The Mitiq Open Source Ecosystem

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Unitary Foundation https://unitary.foundation/

2025 Workshop on Error Resilience in Quantum Computing (werq.shop)
New York University, NYC, July 17, 2025

Unitary Foundation

Outline

- Unitary Foundation
- Open Research
- Mitiq Open Source Ecosystem

We do three main things

Unitary Foundation

Microgrants

- We run a microgrant program to fund explorers across the world to work on quantum technologies. **100+ teams across 31 countries**.

Research

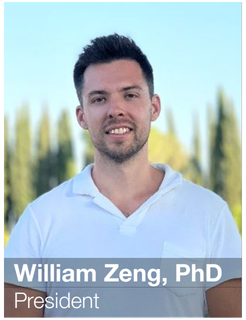
- We do our own research to help the ecosystem as a whole. For example, we are developing (1) **mitiq (250k+ downloads; 120+ citations)**, an open source compiler for error-mitigated quantum programming, (2) **ucc**, a cross-platform compiler and (3) **metriq**, an open community platform for sharing quantum tech benchmarks.

Community

- We host an open source quantum tech community **(4k+ open quantum tech developers)** that runs hackathons, community surveys and events.

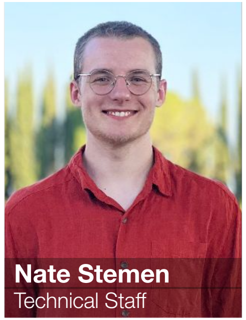
The **Team**

Unitary Foundation

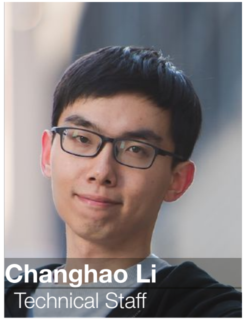

William Zeng, PhD
President

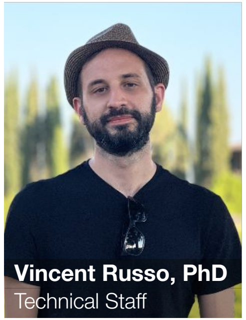

Nathan Shammah, PhD
Chief Technology Officer


Ben Castanon
Chief of Staff

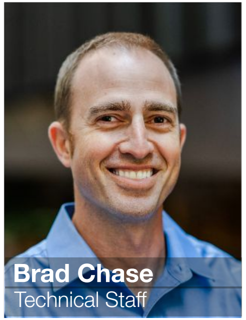

Nate Stemen
Technical Staff


Farrokh Labib
Technical Staff


Changhao Li
Technical Staff


Vincent Russo, PhD
Technical Staff


Alessandro Cosentino
Technical Staff


Brad Chase
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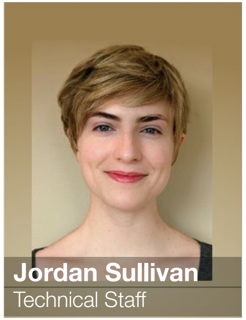
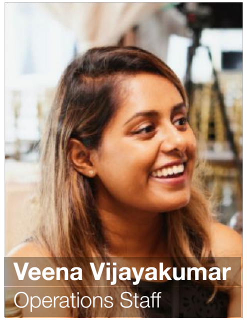

Jordan Sullivan
Technical Staff


Veena Vijayakumar
Operations Staff


Frances Poblete
Marketing & Design

Unitary Foundation

UF Supporters

Core members (2025)

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Additional supporters

- Alphabet X (formerly Google X)
- Atom Computing
- Boston Consulting Group
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- Steve Willis & NYC Quantum Meetup
- EeroQ
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- BlueQubit
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- Michał Stęchły
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- Guillaume Verdon
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- Travis L. Scholten
- Amir Ebrahimi
- Jens Koch
- Christophe Jurczak
- Angelo Danducci II
- Amira Abbas
- Shahnawaz Ahmed
- Tomas Babej
- Ntwali Bashige
- Amy Brown
- Mark Fingerhuth
- Cassandra Granade
- Josh Izaac
- Sarah Kaiser
- Nathan Killoran
- Peter Karalekas
- Alex McCaskey
- Pranav Gokhale
- Will Zeng

UF **Community**

Advisory board

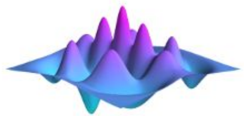
- 10 volunteer experts in quantum systems & software

Discord community

- 5,000+ active members
- **Office hours**
- **Community calls**

QuTiP-qip: Pulse-level circuits simulation by Boxi Li

Collaborators



Board of **Directors**

President. Partner at Quantonation. Fmr. Head of Quantum at Goldman Sachs and product/sw lead at Rigetti. Oxford quantum algorithms PhD.

William Zeng, PhD

Secretary. Quantum Applications Architect at IBM Quantum and Policy Hackers Fellow at the Lincoln Network. PhD in quantum computing from the University of New Mexico (2018).

Travis Scholten, PhD

COO & Co-Founder, Convergent Research, which incubates new kinds of transformative research institutions.

Anastasia Gamick

CTO and Head of the Technical Staff. Managing Director, Unitary Fund France. QuTiP admin. PhD in Physics from Univ. of Southampton.

Nathan Shammah, PhD

Treasurer. Co-founder and managing partner at Quantonation. PhD in Quantum Physics from Ecole Polytechnique.

Christophe Jurczak, PhD

Vice President of QEC Community, Riverlane. Fmr. Director, IBM Quantum & Qiskit Community.

Liz Durst

Microgrants

- We've awarded more than **100 micrograntss** to 31+ countries, resulting in 420+ papers citing micrograntt research, 40+ new libraries, 400+ contributors & maintainers, and helping to form 3 new startups and 1 new non-profit.
- $4,000 + mentoring & validation. 2-minute online video application on **unitary.foundation**
- Latest grants:

6.27.2025

QUANTUM COMPUTING FOR SOFTWARE ENGINEERS

To **Rakhim Davletkaliyev** for **Quantum Computing for Software Engineers**, a free book about the full software stack of superconducting Quantum Computers, targeted towards programmers with no exposure to quantum who are willing to learn its practical aspects.

FINLAND

5.28.2025

PAULI ATLAS: PAULI-BASED COMPUTATION COMPILER FOR QUANTUM ERROR CORRECTION

To **Shuwen Kan and Zefan Du** to build **Pauli Atlas: Pauli-Based Computation Compiler for Quantum Error Correction**, an open-source compiler for Pauli-Based Computation using surface code. The compiler will support flexible topological configurations and enable overhead-efficient mapping of quantum algorithms. PauliAtlas will help researchers and engineers estimate error suppression without requiring deep knowledge of quantum error correction.

USA

5.28.2025

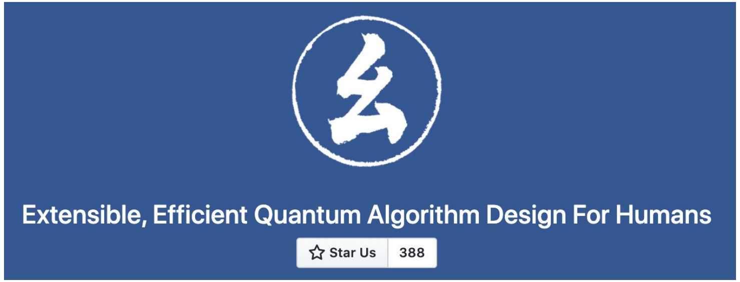
PLANQTN

To **Balint Pato** to develop **PlanqTN** (pronounced "plankton"), which allows users to construct and evaluate tensor network quantum error correction codes in an interactive web app and a community-managed, hosted job execution service.

USA

Connecting the quantum ecosystem

Case Study: Yao.jl + pyZX



SUPPORTED BY UNITARY FUND

+

To Aleks Kissinger and John van de Wetering to support the development of **pyZX**, an optimizing quantum circuit compiler based on a diagrammatic semantics from monoidal categories.

SUPPORTED BY UNITARY FUND

Two publications:
(i) an overview of the pyZX library and (ii) benchmarks showing that **pyZX outperforms the state of the art in reducing T-Count**.

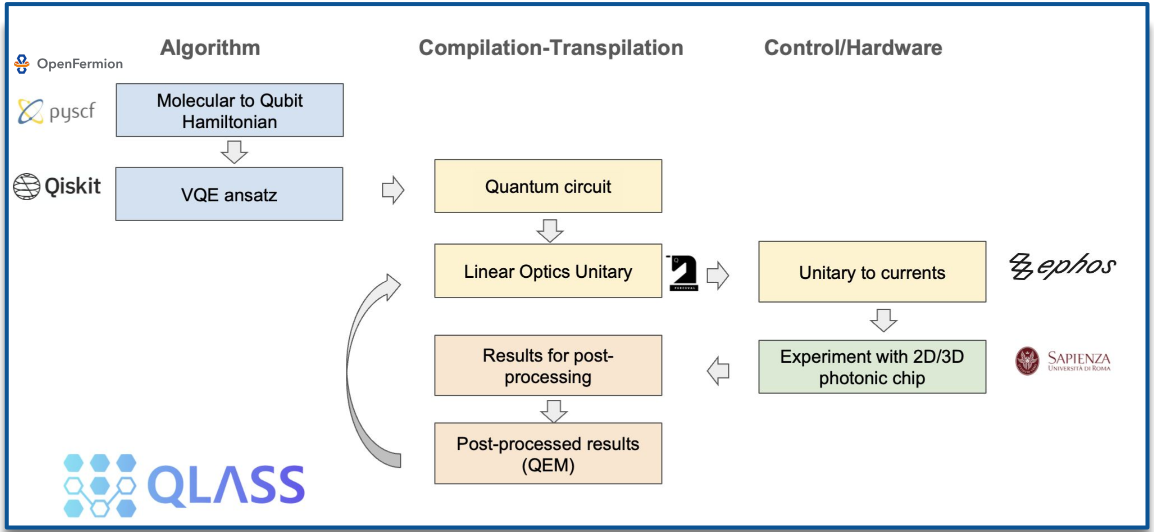
=

Summer 2020: YaoLang released support for its first circuit optimization pass based on ZX calculus.

Building a chemistry-problem-to-compilation photonics platform

Building quantum compilers to run quantum chemistry simulations on photonic quantum processors.

Supported By Horizon Europe



- Designed end-to-end compilation architecture of Lithium battery problem on photonic chip (simulated)
- github.com/unitaryfund/qlass
- Leveraging existing open source infrastructure

Learn more at https://www.qlass-project.eu/

Events: Online and IRL

https://unitaryhack.dev/

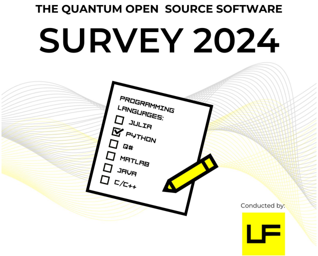
- **902 registrations**
- **54 projects**
- **101 maintainers**
- **5 sponsors**
- **172 Bounties closed**
- **$19,710** earned by **48 hackers**
- **6 HACKdays** in the US, Switzerland, Portugal, Finland, Mexico, and Italy (**doubled** last year's cohort)

QUANTUM WEDNESDAY

Quantum Algorithms: A Call to Action

June 25
09:30 PDT | 12:30 EDT | 18:30 CEST

github.com/unitaryfoundation/quantum-wednesday



WERQSHOP

Workshop **on *Error Resilience* in *Quantum* computing**

📅 July 17–18, 2025 | 📍 New York University, NYC 🗽

unitary CON 2025

Sep 2-4, Albuquerque, NM, USA
@IEEE Quantum Week

unitary.foundation/community/2025/unitaryCON/

Community Impact

With the invaluable support of the Unitary Fund, I was able to take my research to a new level. Their provision of guidance, funding, and access to a fantastic community was instrumental in my progress toward achieving my goals. - ***Matt Lourens, HierarQcal***

The best thing about the Unitary grant is that it puts you in a community where everyone is completing a project. Making progress in such an environment becomes easy.

