardware requirements for acquiring a meaningful computation result.

Besides numerical comparisons of the suitability of different classical optimizers our studies include simulations of the results of VQE for increasing strength of shot noise, depolarizing noise and amplitude and phase damping noise. We observe a systematic shift of the mean values of the resulting energies and find mathematical models for the energy-noise intensity relationship. Furthermore, we can make a suggestion on the methodology to reduce the need of resources for achieving a certain accuracy: Our chosen optimizer is, despite the noise, able to find a set of parameters corresponding to energies close to the ground state energy in the noiseless case. This suggests that the noise level in the last evaluation of the Hamiltonian expectation value is the decisive one for the accuracy of the energy, while other iterations can be performed with higher noise levels, eg. a smaller number of shots. To test the generality of our results we use three different ansatzes, both hardware-efficient and chemically-inspired ones. The findings of the simulations are examined by comparisons with experiments on the superconducting processors of IBM Quantum.

(arXiv: 2209.12803)

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Slowing quantum decoherence of oscillators by hybrid processing

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Quantum information encoded into superposition of coherent states is an illustrative representative of practical applications of macroscopic quantum coherence possessing. However, these states are very sensitive to energy loss, losing their non-classical aspects of coherence very rapidly. An available deterministic strategy to slow down this decoherence process is to apply a Gaussian squeezing transformation prior to the loss as a protective step. In this poster [1], I will present a deterministic hybrid protection scheme utilizing strong but feasible interactions with two-level ancillas immune to spontaneous emission. We verify robustness of the scheme against dephasing of qubit ancilla. Our scheme is applicable to complex superpositions of coherent states in many oscillators, and remarkably, the robustness to loss is enhanced with the amplitude of the coherent states. This scheme can be realized in experiments with atoms, solid-state systems and superconducting circuits.

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Statistical-mechanics mappings for decoding QEC codes under circuit-level noise

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Mapping the decoding of quantum error correcting (QEC) codes to classical disordered statistical mechanics models allows one to determine critical error thresholds of QEC codes under phenomenological noise models. Here, we extend this mapping to admit realistic, multi-parameter noise models of faulty QEC circuits, derive the associated strongly correlated classical spin models, and illustrate this approach for a quantum repetition code with faulty stabilizer readout circuits. We use Monte-Carlo simulations to study the resulting phase diagram and benchmark our results against a minimum weight perfect matching decoder. The presented method provides an avenue to assess fundamental thresholds of QEC circuits, independent of specific decoding strategies, and can thereby help guiding the development of near-term QEC hardware.

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Characterization and mitigation of coherent errors of near-term quantum devices

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Characterization of near-term quantum devices generates insights about their sources of disturbances. State-of-the-art characterization protocols often focus on incoherent noise and thus eliminate the coherent one using Pauli or Clifford twirling techniques. This has the effect of biasing the knowledge about the effective noise and adding a sampling overhead. Here, we extend the incoherent local Pauli noise models [1] to coherent errors and propose a practical protocol for noise characterization of an arbitrary unitary operation. We demonstrate this protocol on a superconducting hardware platform and verify the obtained characterization for a given operation by mitigating its coherent as well as incoherent errors. This new noise characterization procedure seeks to provide guidance for device calibration, future hardware development and improvement of error-mitigation and correction techniques, thereby paving the way towards a software-hardware co-design.

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Implementation of Fractional State Transfer on a Superconducting Qubit Chain

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Superconducting circuits are a promising candidate architecture for quantum computation due to their high coherence times and high-fidelity control, however, qubit connectivity is limited to nearest-neighbour local interactions. Nonetheless, recent studies show that simultaneous local interactions can be harnessed to generate multi-qubit operations and efficiently generate many-body entanglement. In this work we operate a superconducting circuit qubit chain, with fixed-frequency transmon qubits, and flux tunable transmon couplers. By simultaneous parametric drive of the tunable couplers we generate effective multi-qubit interactions and transfer excitations from one end of the chain to the other end, an operation known as perfect state transfer. Furthermore, we demonstrate fractional state transfer, where only a fraction of the state is transferred, as controlled by the frequency and strength of parametric drives on the couplers. We show how this protocol can be used to efficiently generate entangled states and multi-qubit operations. Finally, good agreement with theoretical predictions suggests the scalability of this protocol to longer qubit chains.

A simple error mitigation strategy for variational quantum algorithms

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Many quantum algorithms used on today's NISQ devices are variational. In those algorithms the quantum processing unit is used for preparing a parametrized quantum state with respect to which the expectation value of some observable is measured.

