Final Report for Grant DOE DE-SC0020266ù

Tough Errors Are no Match (TEAM): Optimizing the quantum compiler for noise resilience

Nathan Shammah, Nathaniel T. Stemen, Andrea Mari,
Vincent Russo, Misty Wahl, William J. Zeng

Unitary Fund

Funding Department: Department of Energy, Office of Science

Grant #: DE-SC0020266
Funding Office: DOE ASCR

10 June, 2025

Unitary Fund

Abstract

This report summarizes Unitary Fund's contributions to the Department of Energy's TEAM project (DE-SC0020266) under **Thrust 2: Quantum Programming and Compilation**. The central outcomes of this work have been the development of **Mitiq**, an open-source Python toolkit for applying quantum error mitigation (QEM) techniques to noisy quantum programs, and the invention, benchmarking and theoretical investigation of novel QEM techniques. Additional outcomes include the development of other open source software packages for the usage, simulation and control of quantum computers.

Mitiq supports multiple quantum software platforms (Cirq, Qiskit, Braket, PennyLane, Qibo) and provides implementations of widely used techniques such as zero-noise extrapolation, probabilistic error cancellation, and digital dynamical decoupling. Over the course of the project, Mitiq achieved broad adoption in the quantum computing community, with over 150,000 downloads, contributions from more than 80 developers, and citation in over 100 research publications. The toolkit has been validated in experimental studies demonstrating improved computational outcomes on real quantum hardware. While some proposed directions — notably Task 2.2 on novel programming paradigms — were not pursued beyond early prototyping, the project successfully delivered on its primary goals and laid the groundwork for future integrations of QEM into tomorrow's compiler toolchains to create a more robust quantum software stack. Mitiq continues to serve as a foundation for both research and application in quantum error mitigation, helping to make near-term quantum devices more effective through software-based techniques.

Among the research results, we highlight the introduction of "unitary folding" in the context of digital noise scaling and its thorough exploration, even in the presence of correlated noise; the adaptation of QEM for logical qubits; the theoretical unification of major QEM techniques, such as zero noise extrapolation and probabilistic error cancellation, with the introduction of new hybridized techniques; the benchmarking of default QEM techniques on real quantum hardware; the development of automated workflows for noise-aware QEM and the first overview of open source software solutions for the design, characterization and control of quantum hardware.

Overview of Key Results and Contributions

Introduction

Today's quantum computing world requires much of the same infrastructural tools that were developed for early classical computers to make them more accessible to a wider audience, and to start addressing disruptive applications across many disciplines. It remains a challenge to make quantum computing useful, sooner. The near-term noisy intermediate scale quantum (NISQ) era machines have significant error rates that must be considered by any user. Moreover, the different hardware backends and software front ends that are currently being developed require cross-platform, and software-agnostic tools to allow users to run programs on the machines available to them. A compilation toolbox that leverages techniques from quantum characterization and control, probabilistic programming, and approximate computing is required to improve error robustness in quantum computing hardware in order to begin to address some of the potentially disruptive applications in many areas of national interest (quantum.gov) including chemistry, finance, optimization and security. Efforts focused on NISQ computation must also have direct applicability to future fault tolerant quantum computers as well, and this will require a continued reduction in noise levels and optimizations in quantum circuits that consider the underlying hardware constraints, including noise characteristics.

To address this issue, Unitary Fund has developed the open source quantum error mitigating (QEM) compiler **mitiq**, which uses the new research methods and techniques of error mitigation and software tools to compile programs to be more robust to errors.

Research Objectives

Unitary Fund coordinated Thrust 2 in the TEAM Project (Quantum Programming and Compilation), with the following tasks:

- Develop and test hardware-agnostic and hardware-aware error mitigation techniques
    - The Mitiq toolkit was developed with multiple error mitigation techniques, applied across platforms.
- Develop an advanced error-mitigating toolkit.
    - Mitiq was integrated with multiple software development kits (SDKs) for quantum computing programming (Cirq, Qiskit, Braket, Qibo, PennyLane) and its primitives were upstreamed to the Catalyst compiler, developed using Multi-Level Intermediate Representation (MLIR).

Main results

Main results:

- **Software results:**
    - **Software creation.** UF built Mitiq, a first of its own software to apply quantum error mitigation and error suppression techniques across different SDKs and architectures.
    - **Software adoption.** Mitiq has been a success, used by the quantum open source ecosystem, recognized by main players. Its growth has been witnessed by the

adoption of Mitiq by several entities, from corporate R&D arms like IBM to startups like Xanadu to researchers at academic institutions like Harvard and national labs like Los Alamos, ORNL, LBL and Fermilab.

  - **Software integration.** Within the ARQC TEAM project, UF has successfully coordinated the thrust area and performed research with collaborators. Collaboration and software integration has spilled out from the TEAM project to other DoE Office of Science supported frameworks and programs as part of the US quantum national initiative.
  - **Follow up funding and scope extension.** The ARQC support kick-started the Mitiq project and UF's error mitigation and quantum compilation software development, which has since obtained further support by entities like IBM, National Science Foundation (through a POSE grant awarded solely to UF and focused on Mitiq open source ecosystem growth) and a follow up funding by DoE ASCR within the SMART Stack program where UF is thrust area lead.

