Quantum Error Mitigation

Nathan Shammah, Unitary Fund

nathan@unitary.fund

SQMS Summer School, 26th July 2022
Galileo Galilei Institute, Florence, Italy

Quantum Error Mitigation: Outline

- Introduction to noise in quantum computing
- Motivation & overview of quantum error mitigation
- More in-depth look: Zero-noise extrapolation
- SQMS, Open-source software, Unitary Fund & Mitiq
- Conclusions

This talk

Quantum error mitigation

Today, 3:45 – 5:15 pm CEST

Lab: Quantum error mitigation techniques with Mitiq

Unitary Fund





Quantum Error Mitigation: Outline

- **Introduction to noise in quantum computing**
- Motivation & overview of quantum error mitigation
- More in-depth look: Zero-noise extrapolation
- SQMS, Open-source software, Unitary Fund & Mitiq
- Conclusions

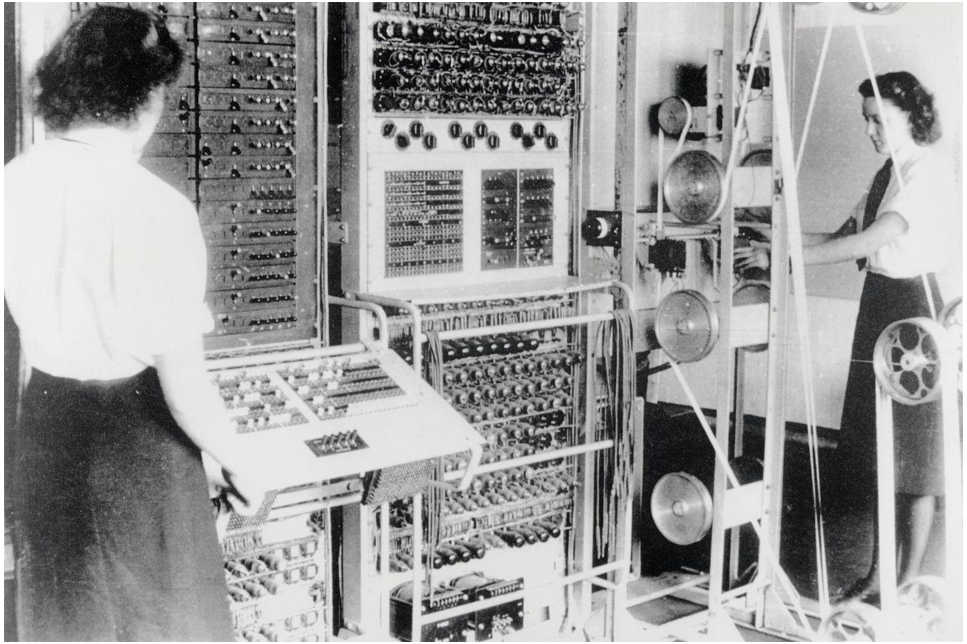

olivetti programma 101

Programma 101 (P101) by Olivetti

- Personal desktop programmable calculator
- By some considered the first commercial PC…
- Presented in NYC in 1965
- Designed by Mario Bellini
- Not supported enough by Olivetti's leadership team

- No screen…
- Hard to code…
- Limited computing capability…
- Limited instruction set…
- Enthusiastically adopted by NASA, LANL, etc.
- Expensive ($3,200, equivalent to ~$27,500)

… Actually NISQ computers have things in common with these



- Very few available worldwide
- Bulky
- Require expert operators

… Noisy intermediate-scale quantum computing devices, still…

- They are connected to the cloud
- They work with open-source software
- They leverage existing UX/UI web stack
- …

Current NISQ quantum computers are a strange hybrid, let's look at what it entails running programs on them

Running programs on quantum computers (or simulators)

Quantum program

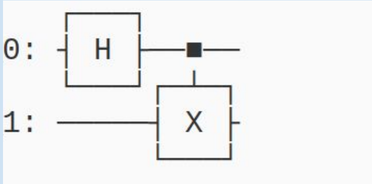
(e.g., VQA: Hybrid CC/QC)

Running programs on quantum computers (or simulators)

Quantum program

(e.g., VQA: Hybrid CC/QC)

Quantum Circuit

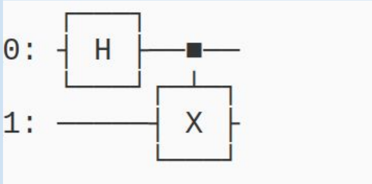


Running programs on quantum computers (or simulators)

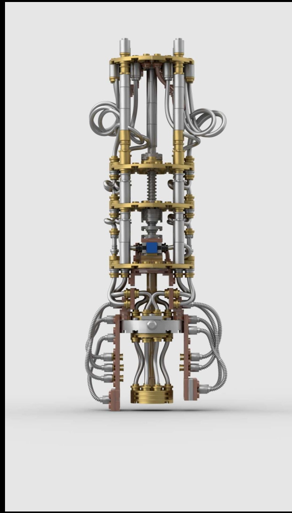
Quantum program

(e.g., VQA: Hybrid CC/QC)