Quantum error correction is not available yet on current quantum hardware. Thus, quantum circuits are subject to noise and hence the measured expectation values inaccurate. The simplest non-trivial error channel for a quantum circuit is the global depolarization channel which can be described by a single parameter. In the literature one can find various methods for estimating this depolarization parameter and subsequently using it to get mitigated results from noisy sampling results [1, 2].

We propose and study a simple error mitigation strategy for variational algorithms. For this purpose, we assume that the error of the variational circuit can be approximated by a global depolarization model whose depolarization parameter is roughly constant for the variational parameters considered. Most variational ansatz circuits have a set of parameters for which the expectation value of the observable in question can be efficiently computed classically (e.g. Hartree-Fock state in quantum chemical problems). Therefore, we calibrate the depolarization model at these points and mitigate the error according to the model at other parameters of interest.

The mitigation strategy is applied to quantum chemical calculation with (Adaptive)-Variational-Quantum- Eigensolvers on IBMs superconducting qubit platform.

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Holi codes and how to find them!

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We construct [1] several non-CSS versions of the 2D color code which we nickname Holi codes, that we ascribe due to the mixed-ness (i.e. involving X, Y, Z Paulis) and color degree of freedom of the fundamental plaquette stabilizers. The construction and partial classification is motivated by two properties: (i) an anti-commutation property, (ii) types of point (vertex) Pauli excitations. There are two important classes we identify based on the number of stabilizers that are unsatisfied for all single qubit (vertex) Pauli operations: (a) those with three, four or five unsatisfied stabilizers, and, (b) with exactly four. By construction, we find that these models are not equivalent to the original color code by a local unitary transformation, however, the code spaces of the original CSS and non-CSS versions are found to be related by local unitaries. We also observe the existence of certain codes that have string-like logical operators that are of a mixed type making them potentially useful for tackling biased Pauli-noise [2] that is physically relevant in certain qubit architectures (see for e.g. [3]).

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Towards a repetitive simple quantum error correction in a nitrogen-vacancy spin system

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ABSTRACT

Nitrogen vacancy center in diamond are one of the leading platforms for quantum technologies that has several advantages, such as room temperature spin initialisation and readout via optical excitations as well as spin manipulations via microwave and radio-frequency fields, and has been extensively used in many applications ranging from quantum sensing [1], to quantum information processing [2]. One of the most essential tasks in quantum information processing is quantum error correction (QEC), implemented for the protection of the quantum system against environment and noises. Up to now most of the QEC realisations with single NV centres make use of a quantum register involving nearby ^{13}C nuclear spins [3], through hyperfine interactions.

Here, we report our work on the stepwise implementation of a repetitive simple quantum error correction code in a dipolar coupled system of NV centres. The work is divided into three stages. The first stage is to model the encoding sequences for multiple coupled NV's and to fabricate them. For the modelling of the encoding sequences simulations of the entanglements of non-symmetrically coupled triple NV centres and their extensions to a larger system are performed using Qiskit [4], while the fabrication method is carried out by organic molecular ion implantations [5]. Experimentally, the building blocks for the encoding sequences that consist of two-qubit CNOT gates and their corresponding tomographic analysis are performed using the Rabi tomography method [6], and further improved by applying quantum optimal control [7]. The second stage involves theoretical and experimental analysis on the multiple spin dynamics under certain noise channels. In the last stage the analysis of the error detection and the information restoration will be obtained. Preliminary experimental results show an improvement of the two-qubit CNOT gate fidelity using the optimal control pulses with a coherence time of few hundred microseconds and a dipolar coupling of 15 kHz. Moreover, a system of triple NV centres with coherence times of tens to hundreds microsecond has been identified.

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Reflectometric readout of quantum devices: microwave sideband interferometer and tank circuits with superconducting inductors

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We present an approach for microwave reflectometry based on the interference of two microwave sidebands. If the measured device only affects one sideband in phase or amplitude, the interference with the other sideband leads to a selectable suppression of either common-mode amplitude or phase noise. We characterize noise suppression and use this scheme to measure time-dependent fluctuations of a NbN superconducting resonator at 25 mK. Furthermore, we discuss tank circuits for gate-based readout of spin qubits where the inductor is integrated on silicon and is based on the kinetic inductance of a superconducting NbN wire. The reduced parasitic capacitance and enhanced quality factor as compared to a tank circuit with copper-coil inductors on a printed-circuit board increases the sensitivity in reflectometric detection of spin qubits.

