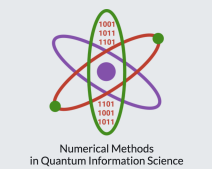
Error Mitigation with Mitiq

Part 1: Zero-Noise Extrapolation & Calibration

Jordan Sullivan, Nate Stemen & Misty Wahl

Aug 17, 2024

Unitary Fund



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

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.

Mitiq the tooklit

README.md

build passing docs passing codecov 98% pypi

Supported By Unitary Fund Discord 212 online.

Mitiq is a Python toolkit for implementing error

Current quantum computers are noisy due to ir
state preparation and measurement errors, etc
level by compiling quantum programs in clever

Want to know more? Check out our documenta

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

README.md

build passing docs passing codecov 98% pypi

Supported By Unitary Fund Discord 212 online.

Mitiq is a Python toolkit for implementing error

Current quantum computers are noisy due to ir
state preparation and measurement errors, etc
level by compiling quantum programs in clever

Want to know more? Check out our documenta

Error mitigation techniq

You can check out currently available

```
mitiq.qem_methods()
```

Technique			
Zero-noise extrapolation			1712.09271 1905.10135
Probabilistic error cancellation			
(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

```
  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
```

Mitiq the tooklit

README.md

mitiq

build passing | docs passing | codecov 98% | pypi

Supported By Unitary Fund | Discord 212 online.

Mitiq is a Python toolkit for implementing error

Current quantum computers are noisy due to ir
state preparation and measurement errors, etc
level by compiling quantum programs in clever

Want to know more? Check out our documenta

Error mitigation techniq

You can check out currently available

```
mitiq.qem_methods()
```

```
  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
```

Technique			
Zero-noise extrapolation			1712.09271 1905.10135
Probabilistic error cancellation			
(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

Mitiq the tooklit

README.md

build passing | docs passing | codecov 98% | pypi

Supported By Unitary Fund | Discord 212 online.

Mitiq is a Python toolkit for implementing error

Current quantum computers are noisy due to ir
state preparation and measurement errors, etc
level by compiling quantum programs in clever

Want to know more? Check out our documenta

Error mitigation techniq

You can check out currently available

```
mitiq.qem_methods()
```

```
  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
```

Technique			
Zero-noise extrapolation			1712.09271 1905.10135
Probabilistic error cancellation			
(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

Experience

1. Who has written a quantum program before?

Experience

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

Experience

1. Who has written a quantum program before?
2. Who has run a quantum program on hardware before?
3. Who has used error mitigation?

Experience

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

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!

- (In)coherent noise
- SPAM errors

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!

- (In)coherent noise
- SPAM errors
- Crosstalk

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!

- (In)coherent noise
- SPAM errors
- Crosstalk
- Calibration errors

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!

- (In)coherent noise
- SPAM errors
- Crosstalk
- Calibration errors
- ...

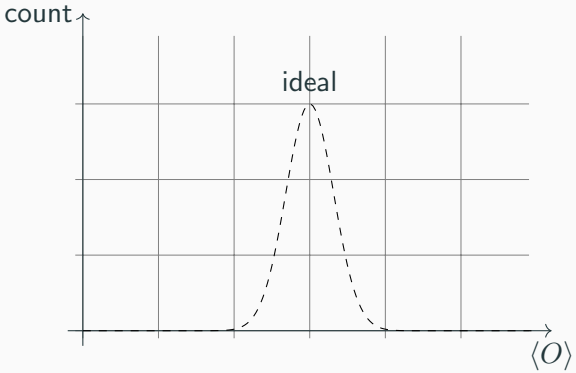
What is Quantum Error Mitigation?

Quantum Error Mitigation (QEM)

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

But we still want to use them!

- (In)coherent noise
- SPAM errors
- Crosstalk
- Calibration errors
- ...



