Error Mitigation with Mitiq

Part 1: Zero-Noise Extrapolation & Calibration

Jordan Sullivan, Nate Stemen & Misty Wahl

Aug 17, 2024

Numerical Methods
in Quantum Information Science

Mitiq Workshop Agenda

Sat Aug 17

Schedule		
9:00 - 9:45	Quantum Error Mitigation	Jordan Sullivan
9:45 - 10:00	Zero Noise Extrapolation in Mitiq	Jordan Sullivan
10:00 - 11:00	Contributing to Mitiq	Nate Stemen
11:15 - 12:00	Break	
14:00 - 15:00	Digital Dynamical Decoupling	Misty Wahl
15:00 - 15:15	Challenge on noise mitigation with benchmarking circuits on simulated noisy backends	Nate Stemen
15:15 - 16:15	Challenge on calibrating noise mitigation with benchmarking circuits on simulated noisy backends	Nate Stemen
	Break	
20:00 - 23:00	Mitiq hackathon and social (pizza party)	

Mitiq the tooklit

README.md

build passing | docs passing | codecov 98% | pypi package 0.29.0 | arXiv 2009.04417 | Downloads 106k | GitHub
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Mitiq is a Python toolkit for implementing error mitigation techniques on quantum computers.

Current quantum computers are noisy due to interactions with the environment, imperfect gate applications, state preparation and measurement errors, etc. Error mitigation seeks to reduce these effects at the software level by compiling quantum programs in clever ways.

Want to know more? Check out our documentation and chat with us on Discord.

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Error mitigation techniques

You can check out currently available quantum error mitigation techniques by calling

```
mitiq.qem_methods()
```

Technique	Documentation	Mitiq module	Paper Reference(s)
Zero-noise extrapolation	ZNE	`mitiq.zne`	1611.09301 1612.02058 1805.04492
Probabilistic error cancellation	PEC	`mitiq.pec`	1612.02058 1712.09271 1905.10135
(Variable-noise) Clifford data regression	CDR	`mitiq.cdr`	2005.10189 2011.01157
Digital dynamical decoupling	DDD	`mitiq.ddd`	9803057 1807.08768
Readout-error mitigation	REM	`mitiq.rem`	1907.08518 2006.14044
Quantum Subspace Expansion	QSE	`mitiq.qse`	1903.05786
Robust Shadow Estimation 🚧	RSE	`mitiq.qse`	2011.09636 2002.08953

Mitiq the tooklit

```
  import cirq
+ import mitiq

  qubit = cirq.LineQubit(1)
  circuit = cirq.Circuit(cirq.X(qubit) for _ in range(100))

- expval = execute(circuit)
+ expval = mitiq.zne.execute_with_zne(circuit, execute)

  print(f"Error: {1 - expval:.3}")
- # Error: 0.244
+ # Error: 0.058
```

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Experience

1. Who has written a quantum program before?

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2. Who has run a quantum program on hardware before?

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3. Who has used error mitigation?

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3. Who has used error mitigation?
4. Who has used Mitiq?

Tutorial goals

1. Understand context, and general ideas of quantum error mitigation (QEM).
2. Understand main ideas of ZNE, PEC, and DDD along with pros and cons of each technique.
3. Ability to use Mitiq to apply these techniques in a quantum pipeline.

What is Quantum Error Mitigation?

Quantum Error Mitigation (QEM)

The acceptance that available quantum devices are noisy. . . maybe very much so.

But we still want to use them!

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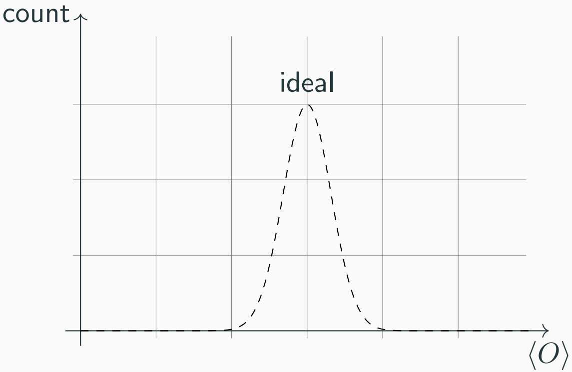