- ***Abdullah Khalid, "A methods-focused QEC guide"***

The microgrant has made it possible to rent out GPUs to discover quantum codes!

- ***Lev Stambler, Rust decoder for QEC***

I have participated from the very first year of this hackathon and always found it a joy! It gave me confidence to further push the frontier not just in quantum but also other fields.

- ***unitaryHACK 2025 participant***

Outline

- Unitary Foundation
- **Open Research**
- Mitiq Open Source Ecosystem

UF Research Output to Date (2020-2025): 31+ staff published papers

Unitary Labs research with Mitiq, QuTiP and long-term projects

1. E. Pelofske, V. Russo, *Digital Zero-Noise Extrapolation with Quantum Circuit Unoptimization*. arXiv preprint (2025), [2503.06341]
2. N. Lambert, E. Giguère, P. Menczel, B. Li, P. Hopf, G. Suárez, M. Gali, J. Lishman, R. Gadhvi, R. Agarwal, A. Galicia, N. Shammah, P. Nation, J. R. Johansson, S. Ahmed, S. Cross, A. Pitchford, F. Nori, *QuTiP 5: The Quantum Toolbox in Python*. arXiv preprint (2024), [2412.04705]
3. W. J. Zeng, F. Labib, V. Russo, *Towards violations of Local Friendliness with quantum computers*. arXiv preprint (2024), [2409.15302]
4. F. Labib, B. D. Clader, N. Stamatopoulos, W. J. Zeng, *Quantum amplitude estimation from classical signal processing*. arXiv preprint (2024), [2405.14697]
5. P. Lougovski, O. Parekh, J. Broz, M. Byrd, J.C. Chapman, Y. Chembo, W.A. de Jong, E. Figueroa, T.S. Humble, J. Larson, G. Quiroz, G. Ravi, N. Shammah, K.M. Svore, W. Wu, W.J. Zeng, *Report for the ASCR Workshop on Basic Research Needs in Quantum Computing and Networking*, January 7, 2024, United States, osti.gov/biblio/2001045, DOI .2172/2001045
6. A. Mari, V. Russo, *Quantum error mitigation by layerwise Richardson extrapolation*, arXiv preprint (2024), [2402.04000]
7. N. Shammah, A. Saha Roy, C. G. Almudever, S. Bourdeauducq, A. Butko, G. Cancelo, S. M. Clark, J. Heinsoo, L. Henriet, G. Huang, C. Jurczak, J. Kotilahti, A. Landra, R. LaRose, A. Mari, K. Nowrouzi, C. Ockeloen-Korppi, G. Prawiroatmodjo, I. Siddiqi, W. J. Zeng, *Open Hardware in Quantum Technology*, arXiv preprint (2023), [2309.17233] *Accepted in APL Quantum*
8. E. Pelofske, V. Russo, R. LaRose, A. Mari, D. Strano, A. Bärtschi, S. Eidenbenz, and W. J. Zeng *Increasing the Measured Effective Quantum Volume with Zero Noise Extrapolation*, arXiv (2023), [2306.15863]
9. M. A. Wahl, A. Mari, N. Shammah, W. J. Zeng, G. S. Ravi *Zero noise extrapolation on logical qubits by scaling the error correction code distance*, arxiv, (2023), [2304.14985], notebooks
10. D. Strano, B. Bollay, A. Blaauw, N. Shammah, W. J. Zeng, and A. Mari, *Exact and approximate simulation of large quantum circuits on a single GPU*, arXiv, (2023), [2304.1469], source code
11. V. Russo, A. Mari, N. Shammah, R. LaRose, and W. J. Zeng *Testing platform-independent quantum error mitigation on noisy quantum computers*, IEEE Transactions on Quantum Engineering, 4, (2022), [2210.07194], source code
12. B. McDonough, A. Mari, N. Shammah, N. T. Stemen, M. Wahl, W. J. Zeng, and P. P. Orth *Automated quantum error mitigation based on probabilistic error reduction*, IEEE/ACM Third International Workshop on Quantum Computing Software (QCS), 83-93, (2022), [2210.08611], source code
13. R. LaRose, A. Mari, V. Russo, D. Strano, and W. J. Zeng *Error mitigation increases the effective quantum volume of quantum computers* arXiv, (2022), [2203.05489], source code
14. R. LaRose, A. Mari, S. Kaiser, P. J. Karalekas, A. A. Alves, P. Czarnik, M. El Mandouh, M. H. Gordon, Y. Hindy, A. Robertson, P. Thakre, M. Wahl, D. Samuel, R. Mistri, M. Tremblay, N. Gardner, N. T. Stemen, N. Shammah, and W. J. Zeng *Mitiq: A software package for error mitigation on noisy quantum computers*, Quantum 6, 774 (2022), [DOI .22331], source code
15. T. G.-Tiron, Y. Hindy, R. LaRose, A. Mari, and W. J. Zeng *Digital zero noise extrapolation for quantum error mitigation*, 2020 IEEE International Conference on Quantum Computing and Engineering (QCE), 306-316, (2021), [2005.10921]
16. A. Mari, N. Shammah, and W. J. Zeng, *Extending quantum probabilistic error cancellation by noise scaling*, Phys. Rev. A, 104, 052607, (2021), [104.052607]
17. B. Li, S. Ahmed, S. Saraogi, N. Lambert, F. Nori, A. Pitchford, N. Shammah *Pulse-level noisy quantum circuits with QuTiP*, Quantum, 6, 630, (2022), [2105.09902]
18. H. Silvério, S. Grijalva, C. Dalyac, L. Leclerc, P. J. Karalekas, N. Shammah, M. Beji, L.-P. Henry, and L. Henriet *Pulser: An open-source package for the design of pulse sequences in programmable neutral-atom arrays* Quantum, 6, 629, (2022), [2104.15044]
19. G. S. Ravi, K. N. Smith, P. Gokhale, A. Mari, N. Earnest, A. J.-Abhari, F. T. Chong *VAQEM: A Variational Approach to Quantum Error Mitigation* IEEE International Symposium on High-Performance Computer Architecture (HPCA), (2021), [202700a288/1Ds0fvoYbCw]
20. K. Schultz, R. LaRose, A. Mari, G. Quiroz, N. Shammah, B. D. Clader, and W. J. Zeng, *Reducing the impact of time-correlated noise on zero-noise extrapolation*, Phys. Rev. A 106, 052406 (2022), [2201.11792]

Other Unitary Foundation staff research

1. T. Gupta, S. Murshid, V. Russo, Somshubhro Bandyopadhyay *Optimal discrimination of quantum sequences*, [2409.08705]
2. A. Philip, S. Rethinasamy, V. Russo, M. M. Wilde, *“Schrödinger as a Quantum Programmer: Estimating Entanglement via Steering”.* Quantum 8, 1366, (2024), [2303.07911]
3. V. Russo, S. Bandyopadhyay, *“Distinguishing a maximally entangled basis using LOCC and shared entanglement”.* arXiv preprint (2024), [2406.13430]
4. Travis L. Scholten, Carl J. Williams, Dustin Moody, Michele Mosca, William Hurley (“whurley”), William J. Zeng, Matthias Troyer, Jay M. Gambetta, *Assessing the Benefits and Risks of Quantum Computers*, arXiv (2024), [2401.16317]
5. A. Mari, *Counting collisions in random circuit sampling for benchmarking quantum computers*, arXiv (2023) [2312.04222]
6. N. Johnston, V. Russo, J. Sikora *Tight bounds for antidistinguishability and circulant sets of pure quantum states*, arXiv (2023), [2311.17047]
7. C. Paddock, V. Russo, T. Silverthorne, and W. Slofstra, *Arkhipov’s theorem, graph minors, and linear system nonlocal games*, Algebraic Combinatorics, 6, 1119-1162, (2023), [2205.0465]
8. G. Piccitto, M. Wauters, F. Nori, and N. Shammah *Symmetries and conserved quantities of boundary time crystals in generalized spin models* Phys. Rev. B, 104, Pages 014307, (2021), [2101.05710]
9. G. Zhang, Z. Chen, D. Xu, N. Shammah, M. Liao, T. Li, L. Tong, S. Zhu, F. Nori, and J. Q. You, *Exceptional Point and Cross-Relaxation Effect in a Hybrid Quantum System*, PRX Quantum, 2, 020307, (2021), [2104.09811]
10. A. Mari, T. R. Bromley, and N. Killoran *Estimating the gradient and higher-order derivatives on quantum hardware*, Phys. Rev. A, 103, 012405, (2020), [2008.06517]
11. J. Alonso, N. Shammah, S. Ahmed, F. Nori, and J. Dressel *Diagnosing quantum chaos with out-of-time-ordered-correlator quasiprobability in the kicked-top model* arXiv, (2022), [2201.08175]

Unitary Foundation Impact via Open Source Quantum Software

Mitiq

Quantum — the open journal for quantum science | PAPERS | PERSPECTIVES

Mitiq: A software package for error mitigation on noisy quantum computers

Ryan LaRose[1,2], Andrea Mari[1], Sarah Kaiser[1], Peter J. Karalekas[1,3], Andre A. Alves[4], Piotr Czarnik[5], Mohamed El Mandouh[6], Max H. Gordon[7], Yousef Hindy[8], Aaron Robertson[9], Purva Thakre[10], Misty Wahl[1], Danny Samuel[1], Rahul Mistri[1], Maxime Tremblay[11], Nick Gardner[8], Nathaniel T. Stemen[1], Nathan Shammah[1], and William J. Zeng[1,8,12]

[1]Unitary Fund
[2]Michigan State University, East Lansing, MI
[3]AWS Center for Quantum Computing, Pasadena, CA 91125, USA
[4]Hamburg University of Applied Sciences, Hamburg, Germany
[5]Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[6]Institute for Quantum Computing, University of Waterloo, Waterloo, ON, N2L 3G1, Canada
[7]Instituto de Física Teórica, UAM/CSIC, Universidad Autónoma de Madrid, Madrid, Spain
[8]Stanford University, Palo Alto, CA
[9]Independent researcher
[10]Southern Illinois University, Carbondale, IL
[11]Institut quantique, Université de Sherbrooke, Sherbrooke, QC, J1K 2R1, Canada
[12]Goldman, Sachs & Co, New York, NY

Quantum 6, 774 (2022).