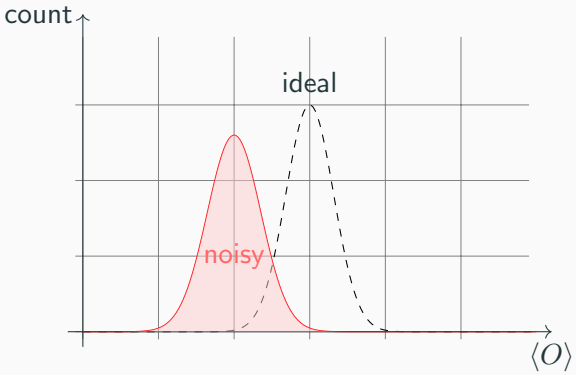
What is Quantum Error Mitigation?

Quantum Error Mitigation (QEM)

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

But we still want to use them!

- (In)coherent noise
- SPAM errors
- Crosstalk
- Calibration errors
- ...



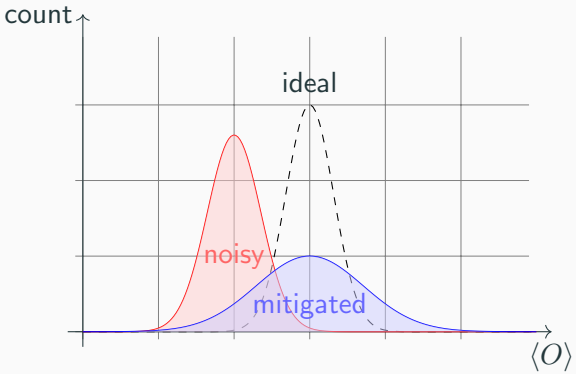
What is Quantum Error Mitigation?

Quantum Error Mitigation (QEM)

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

But we still want to use them!

- (In)coherent noise
- SPAM errors
- Crosstalk
- Calibration errors
- ...



QEM Methods - share what you know!

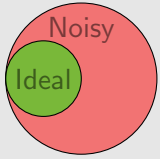
Who is familiar with any existing quantum error mitigation techniques?

QEM Methods

Zero-Noise Extrapolation

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

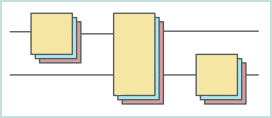
Symmetry-based techniques



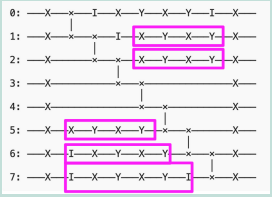
$$M\,|\psi\rangle = |\psi\rangle$$

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

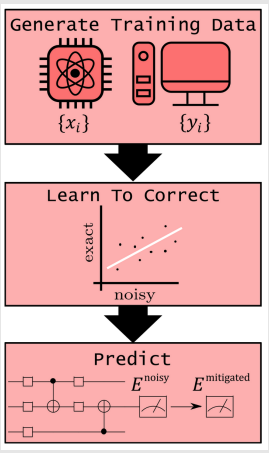
Probabilistic Error Cancellation



Dynamical Decoupling



Learning-based methods



What about quantum error correction?

nature

Explore content | About the journal | Publish with us | Subscribe

nature › articles › article

Article | Published: 22 March 2023

Real-time quantum error correction beyond break-even

V. V. Sivak, A. Eickbusch, B. Royer, S. Singh, I. Tsioutsios, S. Ganjam, A. Miano, B. L. Brock, A. Z. Ding, L. Frunzio, S. M. Girvin, R. J. Schoelkopf & M. H. Devoret

Nature **616**, 50–55 (2023) | Cite this article

16k Accesses | **104** Citations | **251** Altmetric | Metrics

What about quantum error correction?

nature

Explore content | About the journal | Publish with us | Subscribe

nature › articles › article

Article | Published: 22 March 2023

Real-time quantum error correction beyond break-even

V. V. Sivak, A. Eickbusch, B. Royer, S. Singh, I. Tsioutsios, S. Ganjam, A. Miano, B. L. Brock, A. Z. Ding, L. Frunzio, S. M. Girvin, R. J. Schoelkopf & M. H. Devoret

Nature **616**, 50–55 (2023) | Cite this article

16k Accesses | **104** Citations | **251** Altmetric | Metrics

Error Correction

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

What about quantum error correction?