- **Research results.** Within the research results obtained by UF with collaborators, we list each research paper and contribution to international conferences and workshops. Main results are:
  - **Digital QEM.** Demonstration of the feasibility of a gate-level ("digital") approach to quantum error mitigation **[LaRose2022] [Tiron2021].** We tested various ZNE parameters vs. different types of noise affecting a quantum processing unit (QPU) **[Schultz2022]**
  - **QEM Benchmarking.** Exploration and verification of the impactfulness of zero-noise extrapolation for quantum error mitigation, including on cloud-accessible quantum computing providers. **[Pelofske2025] [Lougovski2024] [LaRose2022b] [Pelofske2023] [Russo2022]**
  - **New QEM techniques and theoretical unification framework.** Unification of quantum error mitigation framework with a unified formalism, instrumental in inventing new QEM techniques, such as probabilistic error reduction and virtual ZNE, **[Mari2021] [Ravi2021] [McDonough2022].** This includes theoretical research on layerwise Richardson extrapolation, hybridization of probabilistic error cancellation **[Mari2024]**.
  - **Simulation of QPUs.** This includes noisy quantum circuits **[Li2022]** and GPU-accelerated simulation of exact and approximate quantum programs **[Strano2023].**
  - **Hybridization of QEM with QEC.** We upgraded ZNE to the logical qubit space **[Wahl2023]**
  - **Open source tools for quantum hardware [Shammah2023].** This is the first review on open hardware in quantum technology, including tools to design chips, calibrate qubits and control qubits to mitigate the impact of noise.

Results - Software

This project led to the creation and public release of **mitiq**, a modular Python toolkit for applying quantum error mitigation (QEM) techniques to noisy quantum programs. Mitiq supports major quantum SDKs (Cirq, Qiskit, Braket, PennyLane, Qibo) and allows users to apply error mitigation with minimal overhead or knowledge about QEM techniques.

Core capabilities and techniques

Mitiq provides a unified API for estimating expectation values with error mitigation applied. Users supply a circuit, a method of running circuits, and an optional observable, and Mitiq handles all circuit transformations, batch execution, and post-processing. The toolkit supports multiple techniques originally outlined in the project narrative, as well as additional new techniques from literature on QEM.

- **Zero-Noise Extrapolation (ZNE)**: Estimates noise-free results by executing scaled circuits and extrapolating to zero noise.
- **Probabilistic Error Cancellation (PEC)**: Applies quasiprobabilistic corrections based on noise models. More resource-intensive, but highly accurate.
- **Digital Dynamical Decoupling (DDD)**: Mitigates decoherence by inserting gate sequences which compile to identity, but ensure qubits do not unintentionally couple to each other or the environment.
- **Readout Error Mitigation (REM)**: Corrects measurement noise using confusion matrices.
- Additional implementations include **Clifford Data Regression (CDR)**, **Quantum Subspace Expansion (QSE)**, **Pauli Twirling (PT)**, and **Classical Shadows** — expanding the space of supported methods.

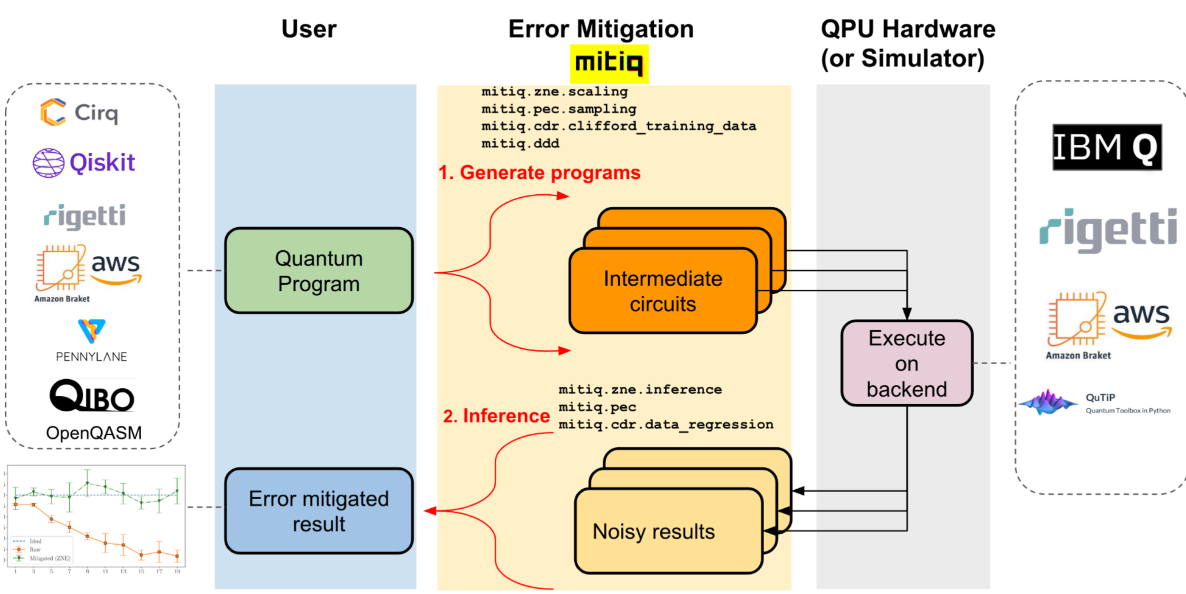


Figure 1. Cross-Platform Quantum Error Mitigation with Mitiq. Diagram highlighting Mitiq usage to mitigate errors of quantum computers and its cross-platform compatibility. Mitiq can be

used by users writing a quantum program using several different alternative software development kits (SDKs), including Cirq, Qiskit, quil, braket, Pennylane, Qibo and OpenQasm. It is QPU hardware agnostic, the backend can be any quantum computer or simulated quantum computer, such as IBM Quantum, Rigetti, AWS-braket cloud or a QuTiP simulator. Mitiq works in two main steps, independently of the specific QEM technique it applies: the first step entails generating several programs that differ from each other for properties that enable sampling more data points in the noise landscape; the second step entails applying inference to the noisy results to obtain a zero-noise (or low-error) inference value.