143 citations (Google Scholar)
250,000 downloads (PyPI)

Pulser

Quantum — the open journal for quantum science | PAPERS | PERSPECTIVES

Pulser: An open-source package for the design of pulse sequences in programmable neutral-atom arrays

Henrique Silvério[1], Sebastián Grijalva[1], Constantin Dalyac[1], Lucas Leclerc[1], Peter J. Karalekas[2], Nathan Shammah[2], Mourad Beji[1], Louis-Paul Henry[1], and Loïc Henriet[1]

[1]Pasqal, 2 avenue Augustin Fresnel, 91120 Palaiseau, France
[2]Unitary Fund, Walnut, CA 91789, USA

Published: 2022-01-24, volume 6, page 629

Quantum 6, 629 (2022).

245,000 downloads (PyPI)

QuTiP-QIP

Quantum — the open journal for quantum science | PAPERS | PERSPECTIVES

Pulse-level noisy quantum circuits with QuTiP

Boxi Li[1], Shahnawaz Ahmed[2], Sidhant Saraogi[3], Neill Lambert[4], Franco Nori[4,5,6], Alexander Pitchford[7], and Nathan Shammah[8]

[1]Peter Grünberg Institute - Quantum Control (PGI-8), Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany
[2]Department of Microtechnology and Nanoscience, Chalmers University of Technology, 412 96 Gothenburg, Sweden
[3]Department of Computer Science, Georgetown University, 3700 O St NW, Washington, DC 20057, United States
[4]Theoretical Quantum Physics Laboratory, RIKEN Cluster for Pioneering Research, Wako-shi, Saitama 351-0198, Japan
[5]RIKEN Center for Quantum Computing (RQC), 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan
[6]Department of Physics, University of Michigan, Ann Arbor, Michigan 48109-1040, USA
[7]Department of Mathematics, Aberystwyth University, Penglais Campus, Aberystwyth, SY23 3BZ, Wales, United Kingdom
[8]Unitary Fund, Walnut, California 91789, USA

Published: 2022-01-24, volume 6, page 630

Quantum 6, 630 (2022).

74k (qutip-qip) + 2.8M downloads (qutip)

arXiv > quant-ph > arXiv:2412.04705 | Search... | Help | Adva

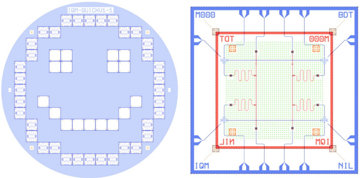
Quantum Physics

[Submitted on 6 Dec 2024]

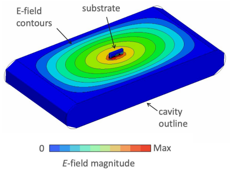
QuTiP 5: The Quantum Toolbox in Python

Neill Lambert, Eric Giguère, Paul Menczel, Boxi Li, Patrick Hopf, Gerardo Suárez, Marc Gali, Jake Lishman, Rushiraj Gadhvi, Rochisha Agarwal, Asier Galicia, Nathan Shammah, Paul Nation, J. R. Johansson, Shahnawaz Ahmed, Simon Cross, Alexander Pitchford, Franco Nori

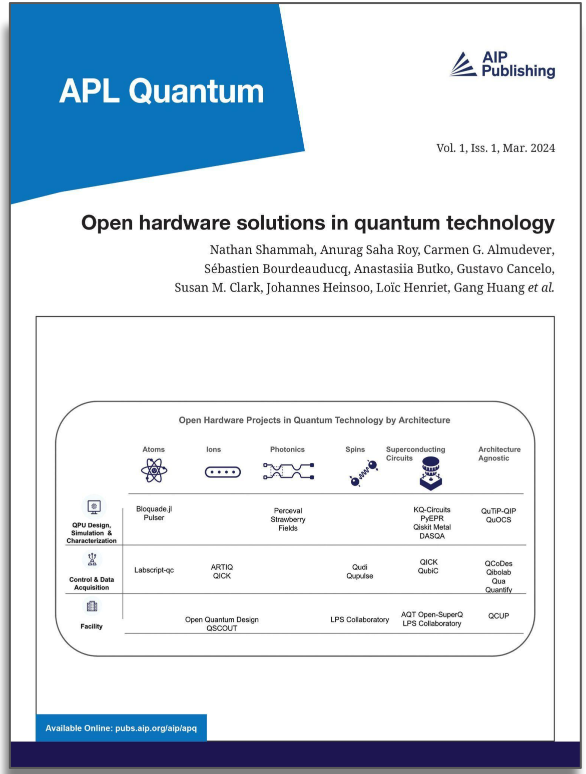
Expanding Open Source to Quantum Hardware



KQCircuits



pyEPR



APL Quantum

AIP Publishing

Vol. 1, Iss. 1, Mar. 2024

Open hardware solutions in quantum technology

Nathan Shammah, Anurag Saha Roy, Carmen G. Almudever, Sébastien Bourdeauducq, Anastasiia Butko, Gustavo Cancelo, Susan M. Clark, Johannes Heinsoo, Loïc Henriet, Gang Huang *et al.*

Open Hardware Projects in Quantum Technology by Architecture

	Atoms	Ions	Photonics	Spins	Superconducting Circuits	Architecture Agnostic
QPU Design, Simulation & Characterization	Bloquade.jl Pulser		Perceval Strawberry Fields		KQ-Circuits PyEPR Qiskit Metal DASQA	QuTiP-QIP QuOCS
Control & Data Acquisition	Labscript-qc	ARTIQ QICK		Qudi Qupulse	QICK QubiC	QCoDes Qibolab Qua Quantify
Facility		Open Quantum Design QSCOUT		LPS Collaboratory	AQT Open-SuperQ LPS Collaboratory	QCUP

Available Online: pubs.aip.org/aip/apq

"Open hardware solutions in quantum technology", N. Shammah et al., APL Quantum 1, 011501 (2024)

- APL Quantum first issue cover
- First review on open hardware in quantum tech

Outline

- Unitary Foundation
- Open Research
- **Mitiq Open Source Ecosystem**

Quantum error mitigation: (Non-exhaustive) overview

Zero Noise Extrapolation

Probabilistic Error Cancellation & Quasi-Probabilistic Repr.ns

Learning-based Methods

Symmetry-based Techniques

Dynamical Decoupling & Randomized Compiling

LF

Quantum error mitigation: (Non-exhaustive) overview

Zero Noise Extrapolation

Key feature: Noise scaling

Probabilistic Error Cancellation & Quasi-Probabilistic Repr.ns

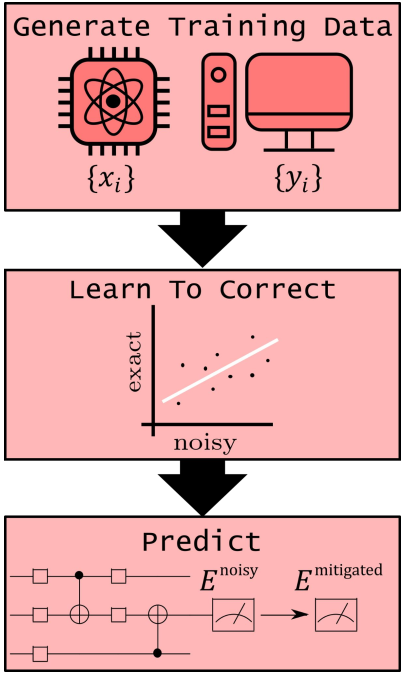
Noisy gate-level representation

Ideal: $\mathcal{U} = \mathcal{G}_t \circ \ldots \mathcal{G}_2 \circ \mathcal{G}_1$

Noisy: $\mathcal{G}_i = \sum_{\alpha} \eta_{i,\alpha} \mathcal{O}_{i,\alpha}$

Learning-based Methods

Learn noise (ML), use Clifford circuits



Symmetry-based Techniques

Dynamical Decoupling & Randomized Compiling

Quantum error mitigation: (Non-exhaustive) overview

Zero Noise Extrapolation

Key feature: Noise scaling

Probabilistic Error Cancellation & Quasi-Probabilistic Repr.ns

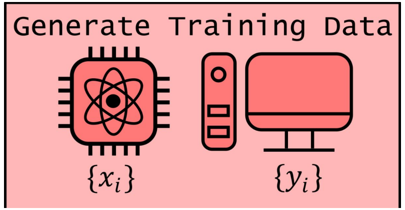
Noisy gate-level representation

Ideal: $\mathcal{U} = \mathcal{G}_t \circ \ldots \mathcal{G}_2 \circ \mathcal{G}_1$

Noisy: $\mathcal{G}_i = \sum_{\alpha} \eta_{i,\alpha} \mathcal{O}_{i,\alpha}$

Learning-based Methods

Learn noise (ML), use Clifford circuits



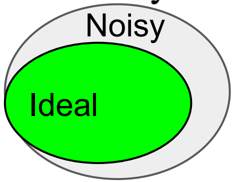
Symmetry-based Techniques

Key feature: Noisy state re-projected

$\hat{M}_s |\psi\rangle = |\psi\rangle$

measuring $\{\hat{M}_i\}$ on the noisy state ρ

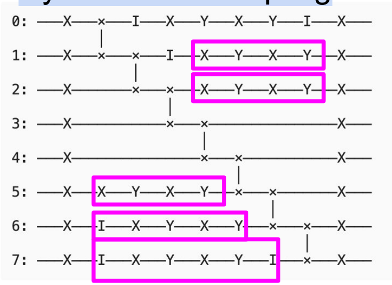
$$\rho_s = \frac{\hat{M}_s \rho \hat{M}_s}{\mathrm{Tr}[\hat{M}_s \rho]}.$$



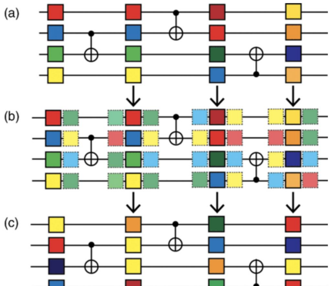
Dynamical Decoupling & Randomized Compiling

Add gates to protect from ‘bad’ noise

Dynamical decoupling



Pauli twirling



Other research

Mix of / specific approaches

Quantum error mitigation: (Non-exhaustive) literature

Zero Noise Extrapolation

Key feature: Noise scaling

K. Temme, et al., **Phys. Rev. Lett.** (2017)
A. Kandala, et al., **Nature**, 567, 491 (2019)
T. Giurgica-Tiron et al., **IEEE Trans.Q.Comp** (2021)
I. Chen, et al., arXiv:2203.08291
E. Huffman *et al.* arxiv:2109.15065

Probabilistic Error Cancellation & Quasi-Probabilistic Repr.ns

Noisy gate-level representation

K. Temme, et al., **Phys. Rev. Lett.** (2017)
H. Pashayan, et al., **Phys. Rev. Lett.** 115, 070501 (2015)
S. Zhang, et al., **Nature Commun.** 11, 587 (2020)
A. Mari et al.,. **Phys. Rev. A** 104, 052607 (2021)
R. LaRose, et al., arXiv:2009.04417 **Quantum** (2022)
C. Piveteau, *et al.*, **Phys Rev Lett.** 127 200505 (2021)
E. van den Berg, arXiv:2201.09866