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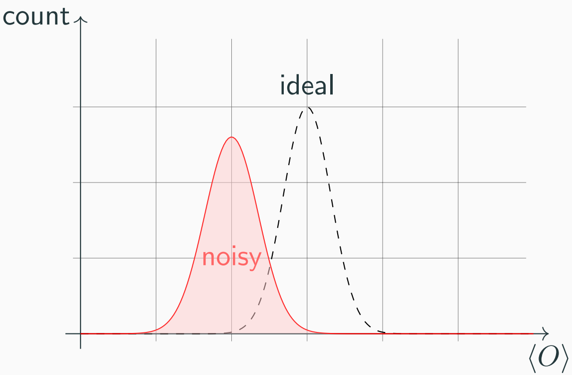

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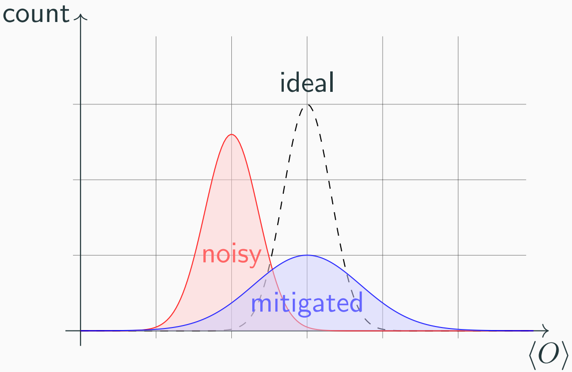


QEM Methods - share what you know!

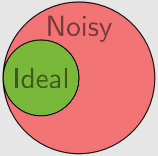
Who is familiar with any existing quantum error mitigation techniques?

QEM Methods

Zero-Noise Extrapolation

$$\partial_t \rho = -i[H,\rho] + \boxed{\lambda}\,\mathcal{L}(\rho)$$

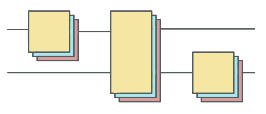
Symmetry-based techniques



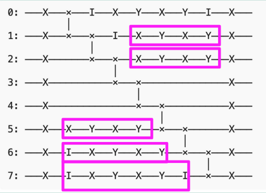
$$M\,|\psi\rangle = |\psi\rangle$$

$$\rho = \frac{M\rho M}{\mathrm{tr}(M\rho)}$$

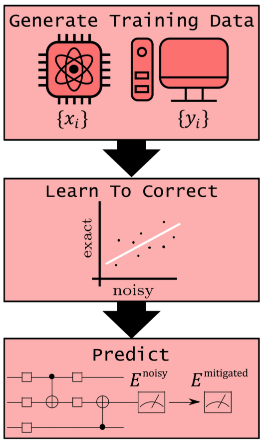
Probabilistic Error Cancellation



Dynamical Decoupling



Learning-based methods



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Error Correction

- Encode logical qubits into many physical qubits
- Intermediate measurements produce syndromes
- Use syndromes to correct errors

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Needs few noisy qubits

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Key Idea

Scale noise up, extrapolate back to zero-noise value.

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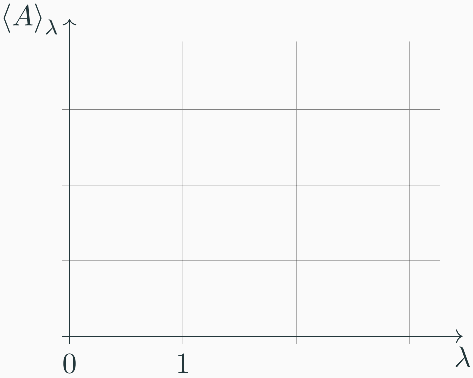

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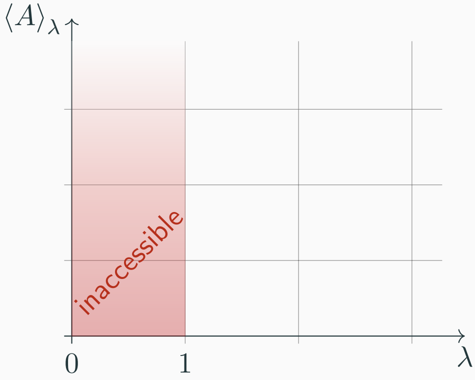

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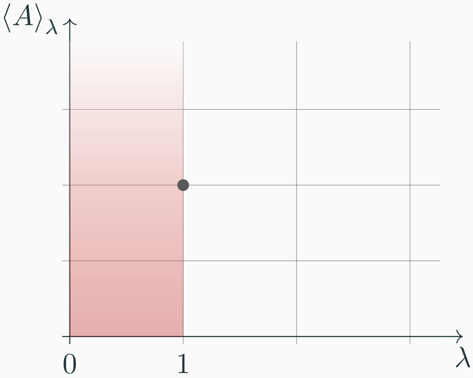