nature

Explore content ⌄ About the journal ⌄ Publish with us ⌄ Subscribe

nature › articles › article

Article | Published: 22 March 2023

Real-time quantum error correction beyond break-even

V. V. Sivak ✉, A. Eickbusch, B. Royer, S. Singh, I. Tsioutsios, S. Ganjam, A. Miano, B. L. Brock, A. Z. Ding, L. Frunzio, S. M. Girvin, R. J. Schoelkopf & M. H. Devoret ✉

Nature **616**, 50–55 (2023) | Cite this article

16k Accesses | **104** Citations | **251** Altmetric | Metrics

Error Correction

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

Error Mitigation

- Perform multiple and different noisy computations
- Collect results
- Infer ideal expectation values

What about quantum error correction?

nature

Explore content | About the journal | Publish with us | Subscribe

nature > articles > article

Article | Published: 22 March 2023

Real-time quantum error correction beyond break-even

V. V. Sivak, A. Eickbusch, B. Royer, S. Singh, I. Tsioutsios, S. Ganjam, A. Miano, B. L. Brock, A. Z. Ding, L. Frunzio, S. M. Girvin, R. J. Schoelkopf & M. H. Devoret

Nature **616**, 50–55 (2023) | Cite this article

16k Accesses | **104** Citations | **251** Altmetric | Metrics

Error Correction

- Encode logical qubits in physical qubits
- Interements produce syndromes
- Use syndromes to correct errors

Needs many high-fidelity qubits

Error Mitigation

- Perform multiple and different noisy computations
- Collect results
- Infer ideal expectation values

What about quantum error correction?

nature

Explore content | About the journal | Publish with us | Subscribe

nature › articles › article

Article | Published: 22 March 2023

Real-time quantum error correction beyond break-even

V. V. Sivak, A. Eickbusch, B. Royer, S. Singh, I. Tsioutsios, S. Ganjam, A. Miano, B. L. Brock, A. Z. Ding, L. Frunzio, S. M. Girvin, R. J. Schoelkopf & M. H. Devoret

Nature **616**, 50–55 (2023) | Cite this article

16k Accesses | **104** Citations | **251** Altmetric | Metrics

Error Correction

- Encode logical qubits in physical qubits
- Interements produce syndromes
- Use syndromes to correct errors

Needs many high-fidelity qubits

Error Mitigation

- Perform multiple and different noisy computations
- Collect
- Infer expectation values

Needs few noisy qubits

Zero-Noise Extrapolation (ZNE)

Key Idea

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

Zero-Noise Extrapolation (ZNE)

Key Idea

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

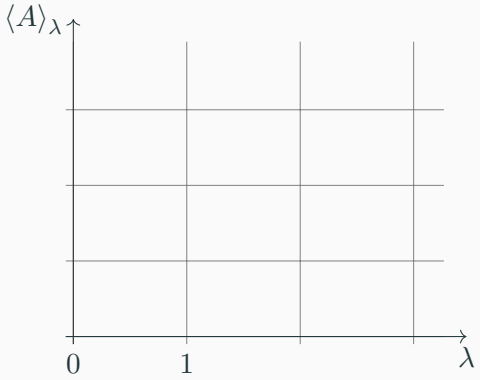
$$\partial_t \rho = -i[H, \rho] + \lambda \mathcal{L}(\rho)$$

Zero-Noise Extrapolation (ZNE)

Key Idea

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

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

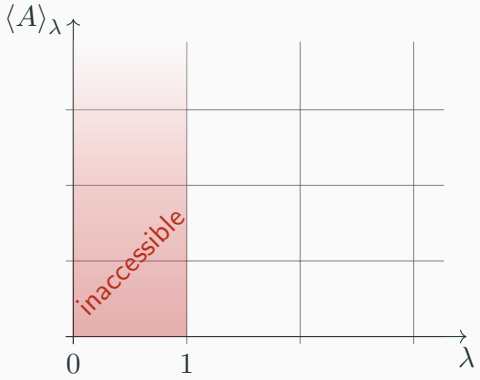


Zero-Noise Extrapolation (ZNE)