Learning-based Methods

Learn noise (ML), use Clifford circuits

P. Czarnik et al., **Quantum** 5, 592, (2021)
A. Strikis, et al., **PRX Quantum** 2, 0(2021)
A. Lowe et al., **Phys. Rev. Res.** 3, 033098 (2021)
Z. Cai, **NPJ Qu. Inf.** 7, 1 (2021)

Symmetry-based Techniques

Key feature: Noisy state re-projected

J. R. McClean, et al., **Phys. Rev. A** 95, 042308 (2017)
X. Bonet-Monroig, et al., **Phys. Rev. A** 98, 062339 (2018)
J. R. McClean, et al., **Nature Commun.** (2020)
R. Sagastizabal, et al., **Phys. Rev. A** 100, 010302 (2019)

Dynamical Decoupling & Randomized Compiling

Add gates to protect from 'bad' noise

L. Viola et al., **Phys. Rev. A** 58, 2733 (1998)
L. Viola et al., **Phys. Rev. Lett.** 82, 2417 (1999)
J. Zhang, et al., **Phys. Rev. Lett.**112, 050502 (2014)
B. Pokharel et al., **Phys. Rev. Lett.** 121, 220502 (2018)
J. J. Wallman, J. Emerson, **Phys. Rev. A** 94, 052325 (2016)

Other research

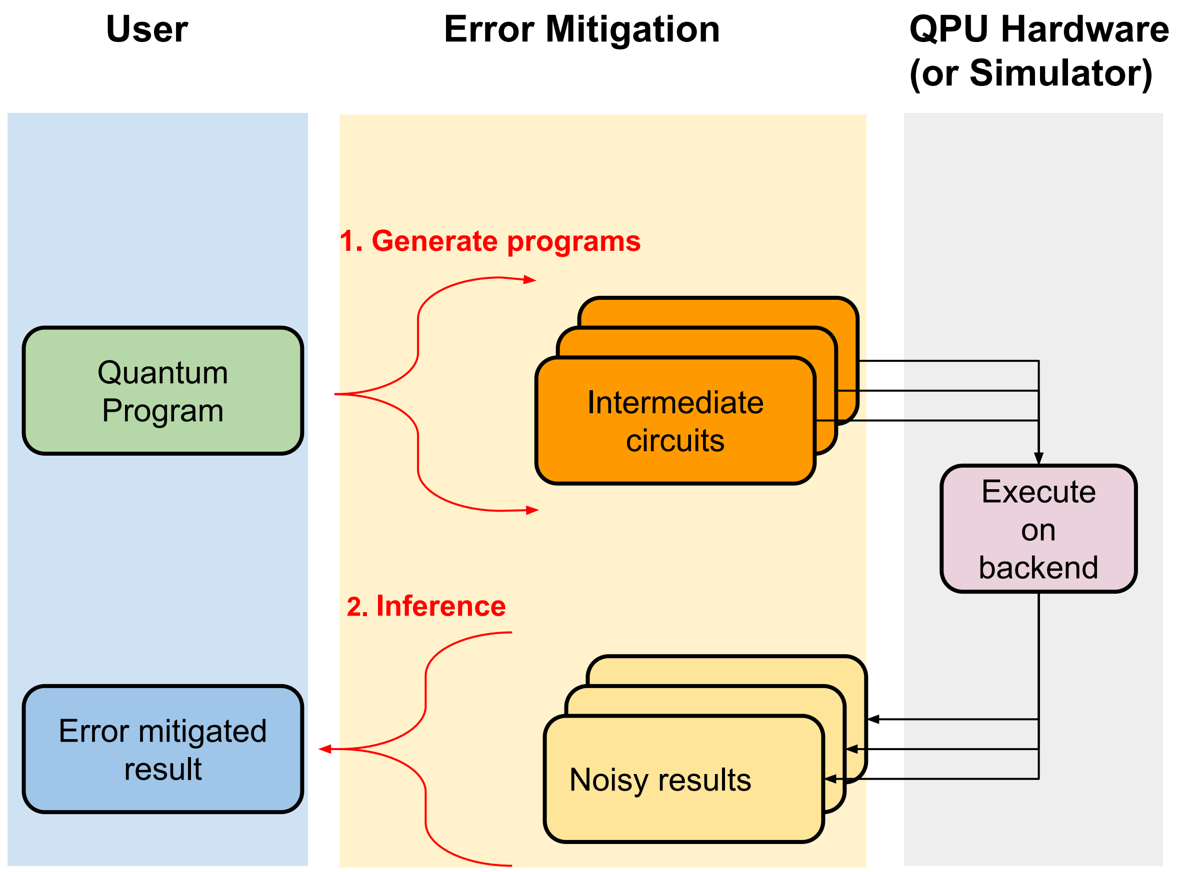
Mix of / specific approaches

R. M. Parrish, et al. **Phys. Rev. Lett.** 122, 230401 (2019)
P. J. J. O'Malley, et al., **Phys. Rev. X** 6, 031007 (2016)
T. Proctor et al. **Nature Phys.** 18, 75 (2021)
Y. Li, S.C. Benjamin **Phys. Rev. X** 7, 021050 (2017)
Jinzhao Sun, et al, **Phys. Rev. Appl.** 15, 034026 (2021)
R. Takagi, **Phys. Rev. Res** (2021)
E. Knill. **Nature** 434, 39 (2005)
S. Endo et al. **Phys. Rev. X** 8, 031027 (2018)
Loock, **Phys. Rev. A** 89, 022316 (2014)

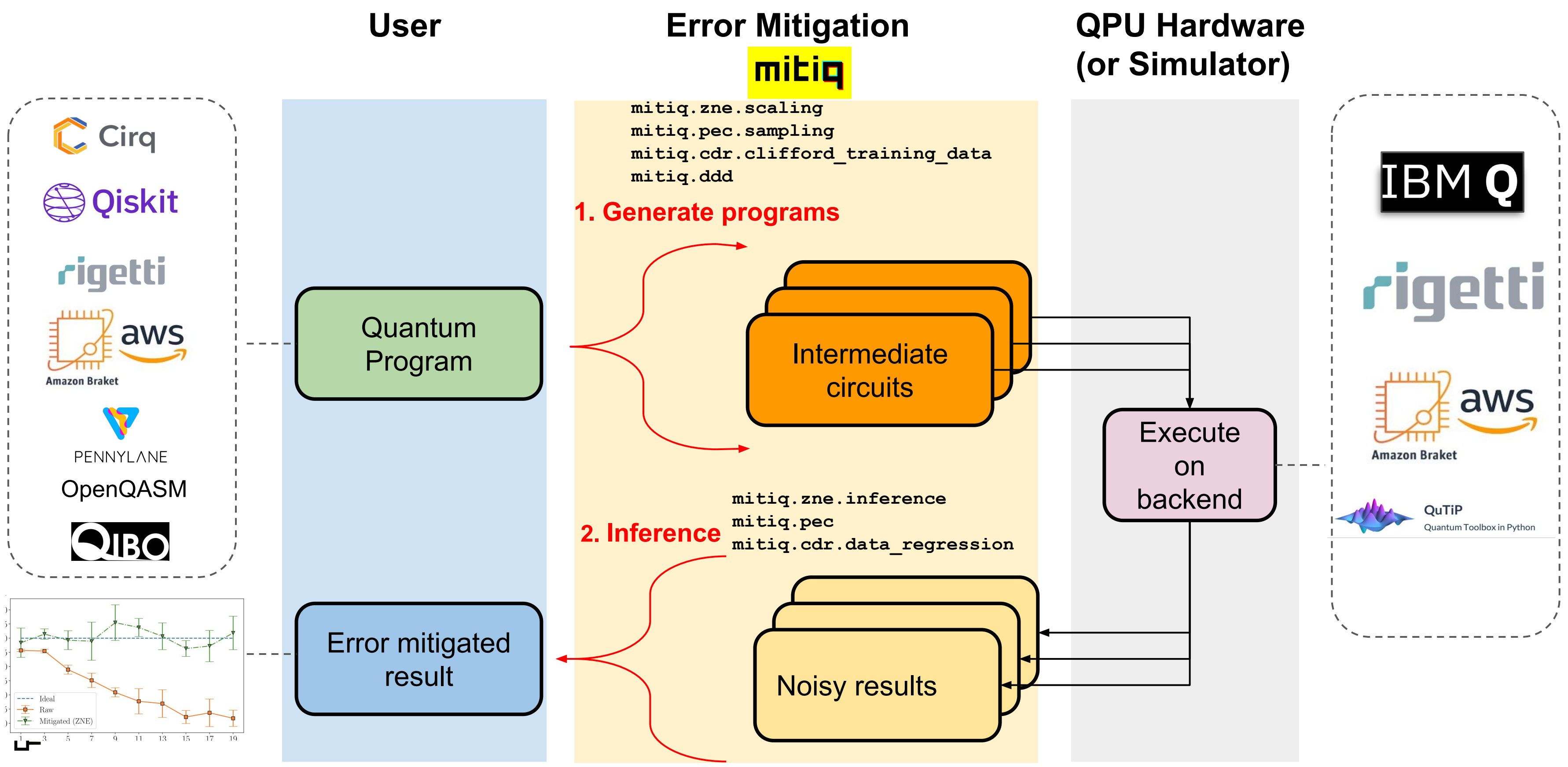
Reviews: S. Endo, *et al.*, J. Phys. Soc. Japan, 90, 032001 (2021) arXiv:2011.01382
Z. Cai, *et al.*, arXiv:2210.00921

All references at: mitiq.readthedocs.io

Key features of most QEM techniques

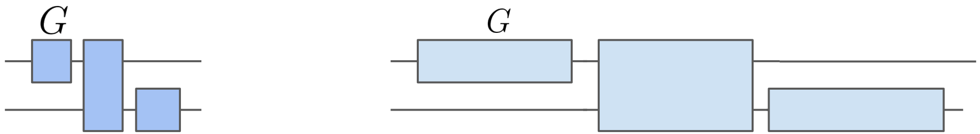


Cross-Platform Quantum Error Mitigation with Mitiq

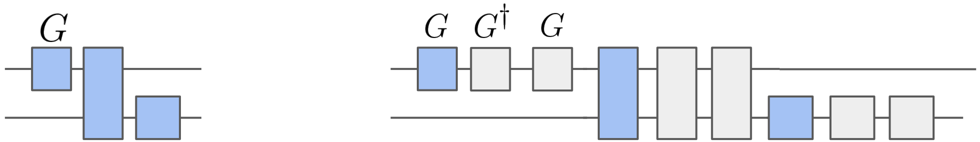


Mitiq works at the digital (gate) level: example for ZNE

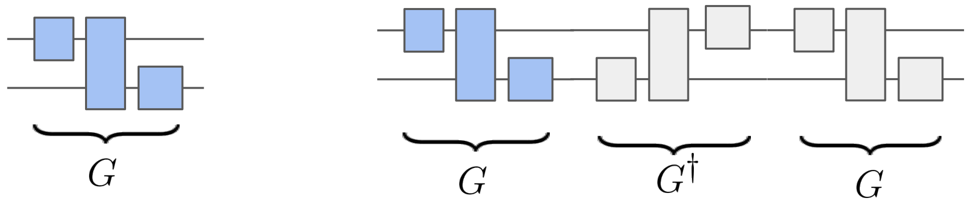
- Pulse stretching



- “Local folding”