Quantum Circuit



Quantum Computer

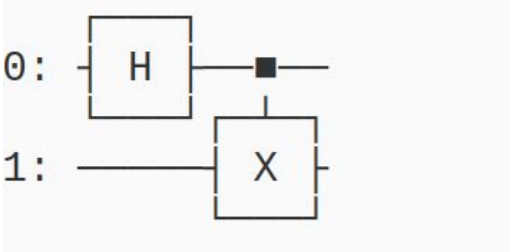


Bitstrings
Run 1: 01011101010010……
Run 2: 01011101010010……

Ideal quantum circuits: unitary gates (+ measurement/barriers)

Ideal Von Neumann master equation: $\partial_t \rho = -i[K(t), \rho]$

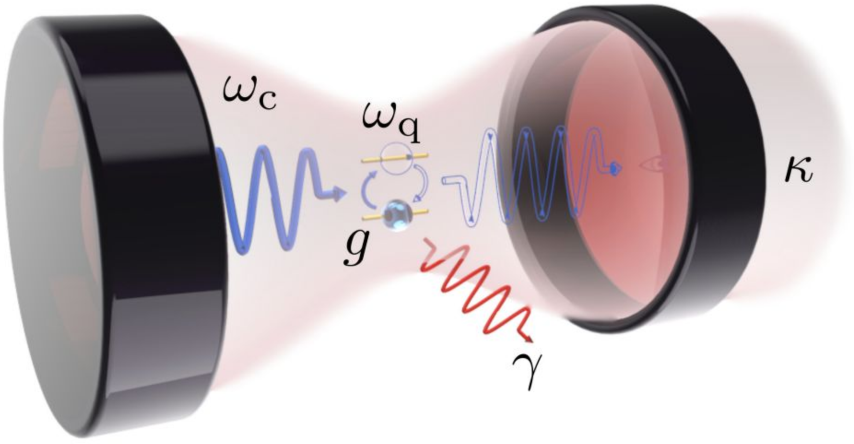
noiseless
Hamiltonian

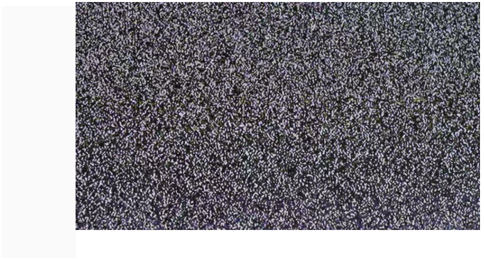


Ideal quantum circuits... on noisy computers

Ideal Von Neumann master equation: $\partial_t \rho = -i[K(t), \rho]$

noiseless
Hamiltonian





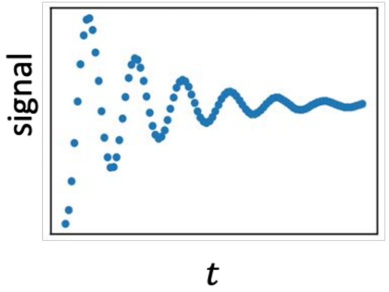
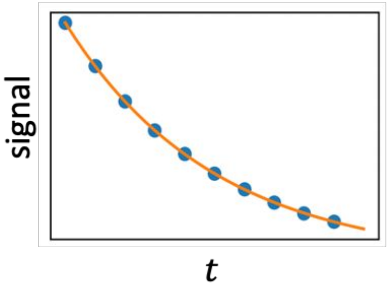
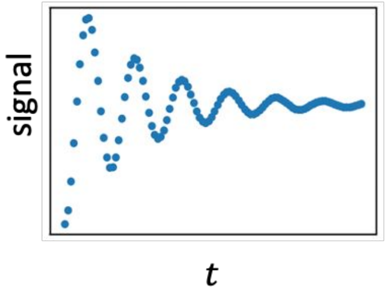


Image credit: doi.org/10.48550/arXiv.1807.11636

Different noise mechanisms affect differently different quantum systems

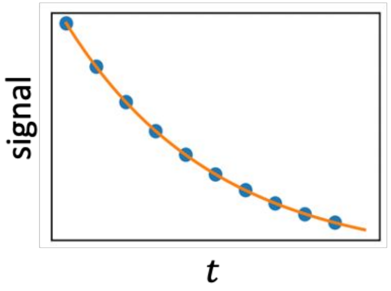
- Decoherence noise

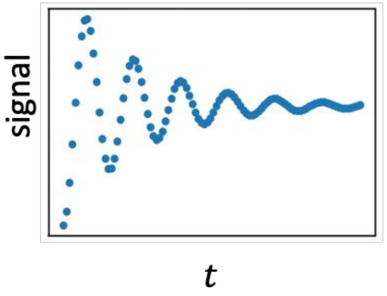




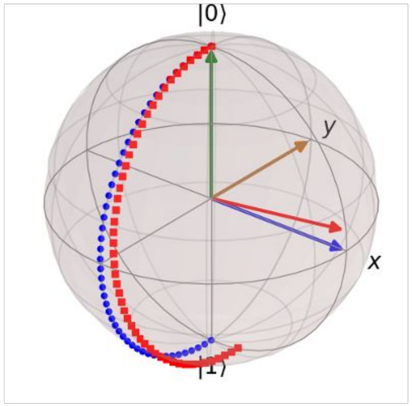
Different noise mechanisms affect differently different quantum systems