Key Idea

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

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

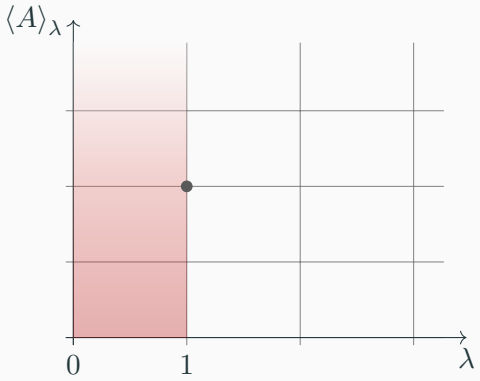


Zero-Noise Extrapolation (ZNE)

Key Idea

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

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

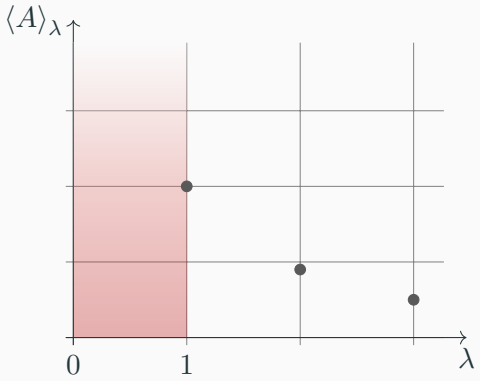


Zero-Noise Extrapolation (ZNE)

Key Idea

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

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

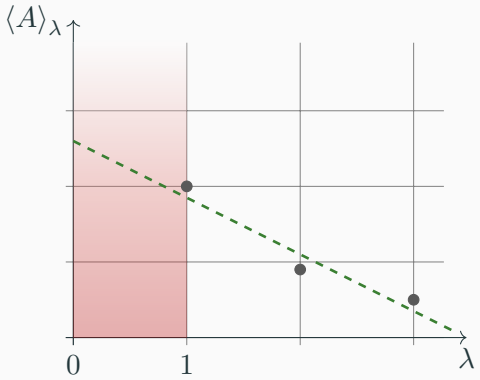


Zero-Noise Extrapolation (ZNE)

Key Idea

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

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

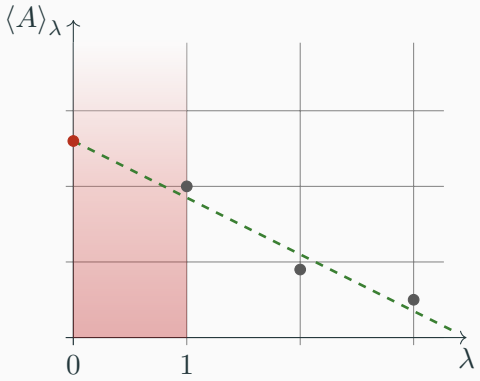


Zero-Noise Extrapolation (ZNE)

Key Idea

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

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



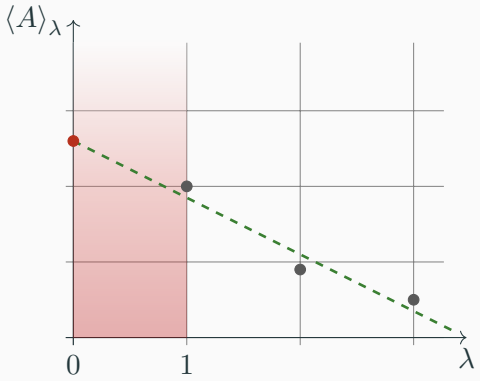
Zero-Noise Extrapolation (ZNE)

Key Idea

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

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

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



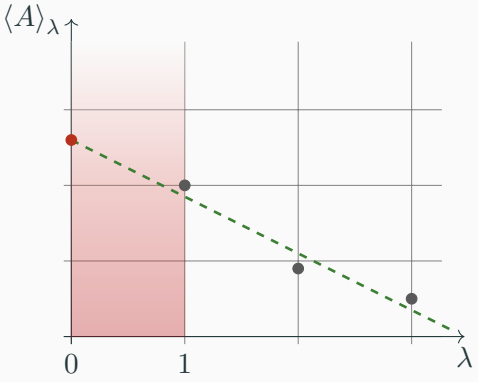
Zero-Noise Extrapolation (ZNE)

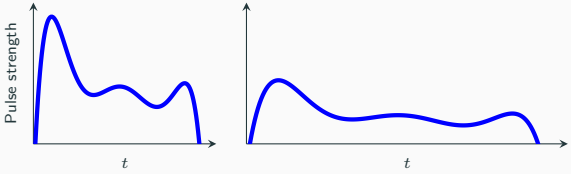
Key Idea

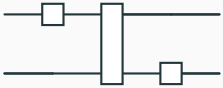
Scale noise up, extrapolate back to zero-noise value.