- “Global folding”



K. Temme, *et al.* PRL. 119, 180509 9 (2017)

T. Giurgica-Tiron, *et al.*, IEEE Int. Conf. QCE (2020) arxiv:2005.10921

Mitiq project: Community, Impact and Dissemination

Quantum **6** 774 (2022)

`pip install` **`mitiq`**

github.com/unitaryfund/mitiq

50+ Releases
Current version: v.0.45
250,000 Downloads

186 “forks” (copies)
80+ contributors
6 Ambassadors

mitiq.readthedocs.io
317 pages of documentation
Full API-docs, 20+ tutorials

discord.unitary.fund
Community Call: Fri 6 pm CET
Quantum Wednesday: 6:30 pm CET

First established thanks
to ARQC TEAM

U.S. DEPARTMENT OF ENERGY
SMART
NSF

Mitiq is used at Ames Nat Lab, IBM, Inst. Polit. Nacional (Mexico), Iowa State, Los Alamos Nat Lab, Michigan State Univ., Perimeter Institute (Canada), Stanford, Univ. Autonoma Madrid (Spain), Univ. Compl. Madrid (Spain), Univ. of Chicago, Yale…

UF Research on Mitiq with DoE collaborations: 9 papers + software

Mitiq white-paper
arxiv:2009.0441

Stanford University

Digital ZNE
arxiv:2005.10921

SQMS

Iowa State University

Efficient PEC arxiv:2210.08611
Mitiq + pyGSTi

Unitary Fund

AIDE-QC

Berkeley Lab
Lawrence Berkeley National Laboratory

Mitiq + BQSKit

BQSKit

APL
The Johns Hopkins University
Applied Physics Laboratory

Time-correlated noise + ZNE
arxiv:2201.11792
Mitiq + Mezze | SchWARMA

Oak Ridge National Laboratory

Mitiq + QCOR/XACC

XACC
QUANTUM FRAMEWORK

PEC by noise scaling
arxiv:2108.02237

QEM increases effective QV
arxiv:2203.05489

Mitiq on Hardware
arxiv:2210.07194

The University of Chicago

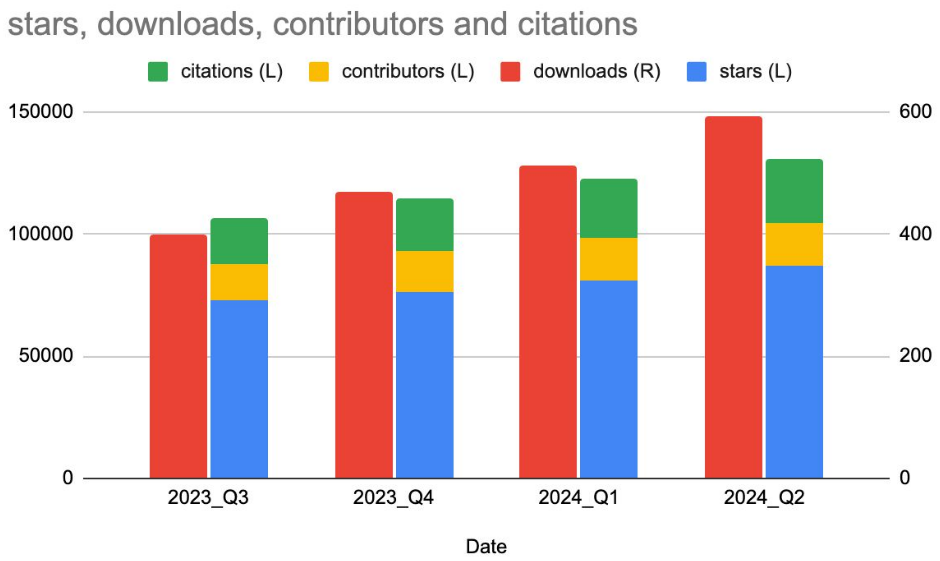
"VAQEM": VQA + QEM
arxiv:2112.05821

QEM+QEC (DS-ZNE)
arxiv:2304.14985

Collabs: DoE | ARQC | TEAM
Output: Papers | Software Integration

UF

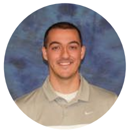
Mitiq project: Community Driven



VINCENT RUSSO

NATE STEMEN

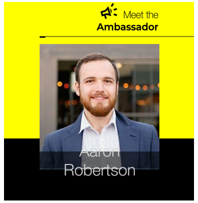
MISTY WAHL



Ryan LaRose, PhD
Asst. Prof. MSU

Peter Karalekas
AWS Quantum

Andrea Mari, PhD
U. Camerino, Italy



Mitiq structure

```
$ tree -L 1 mitiq
    mitiq
     ├── cdr
     ├── ddd
     ├── lre
     ├── pec
     ├── qse
     ├── rem
     ├── zne
     ├── shadows
     ├── vd
     ├── pt
     ├── benchmarks
     ├── interface
    …
     └── calibration
```

QEM Techniques

API: mitiq.xyz.execute_with_xyz

Noise Tailoring

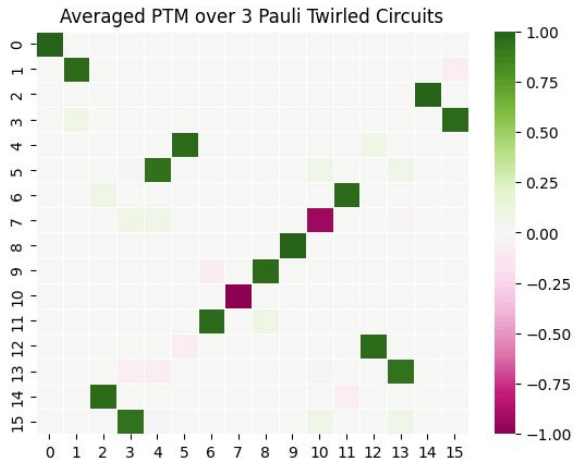
Benchmarks: GHZ
Mirror
(mirror) Quantum Volume
Quantum Phase Estimation
Randomized Benchmarking (RB)
Rotated RB
Clifford+T
W state

Conversions

Calibration

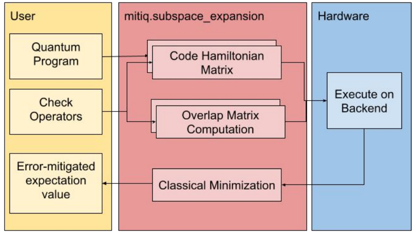
Mitiq 2025 Highlights to Date

- Added Virtual Distillation — UNIVERSITY OF AMSTERDAM
- Improved Layerwise Richardson Extrapolation
- Demonstrated usage with ucc compiler
- Composition of techniques (PT+ZNE) →
- Maintenance



Highlight: Mitiq Collabs

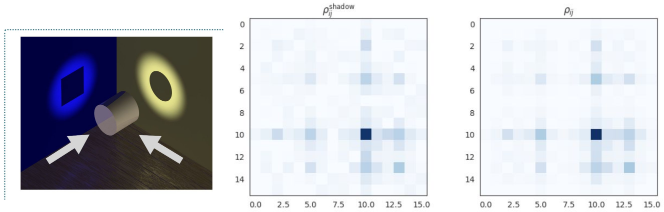
Quantum Subspace Expansion (mitiq.qse)



Collaborators

- Error mitigation inspired by error correction
- Using knowledge that final state obeys some properties ($M|\psi\rangle = |\psi\rangle$), find state with minimal error

Shadow Tomography (mitiq.shadows)

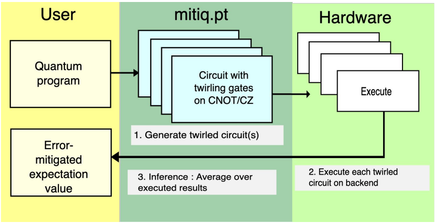


Classical shadow (left) reconstructing a state (right) with mitiq.shadows

Collaborators

- Learn properties of state with minimal measurements.

Pauli Twirling (mitiq.pt)



Collaborators

- Tailor noise from complex noise channels into simpler stochastic Pauli noise channels.
- Current functionality works with CNOT/CZ gates.

QEM Calibration (mitiq.calibrator)

```python
from mitiq import Calibrator

cal = Calibrator(execute, frontend="cirq")
cal.execute_with_mitigation(circuit, expval_executor)
```

```
>>> calibrator.run(log="flat")
```

benchmark	strategy	performance
Type: ghz Num qubits: 2 Circuit depth: 2 Two qubit gate count: 1	Technique: ZNE Factory: Linear Scale factors: 1.0, 2.0, 3.0 Scale method: fold_gates_at_random	✔ Noisy error: 0.04 Mitigated error: 0.02 Improvement factor: 2.0
Type: ghz Num qubits: 2 Circuit depth: 2 Two qubit gate count: 1	Technique: ZNE Factory: Linear Scale factors: 1.0, 3.0, 5.0 Scale method: fold_global	✘ Noisy error: 0.04 Mitigated error: 0.0658 Improvement factor: 0.6076
Type: ghz Num qubits: 2 Circuit depth: 33 Two qubit gate count: 14	Technique: ZNE Factory: Richardson Scale factors: 1.0, 3.0, 5.0 Scale method: fold_global	✘ Noisy error: 0.98 Mitigated error: 1.03 Improvement factor: 0.9515

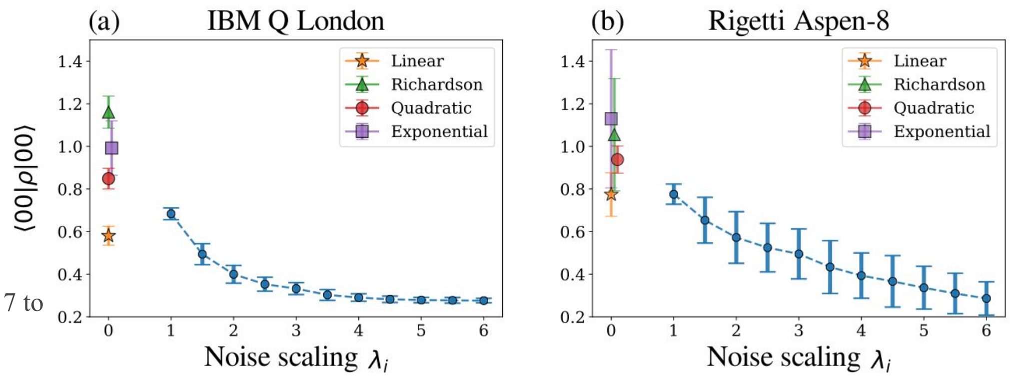
- Test different QEM techniques and associated hyperparameters to find potential investigation areas
- ZNE and PEC currently supported.

Example: Different extrapolation methods with `Factories`

mitiq.zne.inference
.