- Decoherence noise





- Control Noise

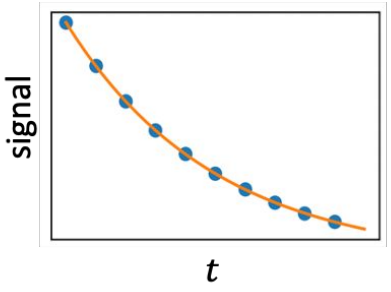


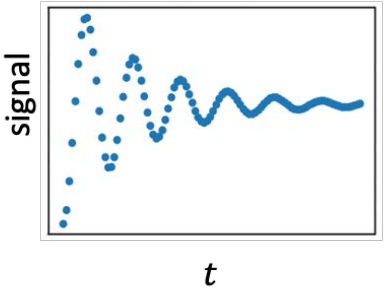
Perfect control: $H = \frac{\sigma_x}{2}$

Imperfect control: $H = \frac{\sigma_x}{2} + \frac{1}{10}\frac{\sigma_z}{2}$

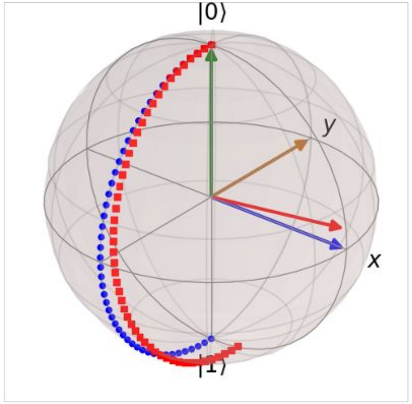
Different noise mechanisms affect differently different quantum systems

- Decoherence noise





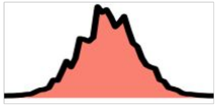
- Control Noise



Perfect control: $H = \frac{\sigma_x}{2}$

Imperfect control: $H = \frac{\sigma_x}{2} + \frac{1}{10}\frac{\sigma_z}{2}$

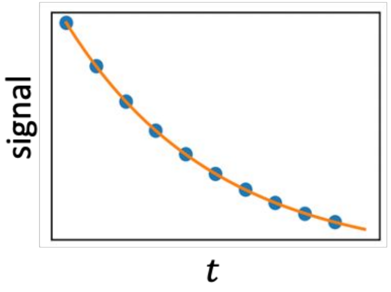
$H = H_{\text{idea}} + H_{\text{noise}}$

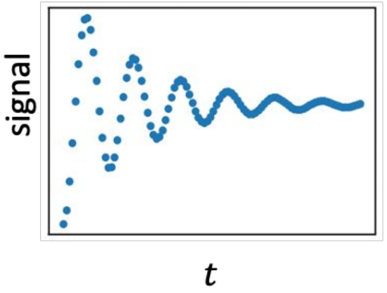


Pulse shape noise

Different noise mechanisms affect differently different quantum systems

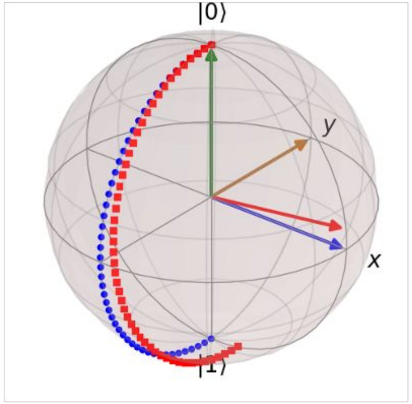
- Decoherence noise





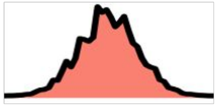
- Control Noise

$$H = H_{\text{idea}} + H_{\text{noise}}$$

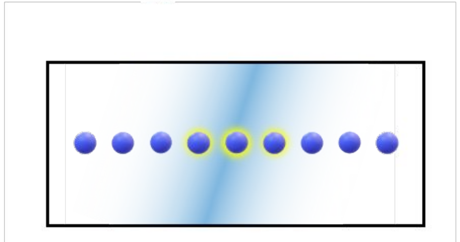


Perfect control: $H = \frac{\sigma_x}{2}$

Imperfect control: $H = \frac{\sigma_x}{2} + \frac{1}{10}\frac{\sigma_z}{2}$



Pulse shape noise

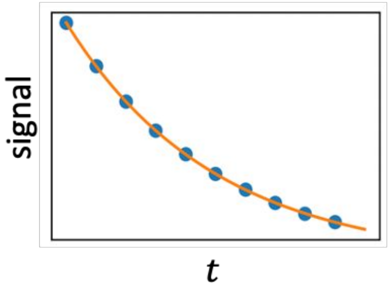


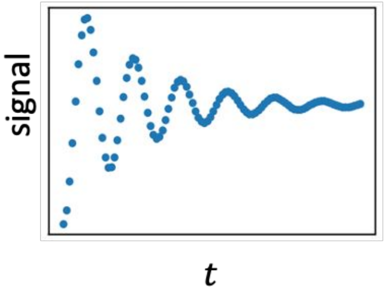
Cross-talk noise

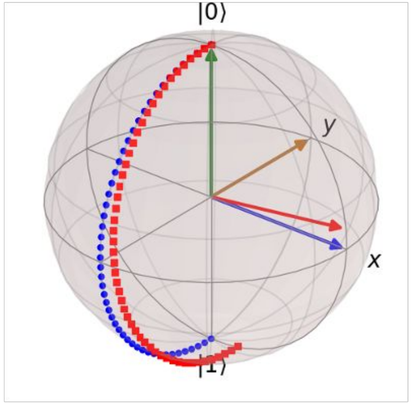
Different noise mechanisms affect differently different quantum systems