In developing Mitiq, there has been a strong collaboration with other TEAM partners and other DoE funded research projects and open-source software, as shown in **Figure 2** below for selected research with software output. Within TEAM members, UF collaborated with the University of Chicago, Applied Physics Lab from Johns Hopkins University, and Stanford University. Beyond TEAM, within the ARQC DoE program, UF collaborated with Lawrence Berkeley National Lab and Oak Ridge National Lab on integration and usability with their SDKs, BQSKit and XACC. Other DoE-funded collaborators include Los Alamos National Lab and Iowa State University, within the NQI SQMS center.

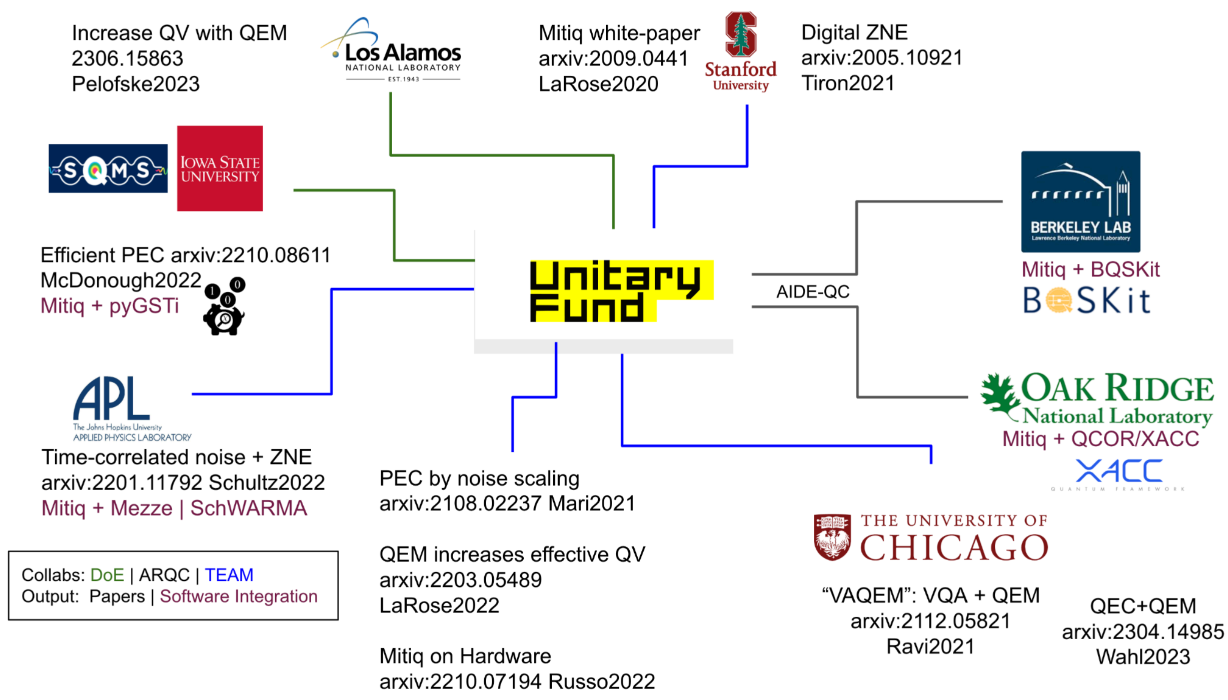


Figure 2. Software-based scientific exploration with DoE-funded partners. A selection of collaborations as an output of the research performed by Unitary Fund in the TEAM project. Selected research papers, with the arXiv code and bibliographic information, are shown, as well as software integrations between Mitiq and other frameworks and tools, such as QCOR-XACC, SchWARMA, pyGSTi, BQSKit.

Research Results – Papers

Overall, research results have been obtained in the field of QEM and with a focus on open-source scientific software development and integration. QEM has been pioneered as a nascent research field through this ARQC-funded project. The various research activities have had impact through 16 published research papers, publicly distributed open-source scientific software and dissemination activities including presentations at workshops, international conferences, summer schools and hackathons.

Digital QEM via automated software

We demonstrated the feasibility of applying QEM at the digital level, that is, as a compilation pass (with subsequent zero-noise extrapolation) with gate insertions in a quantum circuit automatically inserted by software passes. The first demonstrations of QEM relied on pulse-level control in order to artificially extend noise and collect multiple data points via subsequent experiments, then extrapolating the zero-noise value via a classical regression fit. We first upgraded zero noise extrapolation (ZNE) to the digital level by inserting sequences of gates as compilation passes that would artificially make the program longer but with the same logic value. We introduced a nomenclature for this, unitary folding – due to the fact that each inserted gate (or list of gates) is a unitary and is folded with a transposed gate (or list of gates) that gives an identity, due to the property $U^{\dagger}U = 1$, that has since picked up in the literature. Within unitary folding, we demonstrated the feasibility of a gate-level ("digital") approach to quantum error mitigation in **[LaRose2022] [Tiron2021].**

We tested various ZNE parameters vs. different types of noise affecting a quantum processing unit (QPU) **[Schultz2022]** in the presence of correlated noise, simulated with the Schrodinger ARMA model, finding that specific folding strategies, such as global folding, can be more resistant to specific noise characteristics.