Class	Extrapolation Method
`LinearFactory`	Extrapolation with a linear fit.
`RichardsonFactory`	Richardson extrapolation.
`PolyFactory`	Extrapolation with a polynomial fit.
`ExpFactory`	Extrapolation with an exponential fit.
`PolyExpFactory`	Similar to `ExpFactory` but the exponent can be a non-linear polynomial.
`AdaExpFactory`	Similar to `ExpFactory` but the noise scale factors are adaptively chosen.

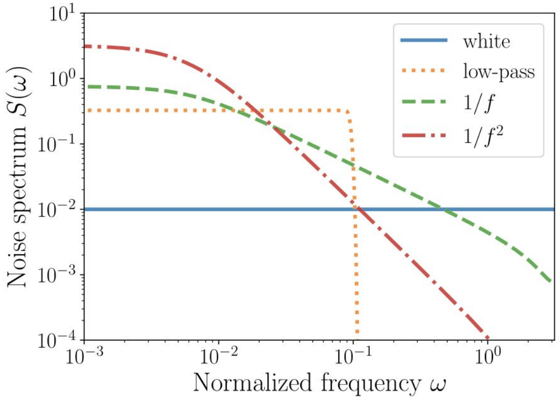
Experiment (2-qubit RB circuit):



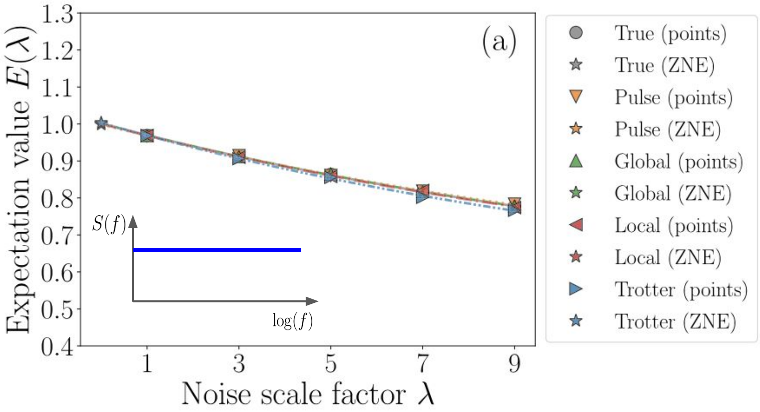
R. LaRose, et al. "Mitiq: A software package for error mitigation on noisy quantum computers", arXiv:2009.04417 to appear in ***Quantum*** (2022).

Impact of correlated noise on Zero-Noise Extrapolation

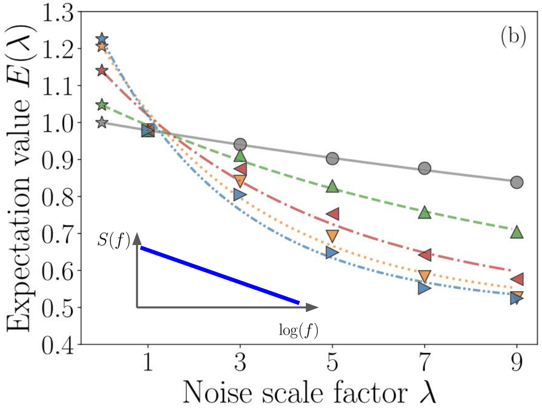
Noise Spectra



ZNE + White Noise



ZNE + $1/f^2$ Correlated Noise

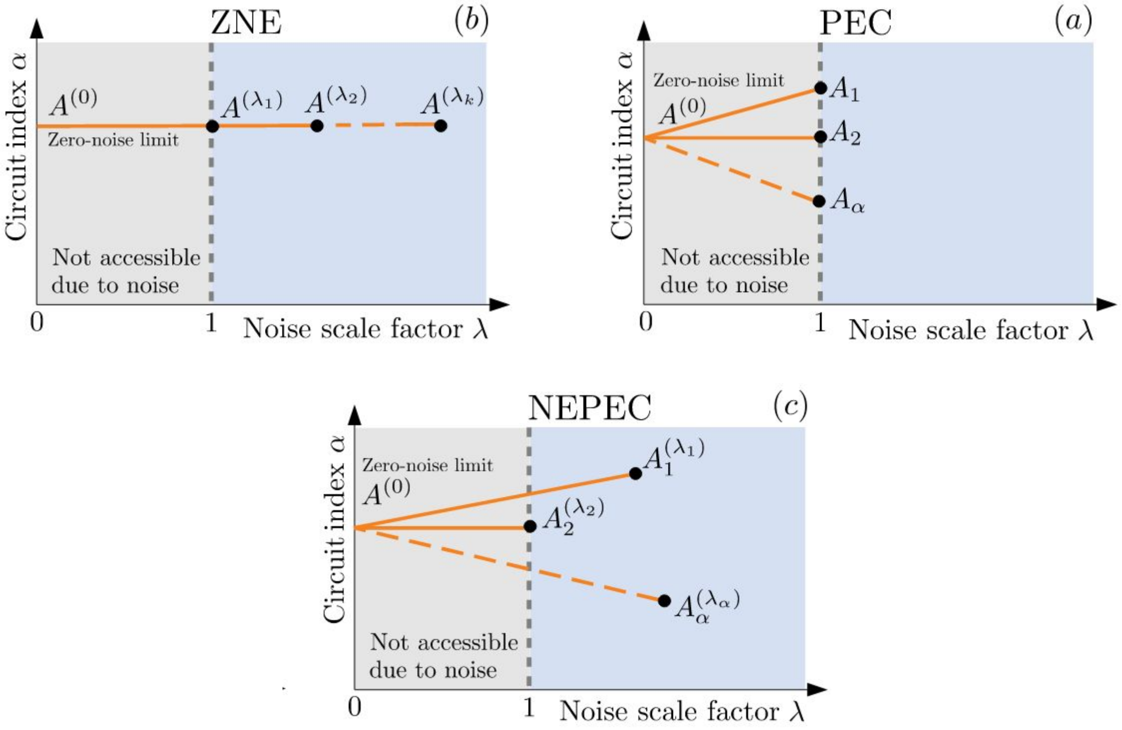


Global folding emerged as the most robust folding method for correlated noise

K. Schultz, R. LaRose, A. Mari, G. Quiroz, N. Shammah, B. David Clader, W. J. Zeng,
"Impact of time-correlated noise on zero-noise extrapolation", Phys. Rev. A **106**, 052406 (2022), arXiv:2201.11792.
Software: Mitiq + Mezze | SchWARMA

We introduced a general framework for error mitigation

Noise-extended Probabilistic Error Cancellation (NEPEC)



A. Mari, N. Shammah, and W. J. Zeng, Phys. Rev. A 104, 052607 (2021). arXiv:2108.02237

Reducing the overheads to apply error mitigation

Noise characterization

Gate Set Tomography (GST)

→

Error Mitigation

Probabilistic Error Cancellation (PEC) mitiq

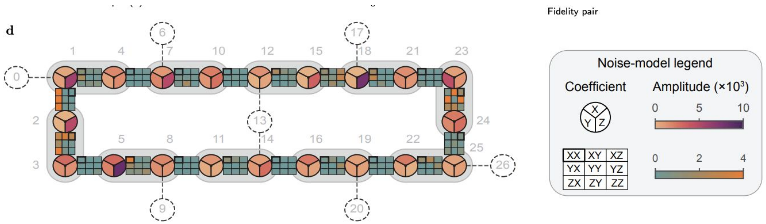
Overhead Reduction

Pauli-Noise Tomography (PNT)

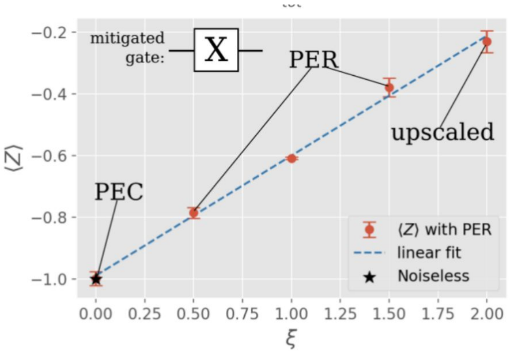
→

Overhead Reduction

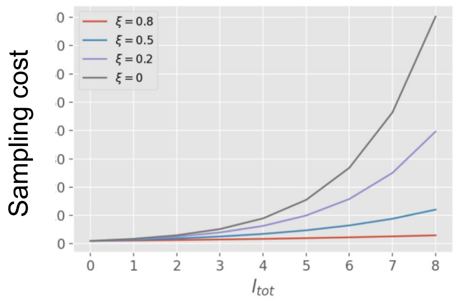
NEPEC Technique:
Probabilistic Error Reduction (PER) mitiq



E. van den Berg, et al., arxiv:2201.09866



Noise scaling factor



Circuit depth

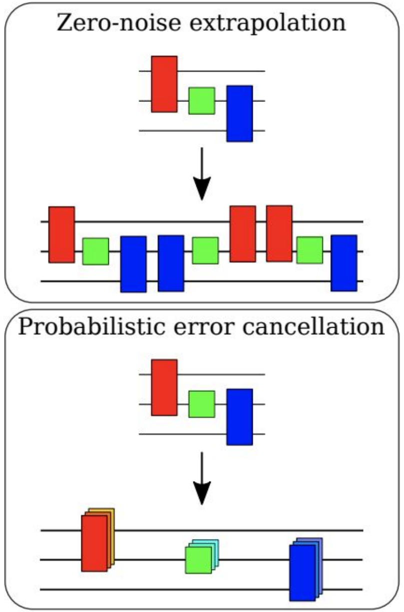
B. McDonough, *et al.*, Proc.IEEE QCE 2020 arxiv:2210.08611

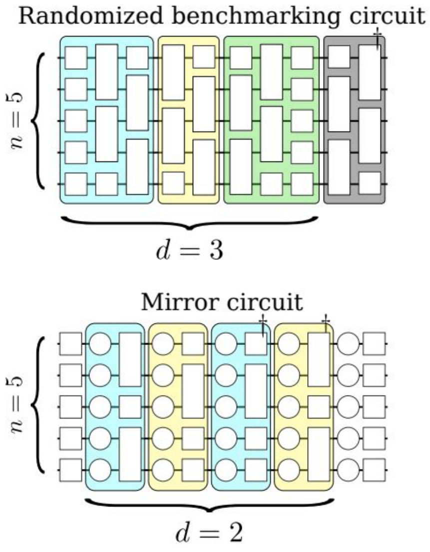
Testing quantum error mitigation on hardware "out-of-the-box"