Impact of Quantum Noise on QGAN Training

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Current noisy intermediate-scale quantum devices suffer from various sources of intrinsic quantum noise. Overcoming the effects of noise is a major challenge, for which different error mitigation and error correction techniques have been proposed. In this paper, we conduct a first study of the performance of quantum Generative Adversarial Networks (qGANs) in the presence of different types of quantum noise, focusing on a simplified use case in high-energy physics. In particular, we explore the effects of readout and two-qubit gate errors on the qGAN training process. Simulating a noisy quantum device classically with IBM's Qiskit framework, we examine the threshold of error rates up to which a reliable training is possible. In addition, we investigate the importance of various hyperparameters for the training process in the presence of different error rates, and we explore the impact of readout error mitigation on the results

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Two qubits in one transmon - QEC without ancilla hardware

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We show that it is theoretically possible to use higher energy levels for storing and controlling two qubits within a superconducting transmon. This is done by relabeling energy levels as qubit product states (Fig. 1). As a proof of concept we realise a complete set of gates necessary for universal computing by numerically optimising control pulses for single qubit gates on each of the qubits, entangling gates between the two qubits in one transmon, and an entangling gate between two qubits from two coupled transmons. For this we model transmons as anharmonic oscillators with weak static coupling. The optimisation procedure considers parameters which could make it possible to validate the concept experimentally. With the optimised control pulses it is in principle possible to double the number of available qubits without any overhead in hardware. The additional qubits could be used in algorithms which need many short-living qubits such as syndrom qubits in error correction.

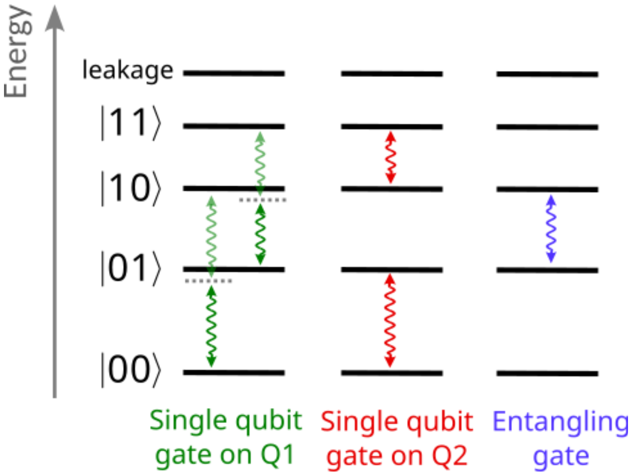

Figure 1: Mapping of energy levels of a transmon to two logical qubits. The arrows indicate transitions that need to be driven in order to realise single- and two-qubit gates within a transmon.

Scalable approach for enhanced-range entanglement of electron spin qubits

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The generation of entanglement over a wide range of distances represents a key challenge in realizing scalable and modular architectures for quantum information processing with semiconductor spin qubits. While the exchange interaction enables rapid gates and coherence-protected qubit encodings with all-electrical control in this platform, the inherently short range of the interaction imposes constraints on the ultimate scalability of both the qubits and their associated control electronics. To address these challenges, we theoretically investigate an approach for relaxing these constraints by extending the range of spin qubit coupling via multielectron mediator quantum dots and photons in microwave cavities, which have enabled recent demonstrations of long-distance interactions for spin qubits in silicon. We find operating regimes for implementing enhanced-range entanglement that exhibit increased flexibility in operation points, frequencies, and coupling through the incorporation of driving fields and intrinsic electric dipole moments that do not require micromagnets for spin-photon interaction. These results suggest a promising route toward scalability and modularity in spin-based quantum information processing.

Efficient decoding schemes for the XYZ^2 hexagonal stabilizer code

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The XYZ^2 code is a topological stabilizer code on a honeycomb lattice which demonstrates high thresholds and highly suppressed logical failure rates for Z-biased noise using maximum-likelihood decoding, under the assumption of perfect stabilizer measurements. The code is equivalent to a concatenation of a low-level two-qubit error detection code, and a high-level YZZY-type surface code. In this work, we investigate an efficient two-step decoding algorithm that uses the concatenated structure of the code with a minimum-weight perfect matching decoder in order to study its behaviour under biased noise error models. We demonstrate that the matching decoder achieves close to optimal performance for certain noise models.