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

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





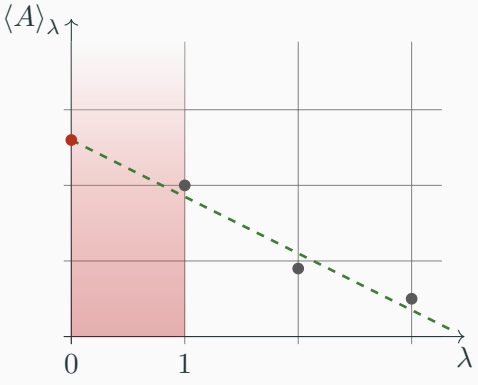


Zero-Noise Extrapolation (ZNE)

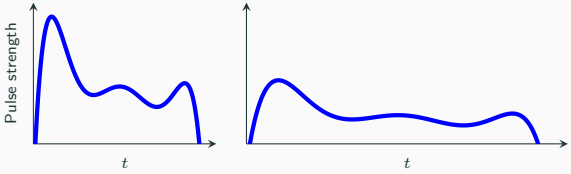
Key Idea

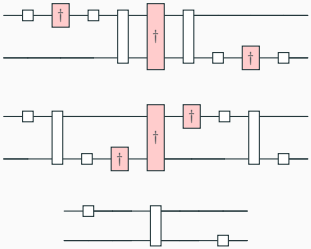
Scale noise up, extrapolate back to zero-noise value.

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

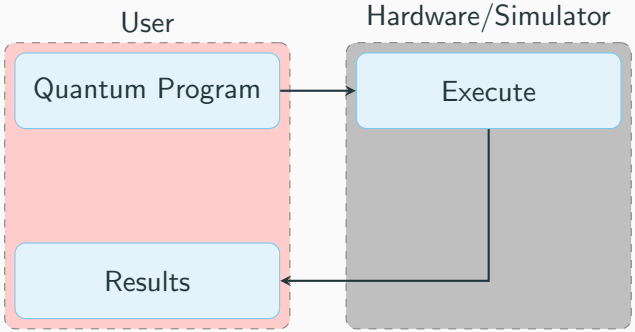


How do we scale the noise **up**?

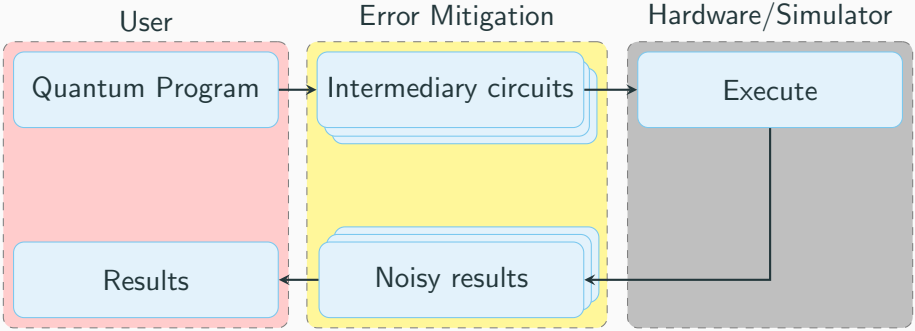




Running quantum programs in practice



Running quantum programs in practice with Mitiq



A peak into the future...

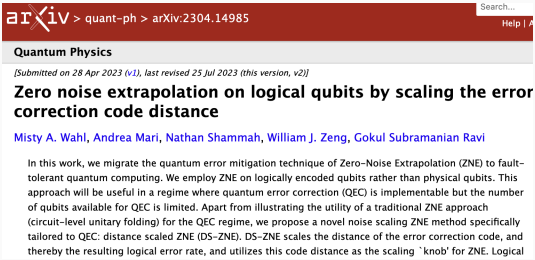
QEC + QEM

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

Search...