QEM Benchmarking

We summarize key advancements from recent studies that have contributed to the development and evaluation of QEM techniques:

LaRose et al. (2022b): Demonstrated that error mitigation techniques, particularly Zero-Noise Extrapolation (ZNE), can effectively increase the *effective quantum volume* of quantum processors. By applying error mitigation, we achieved higher fidelity in quantum computations without additional hardware resources, suggesting that software-level improvements can complement hardware advancements in enhancing quantum performance.

Russo et al. (2022): Conducted a comparative study of QEM techniques, including ZNE and probabilistic error cancellation, across different quantum hardware platforms such as IBM, IonQ, and Rigetti, as shown in **Figure 3**. We introduced the *improvement factor* as a resource-normalized metric to quantify the benefits of error mitigation, finding that QEM generally enhances computational accuracy, both for mirror circuits and randomized benchmarking circuits, though its effectiveness varies depending on the specific hardware and noise characteristics. For example, for PEC, accurate noise modeling is key to obtain better results. Quantum circuits consisting of several hundreds of two-qubit gates were tested.

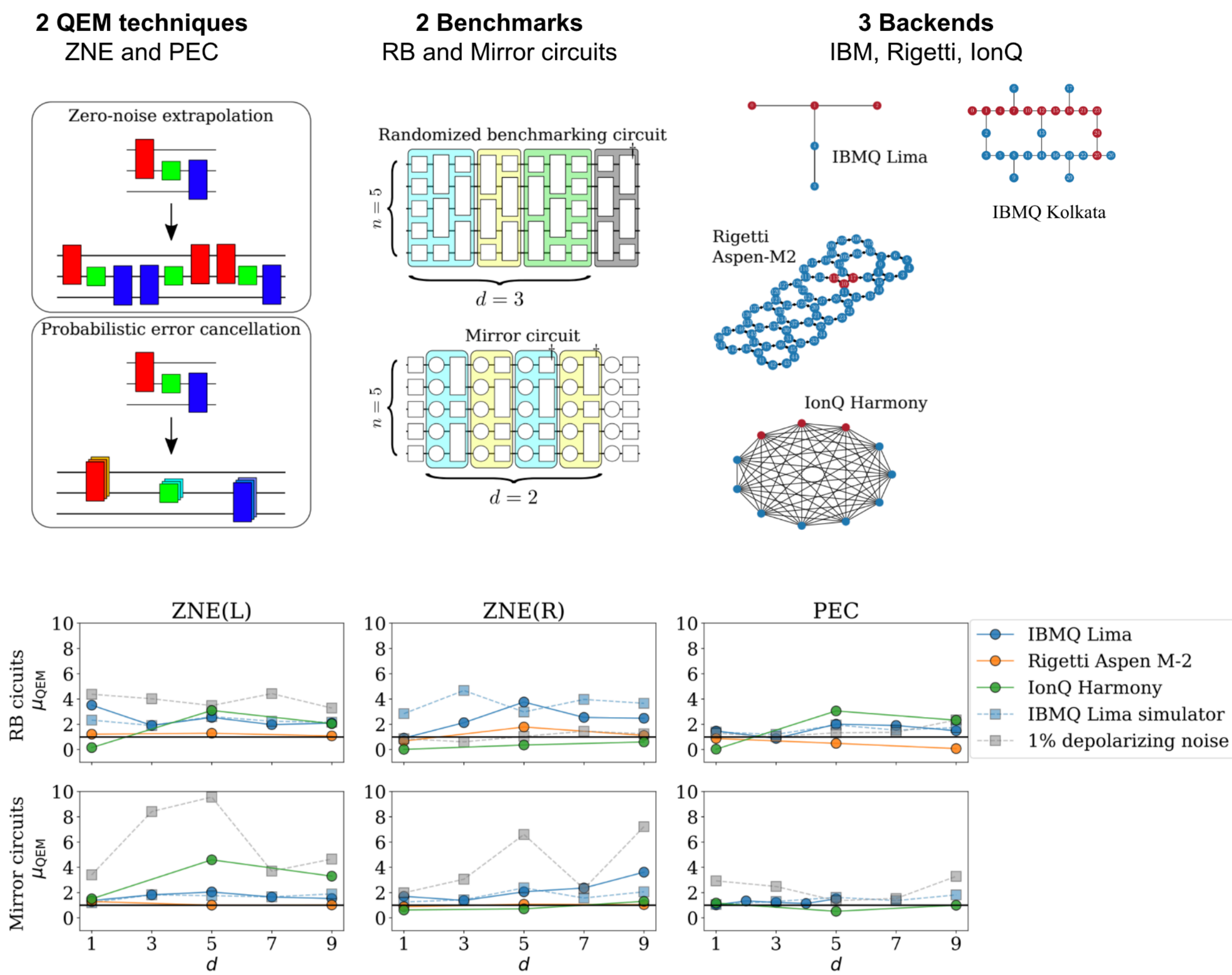


Figure 3: QEM Benchmarking on real quantum hardware. From Ref. [**Russo2022**]. **Top:** Schema summarizing the benchmarking of QEM techniques on various quantum hardware chips. **Bottom:** Results for the improvement factor for two QEM techniques, ZNE [with Linear (L) and Richardson extrapolation (R)] and PEC for the two quantum circuits on four different QPUs and a noisy classical simulator.

Pelofske et al. (2023): Expanded on the concept of effective quantum volume by integrating ZNE into its measurement. This work provided a framework for evaluating the combined performance of quantum hardware and error mitigation techniques, offering a more comprehensive metric for assessing quantum computational capabilities.