Optimizing shadow tomography with generalized measurements

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Advances in quantum technology require scalable techniques to efficiently extract information from a quantum system. Traditional tomography is limited to a handful of qubits and shadow tomography has been suggested as a scalable replacement for larger systems. Shadow tomography is conventionally analysed based on outcomes of ideal projective measurements on the system upon application of randomised unitaries. Here, we suggest that shadow tomography can be much more straightforwardly formulated for generalised measurements, or positive operator valued measures. Based on the idea of the least-square estimator shadow tomography with generalised measurements is both more general and simpler than the traditional formulation with randomisation of unitaries. In particular, this formulation allows us to analyse theoretical aspects of shadow tomography in detail. For example, we provide a detailed study of the implication of symmetries in shadow tomography. Moreover, with this generalisation we also demonstrate how the optimisation of measurements for shadow tomography tailored toward a particular set of observables can be carried out [1].

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Selective error mitigation for hard constraints in approximate quantum optimization algorithms

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We investigate an approach to selective error mitigation in a quantum alternating operator ansatz. In particular we focus on approximate quantum optimization with hard constraints, as they appear in most real-world applications.

The ansatz consists of two alternating types of unitaries, the phase-separation operator which is derived from the cost function of the original problem, and the mixing operator which stems from hard constraints of the original problem. During the application of these unitaries the quantum state is supposed to stay in the feasible (wrt. to the hard constraints) subspace, or at least the probability to measure infeasible states should be suppressed. On a perfect quantum computer this would be assured by appropriate choices of the initial state and the mixing operator. However, in the presence of noise this approach will not hold up and error mitigation methods have to be employed. We investigate such methods on academic problems and how to extend them towards real-world problems.

The domain wall color code

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We introduce the domain wall color code, a new variant of the quantum error correcting color code that exhibits exceptionally high code-capacity error thresholds for qubits subject to biased noise. In the infinite bias regime, a two-dimensional color code decouples into a series of repetition codes, resulting in an error correcting threshold of 50%. At finite bias, our color code demonstrates thresholds significantly exceeding those achievable with noise-tailored surface codes. The advantage is especially remarkable in the regime of moderate biases, common in many physical qubit architectures. Furthermore, the gap between the error correcting threshold of the domain wall color code and the random-code hashing bound is strikingly large, in contrast to the tiny magnitude of this effect estimated in earlier proposals. The proposed code is hence identified as a comparably resource efficient quantum error correcting code highly suitable for realistic noise.

Measurement induced quantum walks on an IBM Quantum Computer

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We study a quantum walk of a single particle that is subject to stroboscopic projective measurements on a graph with two sites. This two-level system is the minimal model of a measurement induced quantum walk. The mean first detected transition and return time are computed on an IBM quantum computer as a function of the hopping matrix element between the sites and the on-site potential. The experimentally monitored quantum walk reveals the theoretically predicted behavior, such as the quantization of the first detected return time and the strong increase of the mean first detected transition time near degenerate points, with high accuracy.

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https://arxiv.org/abs/2210.09941

Precise Quantum Angle Generator Designed for Noisy Quantum Devices

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The Quantum Angle Generator (QAG) constitutes a new quantum machine learning model designed to generate accurate images on current Noise Intermediate Scale (NISQ) Quantum devices. Variational quantum circuits constitute the core of the QAG model, and various circuit architectures are evaluated. In combination with the so-called MERA-upsampling architecture, the QAG model achieves excellent results, which are analysed and evaluated in detail. To our knowledge, it is the first time that such accurate results are achieved by a quantum model. To explore the noise robustness of the model, an extensive quantum noise study is carried out. In this paper it is demonstrated, that the model trained on the quantum device learns the hardware noise behaviour and generates outstanding results with it. It is verified that even a quantum hardware machine calibration change during training of up to 8% can be well tolerated. For demonstration, the model is employed to a crucial high energy physics simulation use case. The simulations are required to measure particle energies and, ultimately, to discover unknown particles at the Large Hadron Collider at CERN.

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Towards entangling gates between bosonic qubits in trapped ions

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Encoding quantum information in a harmonic oscillator offers a resource efficient method for quantum error correction, compared to the use of multiple two-level systems. The Gottesman-Kitaev-Preskill (GKP) encoding [1] is particularly promising and has recently been realized in both trapped ions [2, 3] and superconducting microwave cavities [4].

State preparation, readout, single qubit rotations and error correction have been achieved in both of these architectures. I will describe work towards logical entangling gates between two GKP qubits prepared in the motional modes of two atomic ions trapped in close proximity. The modes are coupled via the Coulomb interaction, which approximates a beam splitter. Combined with single mode squeezing operations this beam splitter interaction can realize universal entangling gates between the two GKP states [5]. In theoretical work, we have investigated this gate for experimentally realistic parameters and finite energy GKP states. In parallel, we are developing an apparatus for these experiments, including fabrication of a suitable ion trap and design and implementation of individual optical addressing with tightly focused laser beams.