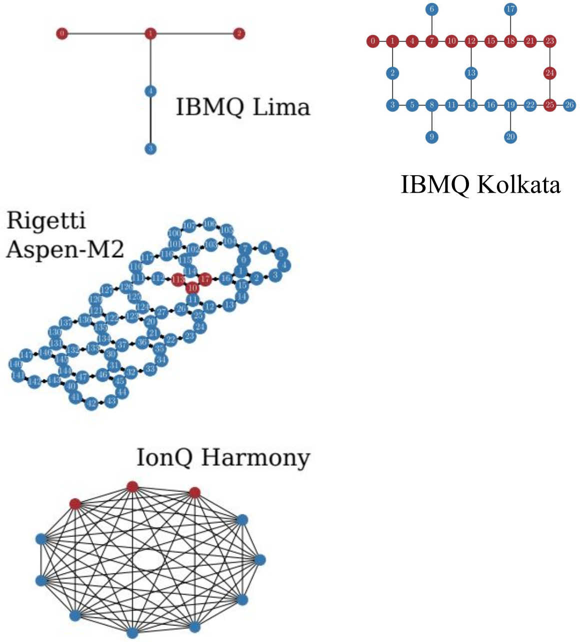
2 QEM techniques
ZNE and PEC

2 Benchmarks
RB and Mirror circuits

3 Backends
IBM, Rigetti, IonQ



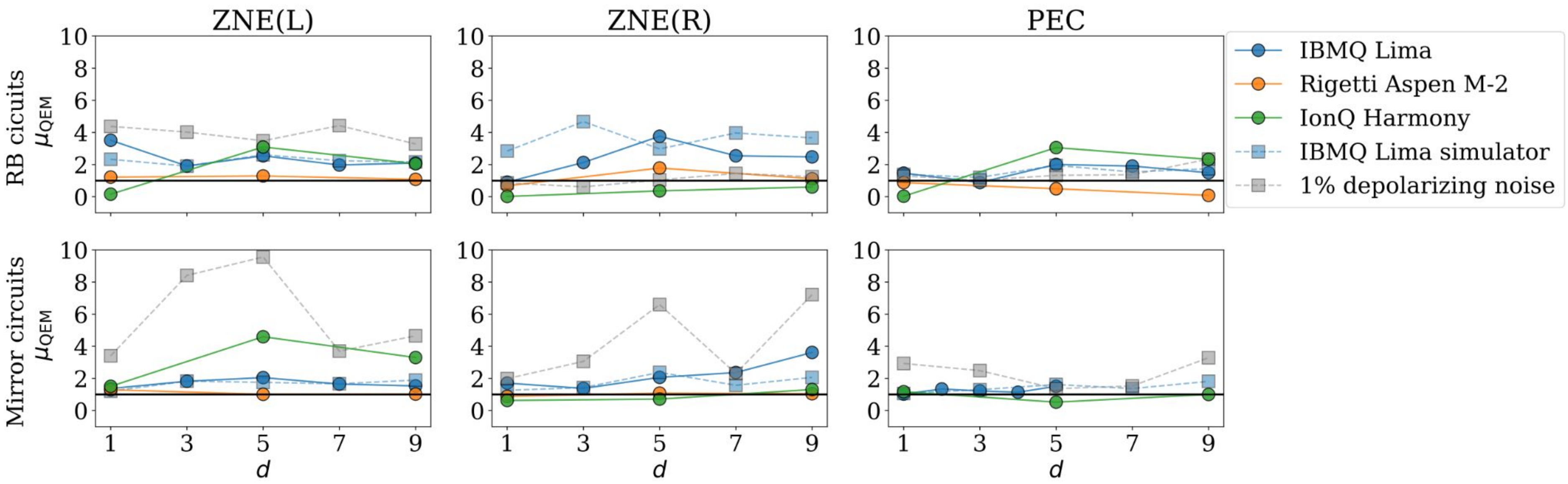




V Russo *et al.*, arXiv:2210.07194

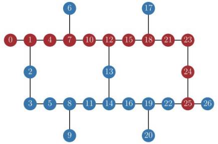
Benchmarking quantum error mitigation on hardware

The improvement factor shows overall improvements even accounting for sampling overheads

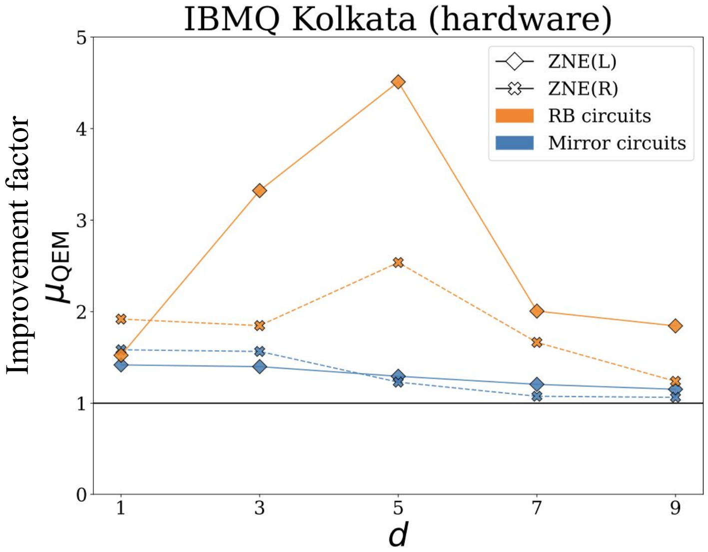


V Russo *et al.*, arXiv:2210.07194

Benchmarking quantum error mitigation: Improvement factor



IBMQ Kolkata *n=12* qubits



d	$n=3$	$n=5$	$n=12$
1	3 (22)	7 (39)	19 (99)
3	6 (44)	11 (73)	36 (204)
5	9 (64)	18 (118)	53 (307)
7	12 (80)	24 (150)	73 (403)
9	15 (108)	31 (194)	89 (506)
12	18 (135)	37 (242)	115 (651)

TABLE II: Average number of two-qubit gates for an n-qubit, depth d RB circuit.

V Russo *et al.*, arXiv:2210.07194

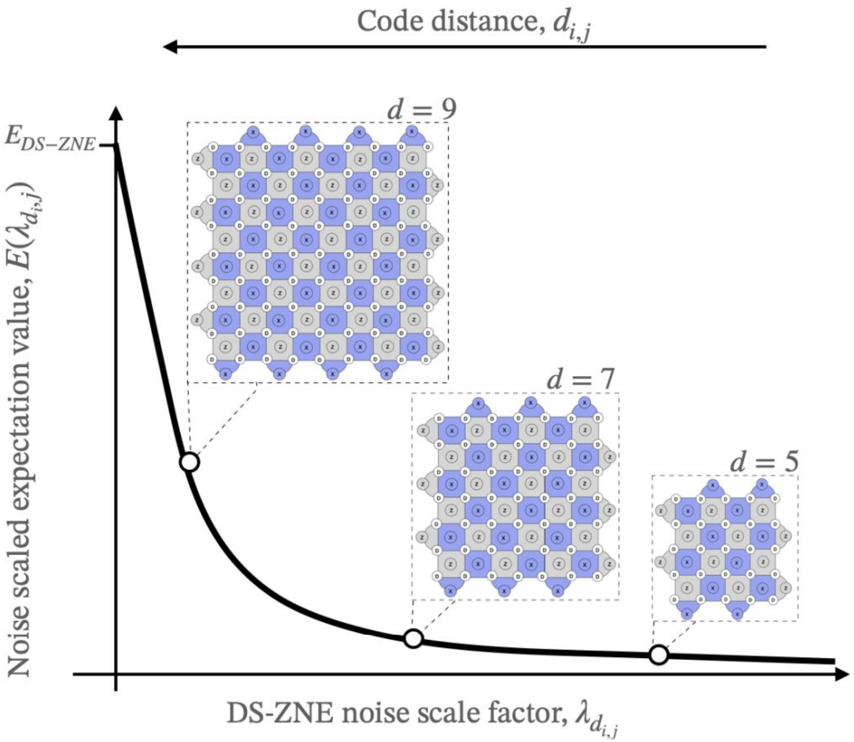
State of the art of quantum error mitigation on QPUs

QEM	Benchmark	Qubits n	Computer(s)	Ref.
ZNE	RB	1, 2	5-qubit superconducting device	[KTC+19]
	RB	2	IBMQ London & Rigetti Aspen-8	[LMK+20]
	RB, PG	2 - 5	IBMQ Lagos & IBMQ Casablanca	[CDM+22]
	RB, MC	3, 5, 12	IBMQ Lima, IBMQ Kolkata, Rigetti Aspen-M2, IonQ Harmony	(This work)
	VQE	4	5-qubit superconducting device	[KTC+19]
	QV	5	IBMQ Belem, IBMQ Lima, & IBMQ Quito	[LMR+22]
	RB, TE	26	27-qubit superconducting device	[KWY+21]
PEC	RB	2	2-qubit trapped ion ($^{171}Yb^+$) device	[ZLZ+20]
	RB, MC	3	Rigetti Aspen-M2, IBMQ Lima, IonQ Harmony	(This work)
	CYC	4	4-qubit superconducting device	[FHV+22]
	TE, CYC	4, 10	27-qubit superconducting device	[BMKT22]
DD	IDLE	1, 2	IBMQX4, IBMQX5, & Rigetti Acorn	[PAFL18]
	Adder, GHZ, QAOA, QFT, VQE	4, 5, 6	IBMQ Guadalupe, & IBMQ Jakarta	[SRM+22]
	QPE	5	IBMQ Paris, IBMQ Guadalupe, & IBMQ Toronto	[DTDQ21]
	QV	6	IBMQ Montreal	[JJAB+21]
	QFT	6, 7	IBMQ Paris, IBMQ Guadalupe, & IBMQ Toronto	[DTDQ21]
	BV	7, 8	IBMQ Paris, IBMQ Guadalupe, & IBMQ Toronto	[DTDQ21]
	QAOA	8, 10	IBMQ Paris, IBMQ Guadalupe, & IBMQ Toronto	[DTDQ21]
CDR	RB, PG	2 - 5	IBMQ Lagos & IBMQ Casablanca	[CDM+22]
	VQE	5	IBMQ Rome	[CACC21]
	VQE	6	IBMQ Toronto	[CMSC22]
	VQE	16	IBMQ Almaden	[ZCN+21]
SSE	VQE	2	2-qubit superconducting device	[CRD+18]
	VQE	2	3-qubit superconducting device	[SBMS+19]
VD	GHZ	5	5-qubit trapped ion, UMD, ($^{171}Yb^+$) device	[SCZ+22]

TABLE I: A history of quantum error mitigation experiments on quantum computers in literature.