Lougovski et al. (2024): The ASCR Workshop report emphasized the necessity of robust QEM strategies for near-term quantum devices. It highlighted the importance of developing benchmarking protocols that can assess QEM performance across various hardware platforms, aligning with the Department of Energy's objectives to advance quantum computing and networking capabilities.

These studies unveiled the role that QEM can play on real hardware, providing both theoretical frameworks and practical QEM benchmarks to guide future developments in the field.

New QEM techniques

Extending Quantum Probabilistic Error Cancellation by Noise Scaling (Mari et al., 2021): This work introduces a unified framework that combines probabilistic error cancellation (PEC) and zero-noise extrapolation (ZNE) through noise scaling, as shown in **Figure 4** below. By representing ideal operations as linear combinations of noisy operations with scaled noise levels, the method encompasses both PEC and ZNE as special cases, allowing for hybrid techniques that balance sampling overhead and bias.

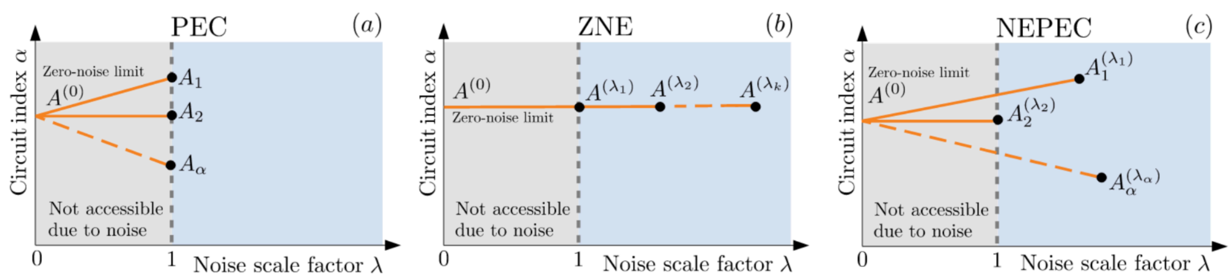


Figure 4. Unifying framework for QEM. Three diagrams showing the concept behind noise extended probabilistic error cancellation [NEPEC, panel (c)], which expands the concept of sampling and extrapolating the results from running different quantum circuits at the same noise level in PEC [panel (a)], with the approach of ZNE, in which the same quantum circuit is scaled at different noise levels [panel (b)]. Adapted from [**Mari2021**].

VAQEM: A Variational Approach to Quantum Error Mitigation (Ravi et al., 2021): VAQEM dynamically tailors existing error mitigation techniques to the actual, dynamic noisy execution characteristics of variational quantum algorithms (VQAs) on a target quantum machine. By tuning specific features of these mitigation techniques, such as single-qubit gate scheduling and the insertion of dynamical decoupling sequences, VAQEM enhances the performance of VQAs on noisy quantum hardware.

Automated Quantum Error Mitigation Based on Probabilistic Error Reduction (McDonough et al., 2022): This study presents an automated framework for probabilistic error reduction (PER), a method that systematically reduces sampling overhead compared to PEC by accepting a controlled bias. The framework includes noise tomography and application of PER to user-specified circuits, facilitating broader adoption of error mitigation techniques.

Quantum Error Mitigation by Layerwise Richardson Extrapolation (Mari & Russo, 2024): This work generalizes traditional Richardson extrapolation to a multivariate setting by introducing layerwise Richardson extrapolation (LRE). By applying noise scaling to individual layers of a quantum circuit, LRE enables more precise error mitigation, particularly in circuits where noise characteristics vary across different segments.

Pelofske and Russo (2025): Introduced *Digital Zero-Noise Extrapolation (ZNE)* using quantum circuit "unoptimization", a method that increases circuit depth to amplify noise systematically, contrary to what circuit optimization strategies do for standard compilers. This approach generates a diverse set of circuit variants, facilitating effective noise averaging and enhancing the robustness of ZNE against unwanted compiler optimizations, sometimes occurring close to the final execution on cloud-accessible QPUs. The technique was validated through simulations on quantum volume and QAOA circuits, demonstrating its capability to recover signals from noisy quantum computations.

Collectively, these advancements introduced new QEM techniques, offering more adaptable and efficient methods to counteract noise in quantum computations.

Simulation of noisy QPUs and pulse-level compilation

We highlight two significant contributions that advance the simulation capabilities for quantum computing research:

Pulse-Level Simulation with QuTiP (Li et al., 2022): This work introduces enhancements to the Quantum Toolbox in Python (QuTiP), enabling pulse-level simulation of noisy quantum circuits. The updated `qutip-qip` package allows for the compilation of quantum circuits into control pulses acting on target Hamiltonians, facilitating realistic modeling of quantum hardware dynamics. Users can incorporate various noise models, such as environment-induced decoherence and control pulse imperfections, using Lindblad master equations or Monte Carlo trajectories. The framework supports simulations on different hardware models, including superconducting qubits and spin chains, and integrates with other software tools for comprehensive analysis.

GPU-Accelerated Simulation with Qrack (Strano et al., 2023): This study presents Qrack, an open-source library designed for high-performance classical simulation of quantum circuits on GPUs. Qrack supports both exact and approximate simulations, offering a trade-off between fidelity and computational resource requirements. Benchmarking results demonstrate the capability to perform exact simulations of quantum Fourier transform (QFT) circuits with up to 27 qubits and approximate simulations of random circuits with 54 qubits and 7 layers, achieving average fidelities above 4%. This approach enables efficient simulation of large-scale quantum circuits on single GPU systems, providing a valuable tool for testing and validating quantum algorithms in the absence of large-scale quantum hardware.