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Quantum Algorithms for the One-Dimensional Poisson Equation

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The Poisson equation is a partial differential equation with wide application in scientific and engineering computing; for example the potential of electrostatic and gravitational fields or heat diffusion in a solid is described by the Poisson equation. We review different approaches to solve the Poisson equation on a quantum computer. The first family of methods is based on the HHL algorithm [1], a quantum algorithm that allows to solve, in a quantum sense, systems of linear equations with potential exponential speed-up provided certain caveats are met. We analyze an algorithm that tailors the HHL algorithm to the one-dimensional Poisson equation and study its scaling as well as its applicability to current noisy-intermediate scale quantum (NISQ) devices [2]. More NISQ friendly approaches are based on variational quantum algorithms, combining classical and quantum computers. In this family of methods we focus on the one proposed by Liu et al. [3] for solving the one-dimensional Poisson equation.

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Generating highly entangled states using a single-shot three-qubit gate

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Whether one is working on noisy intermediate-scale quantum (NISQ) algorithms or towards error correction, the coherence of a quantum processor sets bounds on the depth which can be achieved for any sequence of operations. Each of these cases requires the generation of large, entangled states. This is typically achieved by implementing a universal gate set formed of single- and two-qubit operations. While generating these states is achievable, as devices grow larger in terms of the number of qubits, the depth needed to entangle all qubits increases.

In this work, we extend our gate set to include a three-qubit gate which itself can implement a family of operations. This gate is performed by the simultaneous application of two microwave drives between our target states and a shared common level. Driving this lambda-system with equal strength tones generates an effective controlled interaction between the target states which acts as a combination of a CPhase and a SWAP-like gate. For this reason, we call this gate a Controlled-CZ-SWAP or CCZS. We demonstrate the implementation of this gate and benchmark its performance and the arbitrary control of the swapping angle.

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Co-design for quantum computing devices with optimal control

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The practical application of quantum computing and the research into qubit and device designs are often separate fields. When exploring operating regimes for quantum devices, often specific properties like noise resistance are selected based on previous experience or intuition, resulting in designs like the Transmon [1] and the Fluxonium [2]. In the current NISQ era, there is a demand for functional quantum devices to solve relevant computational problems, which motivates a more utilitarian perspective on device design: The goal is to have a device that is employed to run a given algorithm with state-of-the-art performance.

In this work, we assume this perspective and use optimal control tools [3] to derive the gates required by the algorithm and, in tandem, explore the model space of superconducting quantum computer design to maximize gate fidelity. We investigate candidate designs for two-qubit devices: a tunable coupler setup, tunable qubits with static coupling and fixed qubits with fixed couplings. For each design, we optimize properties like qubit frequencies, anharmonicities and coupling strengths for the best performance of both local and entangling gates, making use of the theory of perfect entanglers [4].

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Error-tolerant quantum convolutional neural networks for the recognition of symmetry-protected topological phases

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The development and application of quantum computers require tools to evaluate noisy quantum data produced by near-term quantum hardware. Quantum neural networks based on parametrized quantum circuits, measurements and feedforward can process large quantum data, to detect non-local quantum correlations with reduced measurement and computational efforts compared to standard characterization techniques. Here we construct quantum convolutional neural networks (QCNNs) based on the multiscale entanglement renormalization ansatz that can recognize different symmetry-protected topological phases of generalized cluster-Ising Hamiltonians in the presence of incoherent errors, simulating the effects of decoherence under NISQ conditions. Using matrix product state simulations, we show that the QCNN output is robust against symmetry-preserving errors if the error channel is invertible. Moreover, the QCNNs tolerate symmetry-breaking errors below a threshold error probability in contrast to previous QCNN designs and string order parameters, which are significantly suppressed for any non-vanishing error probability. Even though the error tolerance is limited close to phase boundaries due to a diverging correlation length, the QCNNs can precisely determine critical values of Hamiltonian parameters. To facilitate the implementation of QCNNs on near-term quantum computers, we show how to shorten a general class of QCNN circuits from logarithmic to constant depth in system size by performing a large part of computation in classical post-processing after the measurement of all qubits. The QCNN with a constant-depth quantum circuit reduces sample complexity exponentially with system size in comparison to the direct sampling of the QCNN output using local Pauli measurements with only logarithmic classical computational costs.