- Decoherence noise
- Control Noise

$$H = H_{\text{idea}} + H_{\text{noise}}$$

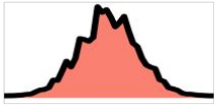




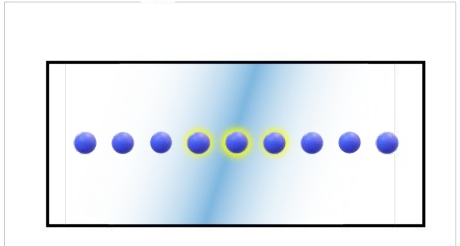


Perfect control: $H = \frac{\sigma_x}{2}$

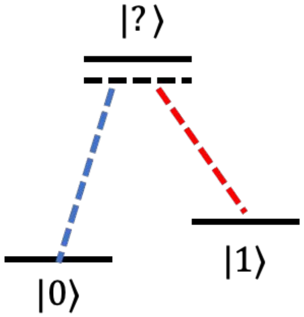
Imperfect control: $H = \frac{\sigma_x}{2} + \frac{1}{10}\frac{\sigma_z}{2}$



Pulse shape noise



Cross-talk noise



Leakage noise

Noise simulation: Reviewing common assumptions

How is noise usually simulated at the gate-level?

- Random Pauli error
- Quantum channel:
    - Decoherence
    - Dephasing
    - Erasure …

Assumptions:

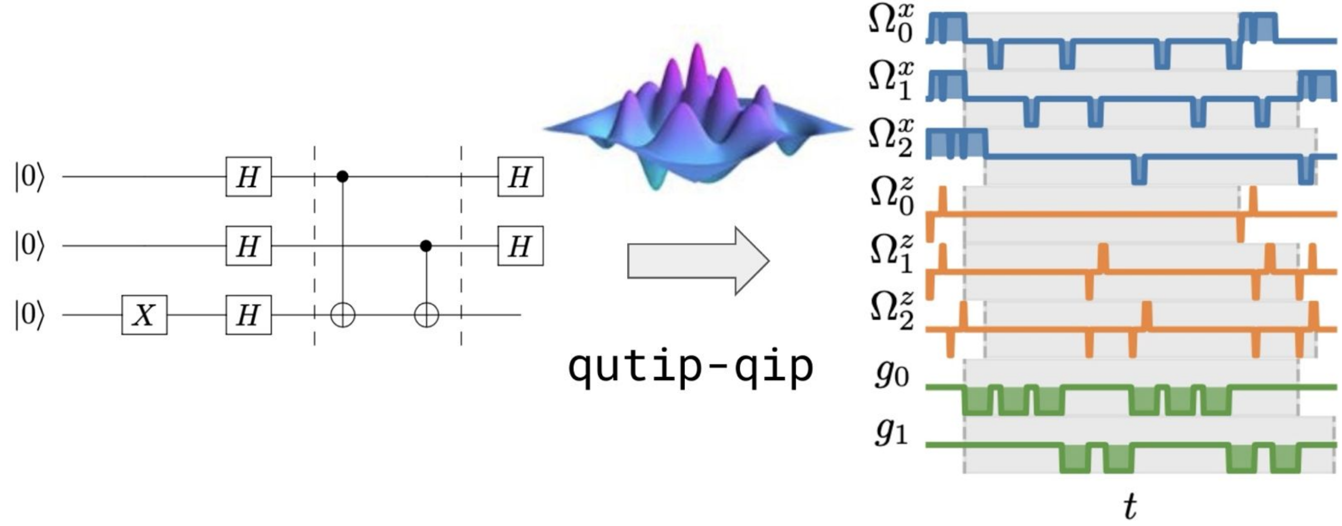
- Noise is usually independent among qubits
- Usually simulated after a perfect gate

More complex picture:

- Noise can be correlated, both in time and in space
- The ideal operation (perfect gate) and noise may not be separable

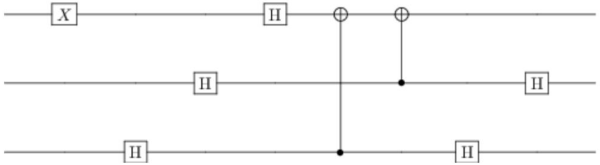
Noise simulation is crucial to understand what's going on

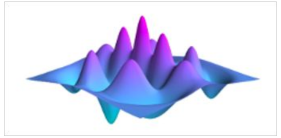
Tools like qutip-qip can help simulate noise, even at the pulse level compilation