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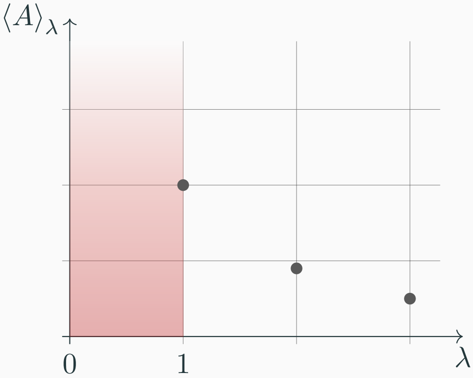

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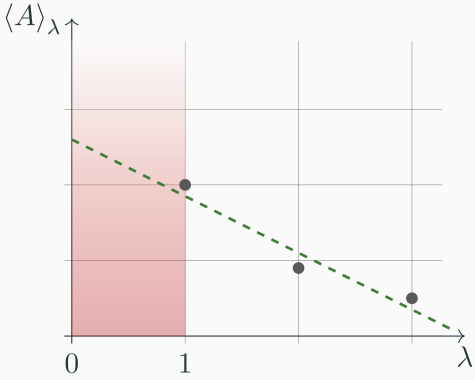

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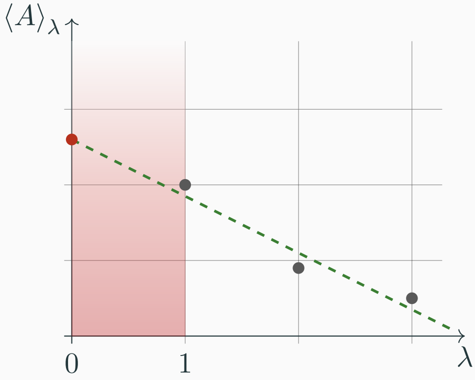

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How do we scale the noise **up**?

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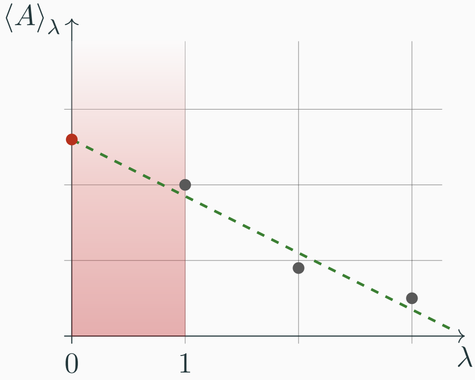

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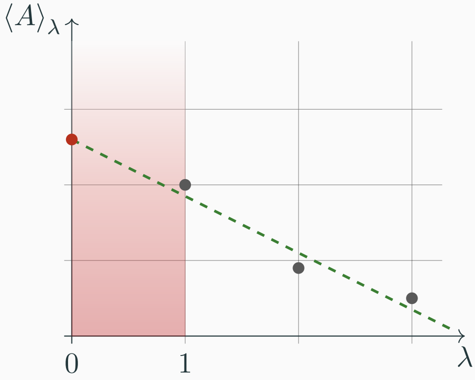