These advancements in simulation tools enhance our ability to model and understand the behavior of noisy quantum processors, simulate at larger scale quantum circuits with classical resources, facilitating the development and benchmarking of quantum algorithms and error mitigation strategies.

<u>Hybridization of QEM with QEC</u>

In Ref. **[Wahl2023]**, we introduced Distance-Scaled Zero Noise Extrapolation (DS-ZNE), a new method for mitigating errors in logical qubits towards fault-tolerant quantum computing. Instead of amplifying physical noise, DS-ZNE varies the quantum error correction code distance to scale logical error rates, enabling zero-noise extrapolation at the logical level, as shown in the left panel of **Figure 5**. This method is particularly advantageous for near-term quantum devices with limited qubit resources, as it allows for parallel execution of circuits at lower code distances, optimizing resource utilization, as shown in the central panel of **Figure 5.** Using the Stim simulator integrated with Mitiq, we demonstrate that this method can achieve effective error rates corresponding to significantly higher code distances—e.g., a physical distance of 11 achieves logical performance equivalent to distance 17, with programs as deep as 10,000 gates, as shown in the right panel of **Figure 5**. DS-ZNE outperforms traditional unitary folding ZNE under fixed resource constraints. This technique offers a scalable, resource-efficient path to improving logical qubit fidelity, advancing the DOE's goals for near-term quantum computing, adding a new resource to hybridize QEM and QEC in regime of early fault tolerance.

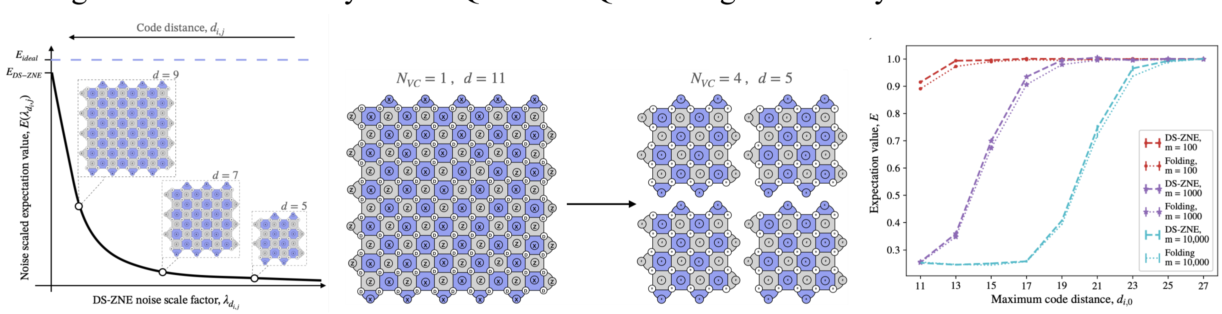
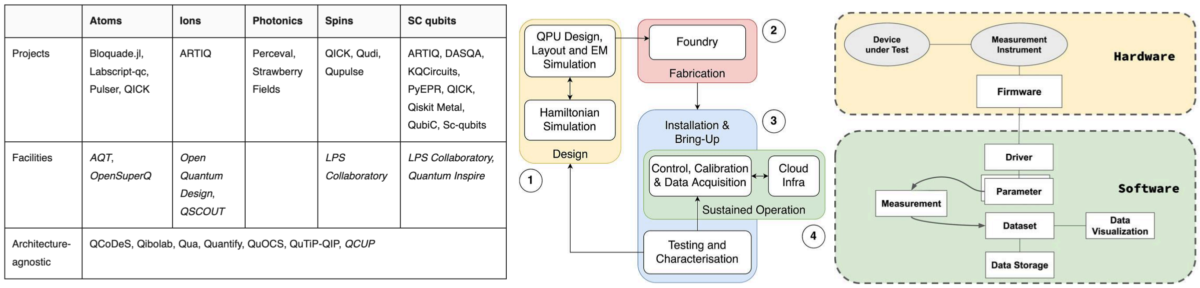


Figure 5: QEM on Logical Qubits. From Ref. [Wahl2023]. **Left:** main principle of DS-ZNE, providing effective noise scaling in the code distance on the x axis. The examples shown use a surface code. **Center**: A virtual core compilation can be implemented to parallelize execution. **Right**: Simulations integrating the Stim simulator for increasing Clifford depth *m*. The ideal value is 1.

<u>Open quantum hardware</u>

In Ref. **[Shammah2023]**, we provided the first review of current open-source software solutions for the design, control, sustained operation, cloud-access, testing of quantum hardware devices.

This review included comparative tables based on qubit architecture, outlining the maturity and tools available for each architecture. A number of examples were provided as deep dives to understand how different projects work, as shown in **Figure 6** below.



	Atoms	Ions	Photonics	Spins	SC qubits
Projects	Bloquade.jl, Labscript-qc, Pulser, QICK	ARTIQ	Perceval, Strawberry Fields	QICK, Qudi, Qupulse	ARTIQ, DASQA, KQCircuits, PyEPR, QICK, Qiskit Metal, QubiC, Sc-qubits
Facilities	*AQT, OpenSuperQ*	*Open Quantum Design, QSCOUT*		*LPS Collaboratory*	*LPS Collaboratory, Quantum Inspire*
Architecture-agnostic	QCoDeS, Qibolab, Qua, Quantify, QuOCS, QuTiP-QIP, *QCUP*				

Figure 6: Open Quantum Hardware Solutions. From Ref. [Shammah2023]. **Left:** Table outlining projects and facilities per qubit architecture. **Center:** Framework for open quantum hardware cycle, from design (1) to fabrication (2) to installation and bring up (3) and sustained operation (4). **Right:** Division between hardware and software components in experiment setup and QPU control.