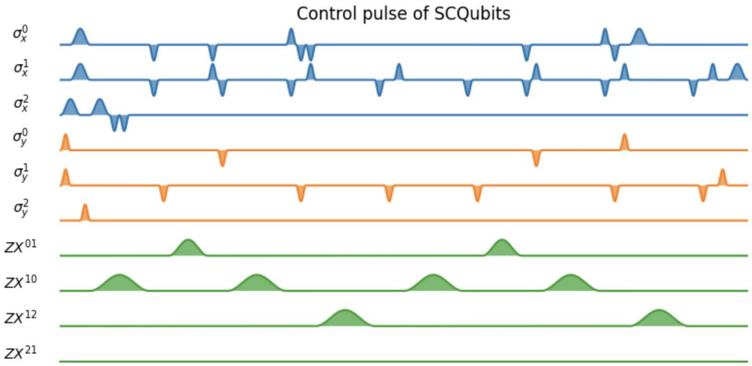
Pulse-level noisy quantum circuits with QuTiP**,** B. Li, S. Ahmed, S. Saraogi, N. Lambert, F. Nori, A. Pitchford, N. Shammah,
Quantum 6, 630 (2022) **arXiv:2105.09902**

Pulse-level simulation of noisy QPU simulators



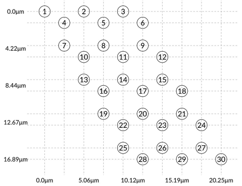


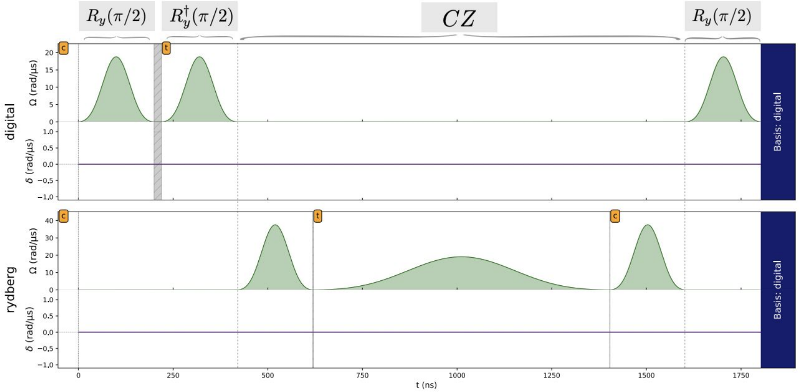
```
processor.plot_pulses(title="Control pulse of SCQubits", figsize=(8, 4), dpi=100);
```



Pulse-level noisy quantum circuits with QuTiP,
B. Li,, et al.. **Quantum 6**, 630, 2022

queracomputing.github.io/Bloqade.jl

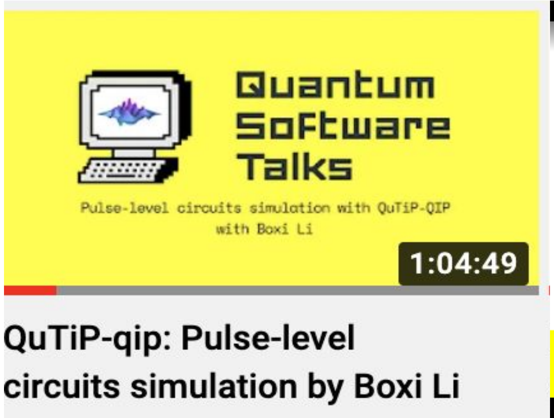


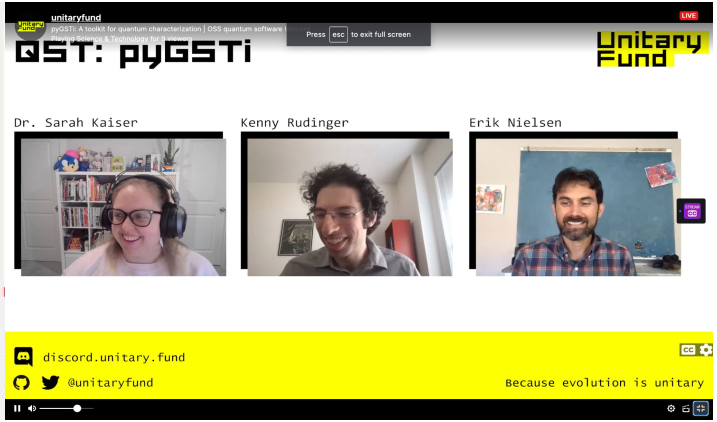


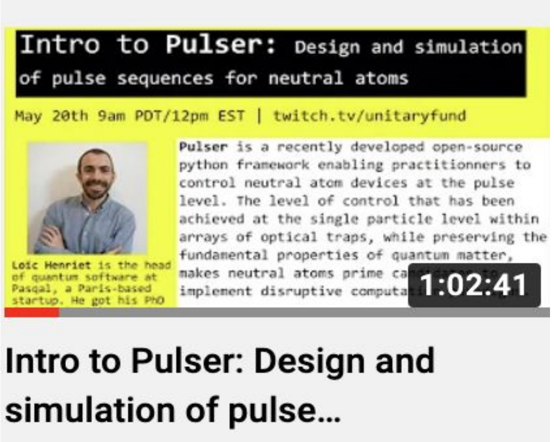
Pulser: An open-source package for the design of pulse sequences in programmable neutral-atom arrays
H. Silvério, S. Grijalva, et al., **Quantum 6**, 629, 2022

Noise simulation & characterization: dive into quantum software talks

Tools like qutip-qip, pyGSTi, Pulser are available: avoid to reinvent the wheel







Unitary Fund - YouTube

Noise affects the ideal quantum computation… with errors

Quantum computation by quantum evolution + operations & measurement

Quantum noise and classical noise can introduce errors

Different quantum systems (“QPUs”) suffer from different noise sources

Different noise models can be employed and tools for characterization, eg. pyGSTi