Help | A

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

A peak into the future...

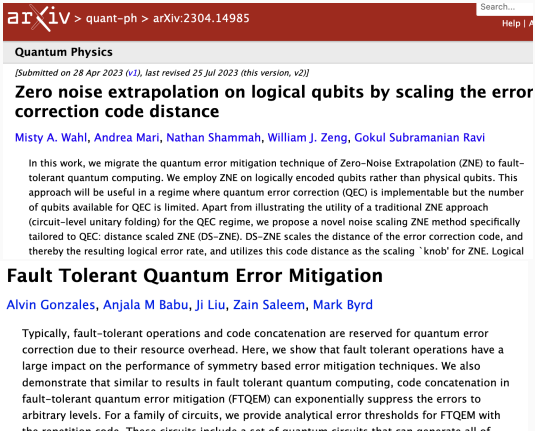
QEC + QEM

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

Search... Help | A

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

Fault Tolerant Quantum Error Mitigation

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

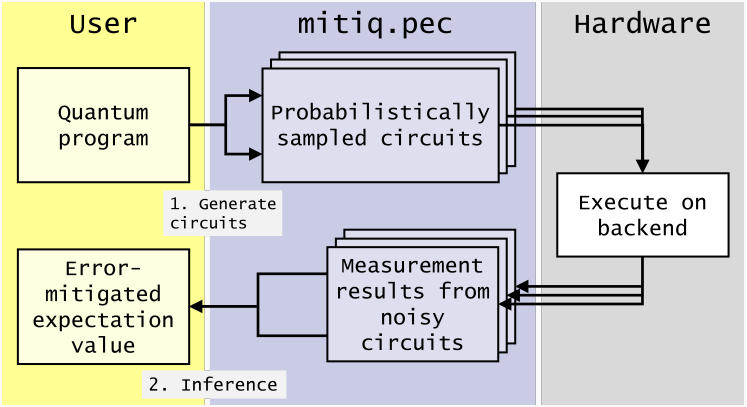
Typically, fault-tolerant operations and code concatenation are reserved for quantum error correction due to their resource overhead. Here, we show that fault tolerant operations have a large impact on the performance of symmetry based error mitigation techniques. We also demonstrate that similar to 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

Let's try Mitiq!

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

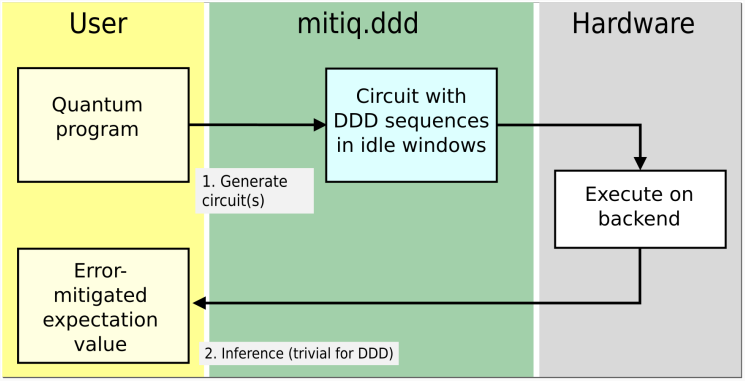
Probabilistic Error Cancellation

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

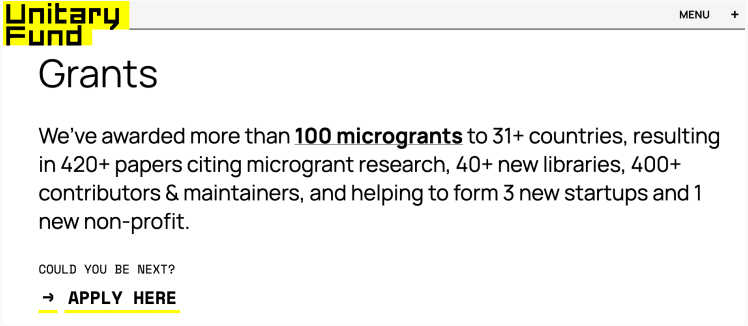


Digital Dynamical Decoupling

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



Interested in this work? Apply for a microgrant!



https://unitary.fund/grants/