Impact

This project significantly advanced the practice, accessibility, reproducibility, and visibility of quantum error mitigation (QEM) in the quantum computing ecosystem.

By releasing **Mitiq** as a cross-platform, open-source toolkit, this project enabled researchers and developers to apply error mitigation techniques directly within their existing quantum software workflows. Mitiq made QEM techniques accessible to users across the quantum programming language landscape — Qiskit Cirq, Braket, PennyLane, and Qibo — many for the first time. The toolkit helped shift the narrative around noisy intermediate-scale quantum (NISQ) devices — demonstrating that meaningful results can be achieved with today’s hardware when paired with well-engineered software mitigation.

Mitiq has become a platform for reproducible QEM research, education, and experimentation. It has also helped define QEM as a distinct, practical layer in the quantum software stack.

Workforce Development

Mitiq has served as an entry point for early-career researchers and students. Some examples include:

- A B.Sc. student at Yale University interned with Unitary Fund in 2022, co-authoring a paper on automated probabilistic error reduction as first author [**McDonough2022**], mentored by UF staff and Iowa State Professor and presenting at **IEEE SC22**. He is now pursuing a PhD at the University of Colorado Boulder in the field of condensed matter with applications to quantum information.

- A PhD student from the University of Urbana Champaign contributed Mitiq's classical shadows module as a 2023 intern and continues to publish on topics related to NISQ computing.
- One of Unitary Fund staff members, began as a volunteer contributor to Mitiq's documentation and PEC module in 2021 before joining full-time and becoming first author of the first research paper applying ZNE to logical qubits [**Wahl2023**].
- A Software Engineering Manager at Amazon Web Service Center for Quantum Computing led a group of students from various universities including Harvard and University of Florida to implement the quantum subspace expansion protocol in mitiq. This was their first major contribution to an open source quantum computing package.

To further support the longevity of the contributor lifecycle, the team launched a **Unitary Foundation Ambassador Program** to recognize and encourage reliable community engagement.

Community Engagement

Through over 50 public talks, a regular community call for users to get help and contributors to talk about their work, workshops, and seminars, Mitiq has helped spread practical knowledge about running quantum programs on hardware in the most effective way.

Products

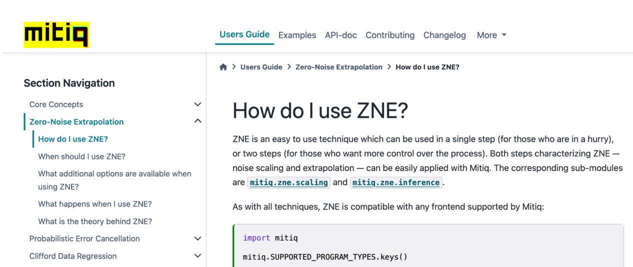
Software Product

The central software output of this project is Mitiq, a Python toolkit for quantum error mitigation (QEM). Mitiq allows users to apply techniques like zero-noise extrapolation, probabilistic error cancellation, and digital dynamical decoupling to circuits written in Cirq, Qiskit, Braket, or PennyLane. The toolkit emphasizes modularity, extensibility, and ease of use.

- GitHub: https://github.com/unitaryfoundation/mitiq
- Documentation: https://mitiq.readthedocs.io,
- PyPI: https://pypi.org/project/mitiq/

As of September 2024, the Mitiq project had:

1. Over 150,000 downloads
2. More than 70 contributors
3. Used in research at various research institutions, including 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
4. Widely used in research, prototyping, education, and workforce development.
5. A documentation of several hundred pages and with over 20 tutorials, as shown in Figure 7 below.



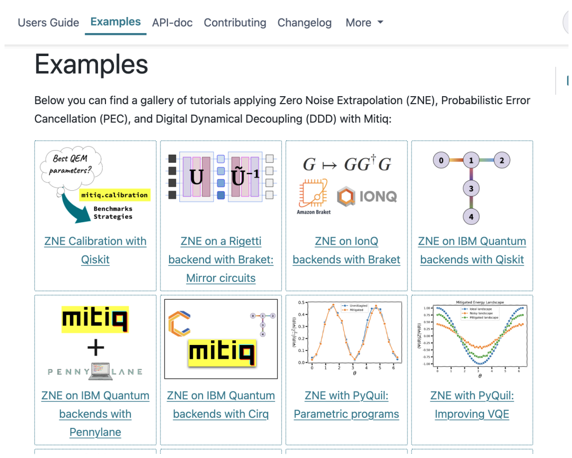


Figure 7. Mitiq's documentation for v.0.37.0, released June 4, 2024. Left: A screenshot of Mitiq's User Guide on ZNE. Right: A screenshot from the Examples page with some tutorials in the form of Jupyter Notebooks.