Noise scale factor
[dimensionless real number]

Markovian master equation: $$\partial_t \rho = -i[K(t), \rho] + \lambda \mathcal{L}[\rho]$$

Density matrix

Noiseless Hamiltonian

Noise operator

What to do with “high level” of noise in current devices?

https://www.scientificamerican.com/article/how-to-fix-quantum-computing-bugs/

Subscribe | Latest Issues

SCIENTIFIC AMERICAN®

Credit: Alice Mollon

How to Fix Quantum Computing Bugs

The same physics that makes quantum computers powerful also makes them finicky. New techniques aim to correct errors faster than they can build up

By Zaira Nazario

AUTHOR

Zaira Nazario is a quantum theorist at the IBM Watson Research Center in Yorktown Heights, N.Y. *Credit: Nick Higgins*

It is a law of physics that everything that is not prohibited is mandatory. Errors are thus unavoidable. They are everywhere: in language, cooking, communication, image processing and, of course, computation. Mitigating and correcting them keeps society running. You can scratch a DVD yet still play it. QR codes can be blurred or torn yet are still readable. Images from space probes can travel hundreds of millions of miles yet still look crisp. Error correction is one of the most fundamental concepts in information technology. Errors may be inevitable, but they are also fixable.

Quantum Error Mitigation: Outline

- **Introduction to noise in quantum computing**
- Motivation & overview of quantum error mitigation
- More in-depth look: Zero-noise extrapolation
- SQMS, Open-source software, Unitary Fund & Mitiq
- Conclusions

Quantum Error Mitigation: Outline

- Introduction to noise in quantum computing
- **Motivation & overview of quantum error mitigation**
- More in-depth look: Zero-noise extrapolation
- SQMS, Open-source software, Unitary Fund & Mitiq
- Conclusions

Why error mitigation?

(Standard) Quantum Error Correction:

- Encode logical qubits into many physical qubits
- Intermediate measurements for syndrome detections
- Correction operations based on the measured syndrome

Scalable but unfeasible with near-term quantum computers

🏗️ 😔

Error mitigation for universal gates on encoded qubits, C. Piveteau, *et al.*, Phys Rev Lett. 2021 (arXiv:2103.04915)

Quantum Error Mitigation:

- Perform **multiple and different** noisy quantum computations
- Collect the results
- **Infer ideal expectation values** from noisy data

Asymptotically unscalable but feasible with near-term quantum computers

😬 😉

Why error mitigation?

Date
19 Jul 2022

Authors

Kristan Temme
Ewout van den Berg
Abhinav Kandala
Jay Gambetta

Topics

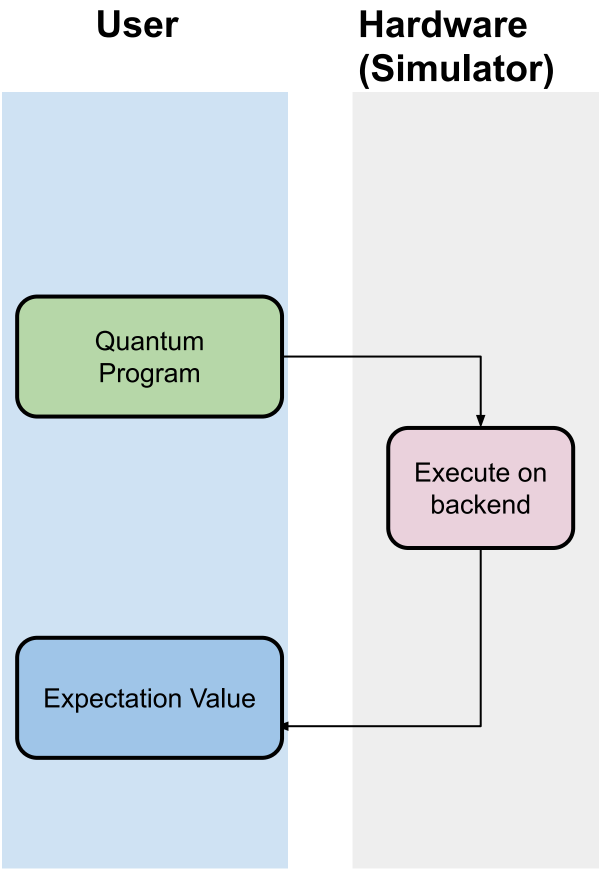
Quantum Circuits and Software
Quantum Error Correction
Quantum Hardware
Quantum Information Science