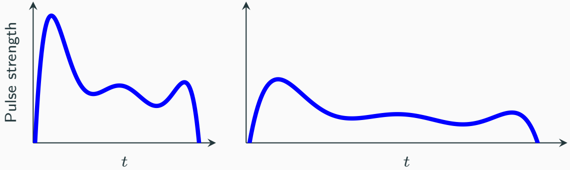

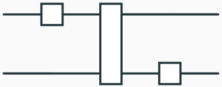

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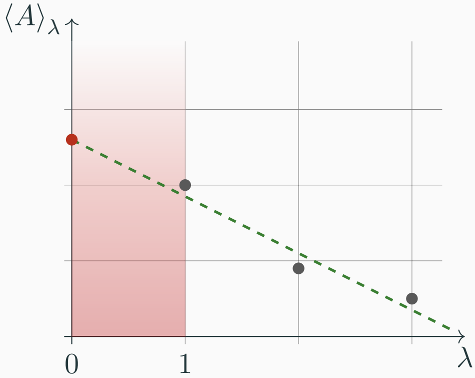
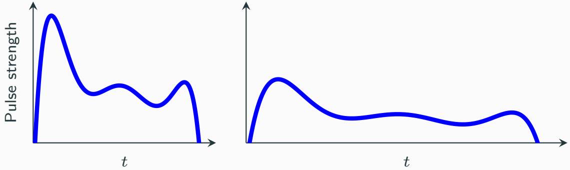
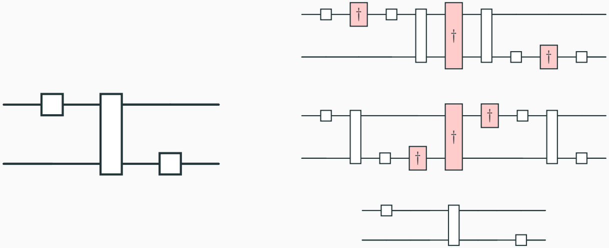
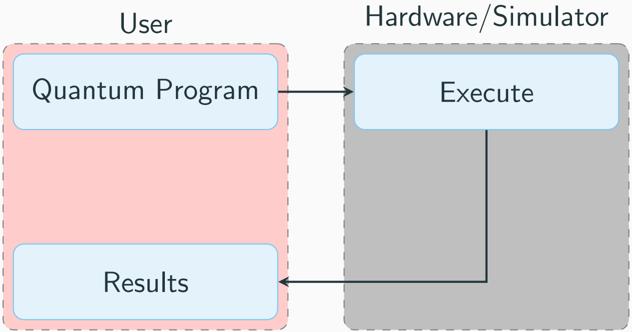


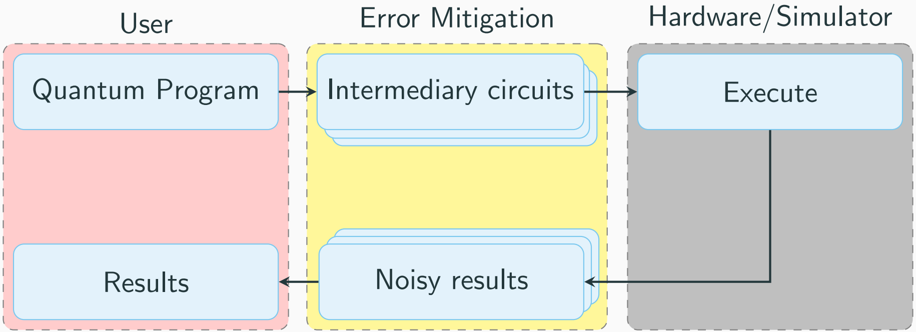




Running quantum programs in practice



Running quantum programs in practice with Mitiq



Quantum Simulation on real hardware with Mitiq

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Quantum Physics

[Submitted on 30 Sep 2021 (v1), last revised 17 Nov 2022 (this version, v3)]

Towards the real-time evolution of gauge-invariant $\mathbb{Z}_2$ and $U(1)$ quantum link models on NISQ Hardware with error-mitigation

Emilie Huffman, Miguel García Vera, Debasish Banerjee

Practical quantum computing holds clear promise in addressing problems not generally tractable with classical simulation techniques, and some key physically interesting applications are those of real-time dynamics in strongly coupled lattice gauge theories. In this article, we benchmark the real-time dynamics of $\mathbb{Z}_2$ and $U(1)$ gauge invariant plaquette models using noisy intermediate scale quantum (NISQ) hardware, specifically the superconducting-qubit-based quantum IBM Q computers. We design quantum circuits for models of increasing complexity and measure physical observables such as the return probability to the initial state, and locally conserved charges. NISQ hardware suffers from significant decoherence and corresponding difficulty to interpret the results. We demonstrate the use of hardware-agnostic error mitigation techniques, such as circuit folding methods implemented via the Mitiq package, and show what they can achieve within the quantum volume restrictions for the hardware. Our study provides insight into the choice of Hamiltonians, construction of circuits, and the utility of error mitigation methods to devise large-scale quantum computation strategies for lattice gauge theories.

A peak into the future...

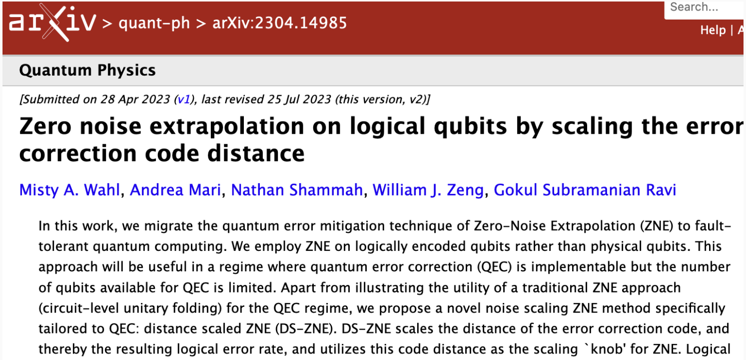
QEC + QEM

Mitigate errors on encoded logical qubits.