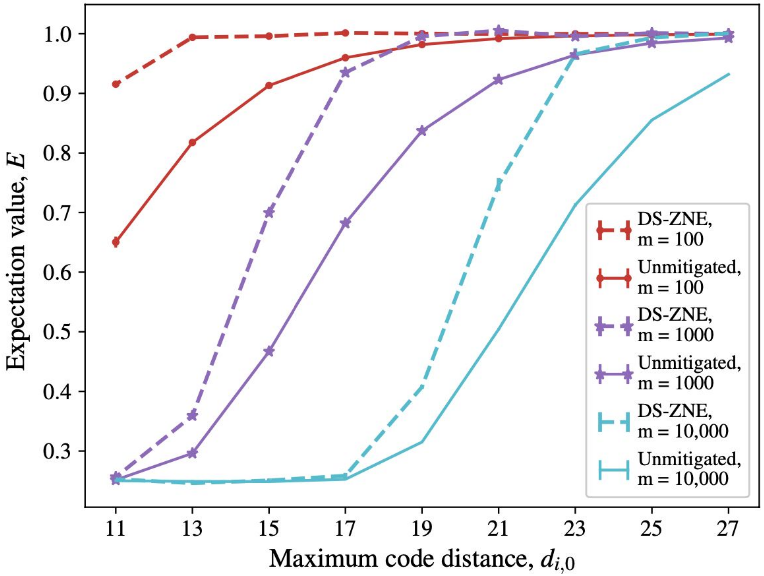
V Russo *et al.*, arXiv:2210.07194

ZNE on logical qubits by scaling the error correction code distance



M. Wahl, *et al.*, arxiv:2304.1495

ZNE on logical qubits by scaling the error correction code distance



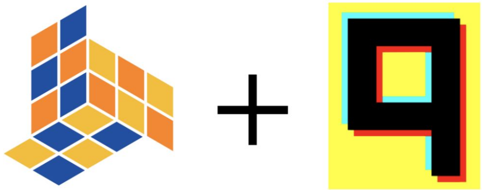
We show gain at deeper circuits (up to depth *m*=10'000), using `stim`

M. Wahl, *et al.*, arxiv:2304.1495

H. Jnane, et al., Phys. Rev. Appl. **18**, 044064 (2022)

Blog post: Upgrading error mitigation to the fault tolerant regime with Mitiq. unitary.fund/blog

Tutorial: Mitiq + Stim (mitiq docs)



Impact: Mitiq is enables research on QEM and *with* QEM

Toward the real-time evolution of gauge-invariant $\mathbb{Z}_2$ and $U(1)$ quantum link models on noisy intermediate-scale quantum hardware with error mitigation
E Huffman, MG Vera, D Banerjee - Physical Review D, 2022 - APS

Quantum simulation of dynamical phase transitions in noisy quantum devices
Y Javanmard, U Liaubaite, TJ Osborne… - arXiv preprint arXiv …, 2022 - arxiv.org

[HTML] Algebraic Bethe Circuits
A Sopena, MH Gordon, D García-Martín, G Sierra… - Quantum, 2022 - quantum-journal.org

Error-mitigated simulation of quantum many-body scars on quantum computers with pulse-level control
IC Chen, B Burdick, Y Yao, PP Orth, T Iadecola - Physical Review Research, 2022 - APS

Real-time simulation of light-driven spin chains on quantum computers
M Rodriguez-Vega, E Carlander, A Bahri, ZX Lin… - Physical Review …, 2022 - APS

Simulating quench dynamics on a digital quantum computer with data-driven error mitigation
A Sopena, MH Gordon, G Sierra… - Quantum Science and …, 2021 - iopscience.iop.org

…

mitiq

Mitiq is used at

- Ames Nat Lab
- IBM
- Inst. Polit. Nacional (Mexico)
- Iowa State
- Los Alamos Nat Lab
- Michigan State Univ.
- Perimeter Institute (Canada)
- Stanford
- Univ. Autonoma Madrid (Spain)
- Univ. Compl. Madrid (Spain)
- Univ. of Chicago
- Yale

…

LF

Integrating Mitiq with early-FT quantum compilation

Mitiq

mitiq

`pip install mitiq`

- Quantum Error Mitigation Toolkit
- 250k downloads, 80+ contributors
- Several mitigation techniques
- Fully compatible with front/backends
- Composable techniques

Unitary Compiler Collection (ucc)

- Best-in-Class Compilation
- No Code Changes to Switch Between Frontends
- Compatible with Any Backend Supporting OpenQASM

- github.com/unitaryfoundation/ucc

← BACK TO BLOG

18.6.2025 nate stemen and Jordan Sullivan

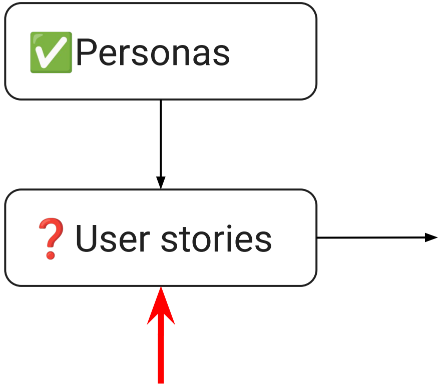
Better Together: Mitiq meets UCC

Combining error mitigation and compilation for stronger quantum performance

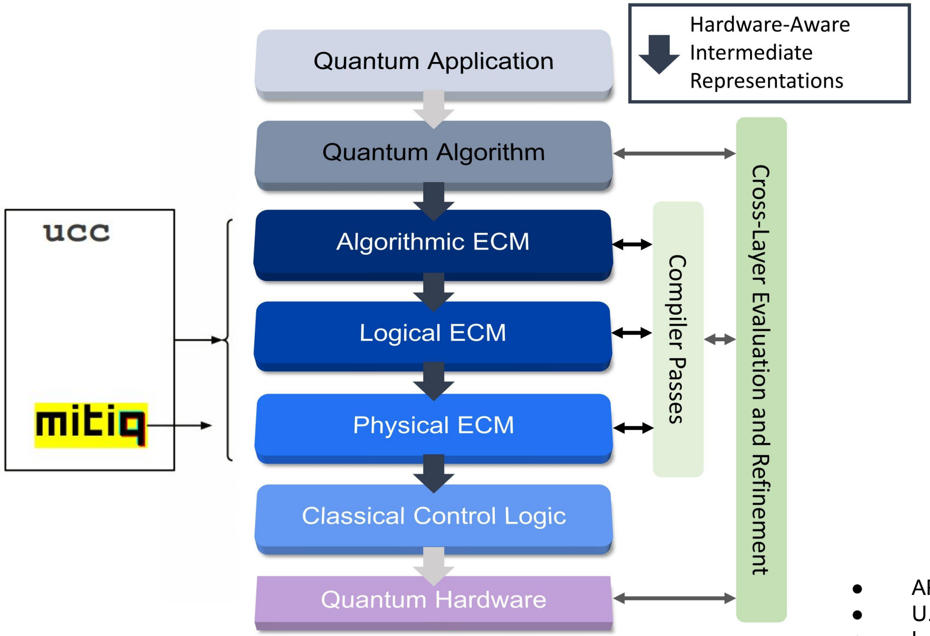
https://unitary.foundation/blog/

Tooling for **scalable** early-FT quantum compilation

SMART: Scalable, Modular, Adaptable, Reconfigurable, error-Targeted Approaches to Quantum Stack Design



Missing (across industry), especially early FTQC



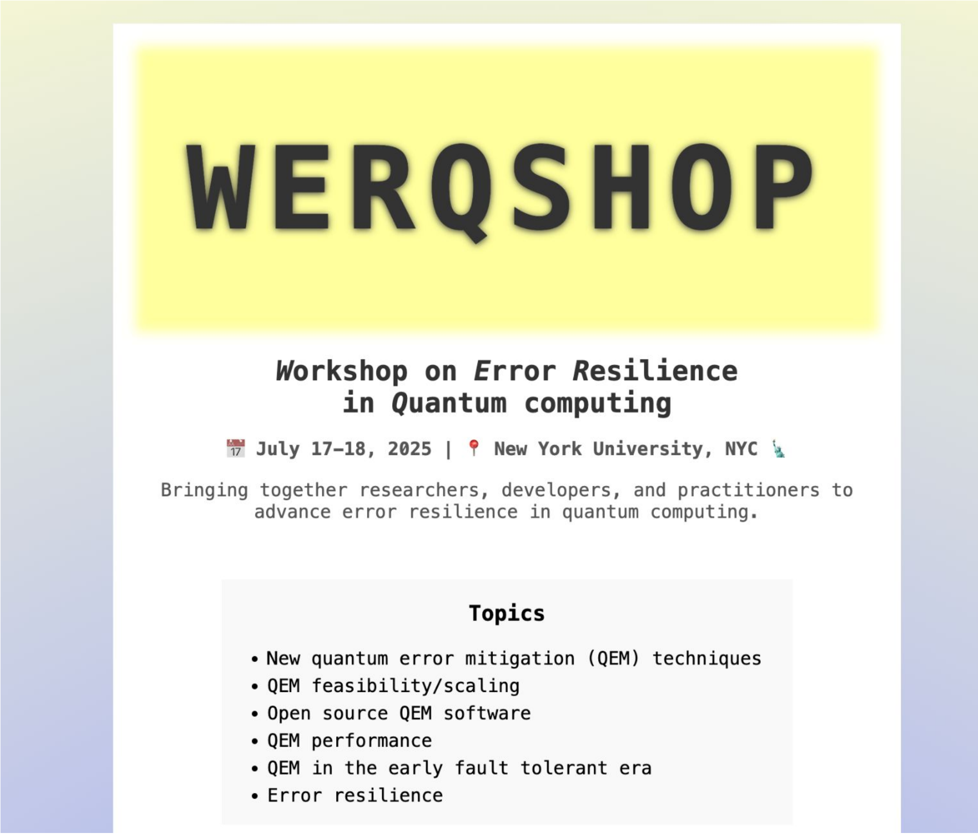
- APL Johns Hopkins U.
- U. Chicago
- L. Livermore Nat. Lab
- Inflegtion
- U. Michigan
- Unitary Foundation

SMART

U.S. DEPARTMENT OF ENERGY

NSF

https://sites.krieger.jhu.edu/arqc-smart/



https://werq.shop/

- Insights for Mitiq & ucc development
- Open Source Governance for Mitiq
- Collaborate on new experiments and research ideas

Trends (and wishes) in quantum error mitigation and early logical qubits

- **Hybridization of QEC with QEM.** While QEM is generally presented as an alternative approach to QEC, the two frameworks can be hybridized. QEM subroutines can be used to reduce QEC's overhead.

- **Stacking of multiple QEM techniques together.** Some quantum error mitigation techniques and error control strategies can be stacked together, or hybridized.

- **Co-development with hardware architectures and noise models.** Characterization. Select QEM based on HW. Or even make hardware design choices based on estimates of the algorithmic family to run on the quantum chip. Open-source tools and shared facilities needed for successes and dead ends.

- **Integration of error control and QEM into compilation stack.** OSS vs. closed-source toolkits. Directly integrated by quantum hardware providers. Further integration with high performance computing (HPC) infrastructure is needed together with. Transparent error control operations for QEM researchers.

- **Benchmarks.** The field is progressing only as fast as it can demonstrate. Systemic and application-oriented benchmarks. Disclose QEM in benchmarking: Open-source methods are to be preferable. Also, resource estimation of the related compilation stack.

- **Integration with noise characterization.** Understand the noise budget, platform dependent.

N. Shammah, "Quantum Error Control and Mitigation Strategies", to appear in: "Quantum Technologies Trends and Implications for Cyber Defence", Editors: JJ Accard et al., Springer 2025

Under-explored quantum error mitigation areas

- **QEM beyond qubit systems.** Qudits, bosonic systems, photonics-based quantum computing platforms, cat qubits or autonomous QEC.

- **QEM beyond quantum computing.** There are only a few initial studies on the use of QEM beyond quantum computing, used to enhance the signal-to-noise ratio in quantum sensing and quantum communication.

N. Shammah, "Quantum Error Control and Mitigation Strategies", to appear in: "Quantum Technologies Trends and Implications for Cyber Defence", Editors: JJ Accard et al., Springer 2025

Thank you

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