Deep Dive | 10 minute read

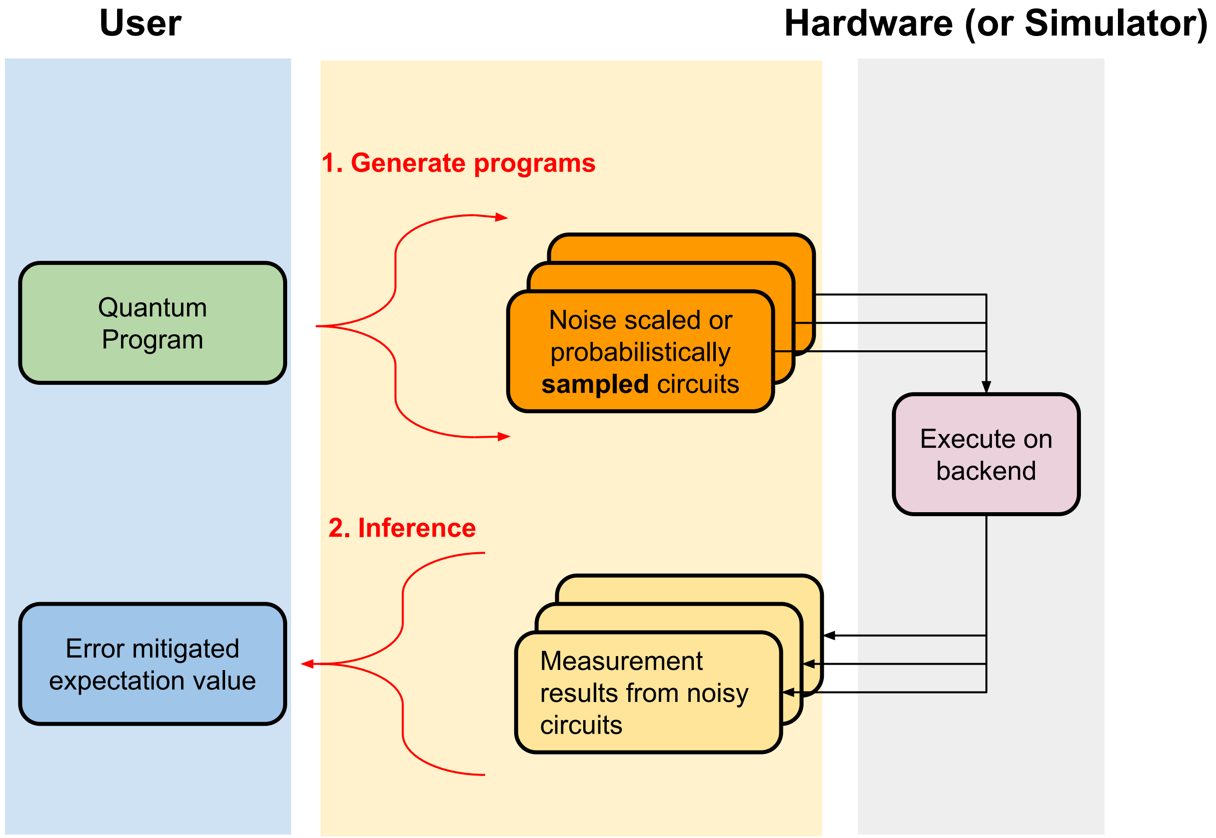
With fault tolerance the ultimate goal, error mitigation is the path that gets quantum computing to usefulness

Quantum error mitigation is the continuous path that will take us from today's quantum hardware to tomorrow's fault-tolerant quantum computers. This path will let us run larger circuits needed for quantum advantage, one hardware improvement at a time.

Typical workflow to run program on a quantum computer



Key features of most QEM techniques: quantum sampling and classical inference



Quantum error mitigation: an emerging field

Relations to adjacent fields

- Open quantum systems
- **Quantum error mitigation**
- Quantum error correction
- Quantum characterization verification & validation (QCVV)
- Variational quantum algorithms
- Quantum optimal control

Quantum error mitigation: (Non-exhaustive) overview

Zero Noise Extrapolation

Probabilistic Error Cancellation & Quasi-Probabilistic Repr.ns

Clifford Data Regression, Learning-based & hybrid techn.s

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

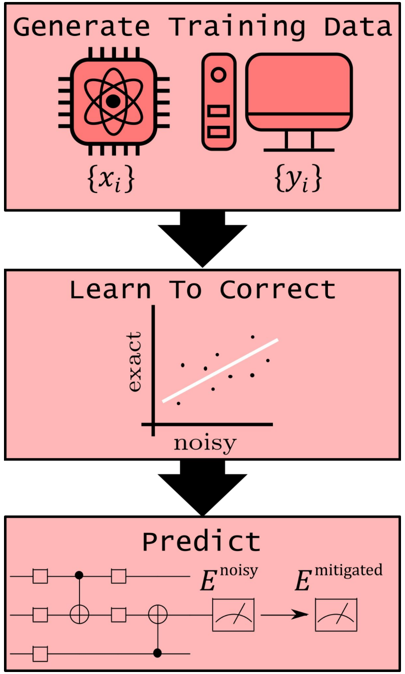
Noisy gate-level representation

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

Dynamical Decoupling & Randomized Compiling

Quantum error mitigation: (Non-exhaustive) overview

Zero Noise Extrapolation

Key feature: Noise scaling

Probabilistic Error Cancellation & Quasi-Probabilistic Repr.ns

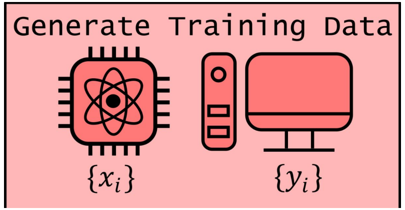
Noisy gate-level representation

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



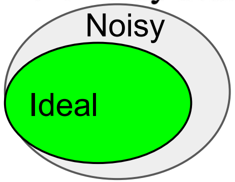
Symmetry-based Techniques

Key feature: Noisy state re-projected

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

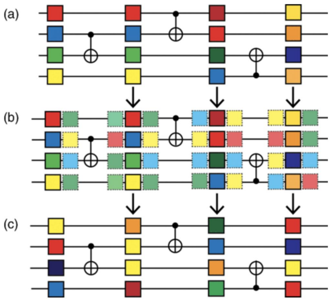
measuring $\{\hat{M}_i\}$ on the noisy state ρ