When should we use which techniques?

How do we balance classical and quantum resources?

Open questions! For instance...


arXiv > quant-ph > arXiv:2304.14985

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Quantum Physics

[Submitted on 28 Apr 2023 (v1), last revised 25 Jul 2023 (this version, v2)]

Zero noise extrapolation on logical qubits by scaling the error correction code distance

Misty A. Wahl, Andrea Mari, Nathan Shammah, William J. Zeng, Gokul Subramanian Ravi

In this work, we migrate the quantum error mitigation technique of Zero-Noise Extrapolation (ZNE) to fault-tolerant quantum computing. We employ ZNE on logically encoded qubits rather than physical qubits. This approach will be useful in a regime where quantum error correction (QEC) is implementable but the number of qubits available for QEC is limited. Apart from illustrating the utility of a traditional ZNE approach (circuit-level unitary folding) for the QEC regime, we propose a novel noise scaling ZNE method specifically tailored to QEC: distance scaled ZNE (DS-ZNE). DS-ZNE scales the distance of the error correction code, and thereby the resulting logical error rate, and utilizes this code distance as the scaling `knob' for ZNE. Logical

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(circuit-level unitary folding) for the QEC reg
tailored to QEC: distance scaled ZNE (DS-ZN
thereby the resulting logical error rate, and

Fault Tolerant Quantum Error Mitigation

Alvin Gonzales, Anjala M Babu, Ji Liu, Zain Saleem, Mark Byrd

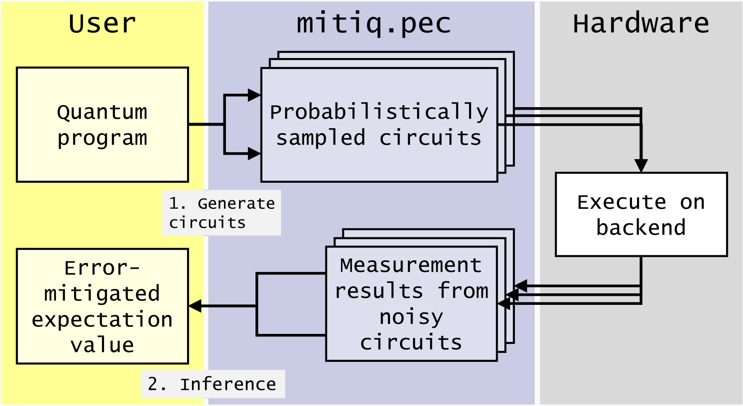
Typically, fault-tolerant operations and code concatenation are reserved for quantum error correction due to their resource overhead. Here, we show that fault tolerant operations have a large impact on the performance of symmetry based error mitigation techniques. We also demonstrate that similar to results in fault tolerant quantum computing, code concatenation in fault-tolerant quantum error mitigation (FTQEM) can exponentially suppress the errors to arbitrary levels. For a family of circuits, we provide analytical error thresholds for FTQEM with the repetition code. These circuits include a set of quantum circuits that can generate all of reversible classical computing. The post-selection rate in FTQEM can also be increased by correcting some of the outcomes. Our threshold results can also be viewed from the perspective of quantifying the number of gate operations we can delay checking the stabilizers

Let's try Mitiq!

https://github.com/unitaryfund/
Mitiq-Workshop-QNumerics-Summer-School/blob/main/part1_zne.ipynb

Probabilistic Error Cancellation

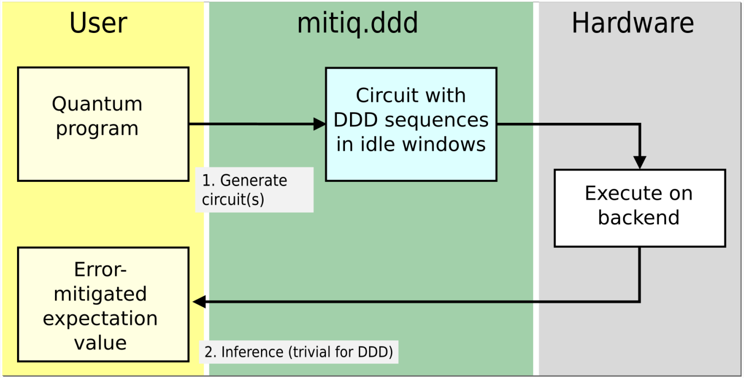
Key Idea: Use noisy operations to build up noiseless ones by selective cancellation and sampling.



Sneak Preview of Part II

Digital Dynamical Decoupling

Key Idea: The devil finds work for idle [qubits].



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