Research Papers – List

1. **[Tiron2021]**
   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), DOI:10.1109/QCE49297.2020.00045.
2. **[Mari2021]**
   A. Mari, N. Shammah, and W. J. Zeng. *Extending quantum probabilistic error cancellation by noise scaling*, Phys. Rev. A, 104, 052607, (2021), DOI:10.1103/PhysRevA.104.052607.
3. **[Ravi2021]**
   G. S. Ravi, K. N. Smith, P. Gokhale, A. Mari, N. Earnest, A. Javadi-Abhari, F. T. Chong. *VAQEM: A Variational Approach to Quantum Error Mitigation*, Proceedings of the 28th IEEE International Symposium on High-Performance Computer Architecture (HPCA), 288-303, (2022), DOI:10.1109/HPCA53966.2022.00029.
4. **[Li2022]**
   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), DOI:10.22331/q-2022-01-24-630.
5. **[LaRose2022]**
   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:10.22331/q-2022-08-11-774.

6. **[LaRose2022b]**
R. LaRose, A. Mari, V. Russo, D. Strano, and W. J. Zeng. *Error mitigation increases the effective quantum volume of quantum computers*, arXiv (2022), arXiv:2203.05489.
7. **[Russo2022]**
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), DOI:10.1109/TQE.2023.3305232.
8. **[McDonough2022]**
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), DOI:10.1109/QCS56647.2022.00015.
9. **[Schultz2022]**
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), DOI:10.1103/PhysRevA.106.052406.
10. **[Shammah2023]**
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 Solutions in Quantum Technology*, APL Quantum, 1, 011501, (2024), DOI:10.1063/5.0180987.
11. **[Strano2023]**
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*, 2023 IEEE International Conference on Quantum Computing and Engineering (QCE), Bellevue, WA, USA, 2023, pp. 949-958, arXiv:2304.14969, https://ieeexplore.ieee.org/abstract/document/10313711.
12. **[Wahl2023]**
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*, 2023 IEEE International Conference on Quantum Computing and Engineering (QCE), arXiv:2304.14985, https://doi.org/10.1109/QCE57702.2023.00103
13. **[Pelofske2023]**
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*, ACM Transactions on Quantum Computing (2024), arXiv:2306.15863, https://doi.org/10.1145/3680290.

14. **[Lougovski2024]**
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* (2024), United States, DOI:[10.2172/2001045](https://doi.org/10.2172/2001045).
15. **[Mari2024]**
A. Mari, V. Russo. *Quantum error mitigation by layerwise Richardson extrapolation*, Phys. Rev. A, 110, 062420, (2024), DOI:[10.1103/PhysRevA.110.062420](https://doi.org/10.1103/PhysRevA.110.062420).
16. **[Pelofske2025]**
E. Pelofske, V. Russo. *Digital Zero-Noise Extrapolation with Quantum Circuit Unoptimization*, arXiv preprint (2025), [arXiv:2503.06341](https://arxiv.org/abs/2503.06341).

Presentations and Outreach

The Mitiq team presented this work at over 50 events across academia, industry, and community conferences. Highlights include:

- **IWQC, 4th International Workshop on Quantum Compilation** (2020), **Quantum Africa 6 Conference** (2022), **QIQT Conference** (2023), **NISQAH Conference** (2023): technical presentations
- **IEEE Quantum Week** (2023, 2024): Tutorials and technical paper presentations
- **PLDI Workshop on Quantum Software** (2024): Keynote on QEM integration
- **APS March Meeting** (2023, 2024): Talks and posters on benchmarking and scalable mitigation
- **UnitaryCON, Galileo Galilei Institute/SQMS Summer School** and **Numerical Methods in Quantum Information Science Summer School at U. Mass. Amherst**: Hands-on workshops and summer schools
- **Academic seminars**: Harvard, IBM, Northwestern University, University of Milan, and others
- **Community events**: QHack, PyData Seattle, Qiskit Seminar Series, Qiskit Demo Days

A complete list of materials, slides, and recordings is available at on the mitiq wiki.

Conclusions

Over the course of this project, Unitary Fund successfully delivered a core component of Thrust 2: a practical, extensible, and widely adopted toolkit for quantum error mitigation. **Mitiq** has enabled researchers and developers to apply advanced error mitigation techniques across a range of quantum software platforms and hardware backends — helping to close the gap between theoretical quantum algorithms and the constraints of real NISQ devices.

The project emphasized accessibility, interoperability, and experimental validation. Through community engagement, cross-platform support, and sustained open-source development, Mitiq has grown into a trusted tool for research and experimentation in quantum software.

The TEAM program supported Unitary Foundation and collaborators in building a robust open-source software foundation, pioneering quantum error mitigation software and enabling for real-world use and future exploration. Ongoing collaborations, such as compiler integration efforts, signal the continued relevance of this work as the quantum software ecosystem matures.

This project demonstrated that **well-engineered software tools can extend the capabilities of quantum hardware**, and that open, community-driven development is a powerful model for accelerating innovation in quantum computing. The over 150,000 downloads of Mitiq are a powerful metric of its widespread adoption and scientific impact.

On the research side, within the TEAM project, Unitary Fund has pioneered the deep investigation of gate-level (also called digital level) quantum error mitigation and demonstrated that it could be abstracted to the level of automated compilation passes in a software toolkit. The explorations in ZNE and unification within a single framework with PEC are among the most important results. The upgrade of ZNE to fault tolerance and logical qubits is another important result in a field in rapid development.

A common thread of research has been the focus on developing open source software. This task has been performed for QEM but also with outputs in adjacent fields, to the benefit of QEM research and software tooling, such as in the simulation of QPUs, noise characterization, and open hardware.

The output of over 15 research papers, published in international and peer-reviewed journals witnesses the impact on scientific production. Collaboration with the DoE funded Tough Errors Are no Match (TEAM) project has been tight and produced several of the listed publications.