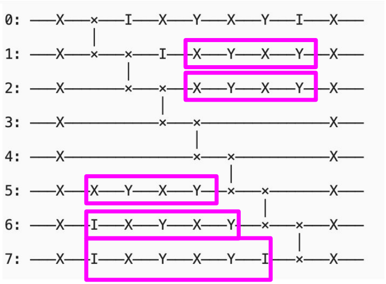
$$\rho_s = \frac{\hat{M}_s \rho \hat{M}_s}{\mathrm{Tr}[\hat{M}_s \rho]}.$$



Dynamical Decoupling & Randomized Compiling

Add gates to protect from 'bad' noise





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)

Review: S. Endo, *et al.*, Hybrid quantum-classical algorithms and quantum error mitigation. J. Phys. Soc. Japan, 90, 032001 (2021) arXiv:2011.01382

All references at: mitiq.readthedocs.io

Quantum error mitigation: Useful add-on for benchmarking

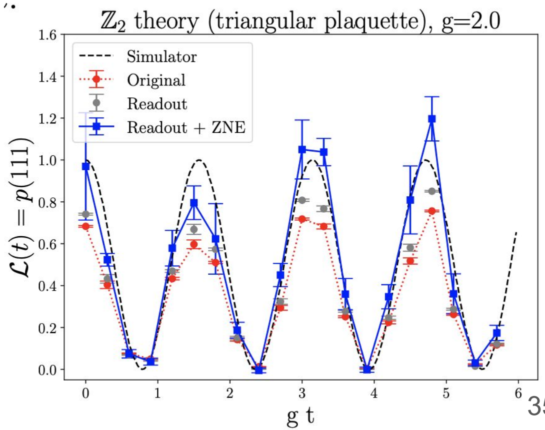
Probable workflow for much of current & near-future research on NISQ devices

Problem of interest (e.g., Quantum simulation of quantum field theory) → Compile into quantum circuit (e.g., Trotterize) → Choose best hardware spec fit → Run on hardware with quantum error mitigation → Benchmark & compare

Publish, Open source code & data

Real-time dynamics of Plaquette Models using NISQ Hardware, E. Huffman *et al.* [arxiv:2109.15065](https://arxiv.org/abs/2109.15065)

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 real-time dynamics of ℤ2 and U(1) gauge invariant plaquette models using 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. Even though the quantum hardware suffers from decoherence, **we demonstrate the use of 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 IBM Q quantum computers.** Our study provides insight into the choice of quantum hardware topologies, construction of circuits, and the utility of error mitigation methods to devise large-scale quantum computation strategies for lattice gauge theories.



Running programs on cloud quantum computers: QEM in practice

Front end

- Qiskit
- Braket SDK
- Pyquil
- Q#
- Cirq
- …

Cloud service

- IBM-Q Experience
- AWS (Braket)
- Rigetti Cloud Services
- Azure Quantum
- IonQ Cloud
- …

Back-end provider

- IBM-Q QPU
- Rigetti QPU
- IonQ QPU
- Quantinuum QPU
- …

Running programs on cloud quantum computers: QEM in practice

Front end → **Cloud service** → **Back-end provider**

Front end
- Qiskit
- **Braket SDK**
- Pyquil
- Q#
- Cirq
- …

Cloud service
- IBM-Q Experience
- **AWS (Braket)**
- Rigetti Cloud Services
- Azure Quantum
- IonQ Cloud
- …

Back-end provider
- IBM-Q QPU
- **Rigetti QPU**
- IonQ QPU
- Quantinuum QPU
- …

Running programs on cloud quantum computers: QEM in practice

Front end → **Cloud service** → **Back-end provider**

Front end
- Qiskit
- **Braket SDK**
- Pyquil
- Q#
- Cirq
- …

Cloud service
- IBM-Q Experience
- **AWS (Braket)**
- Rigetti Cloud Services
- Azure Quantum
- IonQ Cloud
- …

Back-end provider
- IBM-Q QPU
- Rigetti QPU
- **IonQ QPU**
- Quantinuum QPU
- …

Advanced Feature

Low-level compile control (disabled)

Running programs on cloud quantum computers: QEM in practice

Front end → **Cloud service** → **Back-end provider**

Front end

- Qiskit
- Braket SDK
- Pyquil
- Q#
- Cirq
- …

Cloud service

- IBM-Q Experience
- AWS (Braket)
- Rigetti Cloud Services
- Azure Quantum
- **IonQ Cloud**
- …

Back-end provider

- IBM-Q QPU
- Rigetti QPU
- **IonQ QPU**
- Quantinuum QPU
- …

“Advanced Feature”

Low-level compile control (disabled)

Quantum Error Mitigation: Outline

- Introduction to noise in quantum computing
- **Motivation & overview of quantum error mitigation**
- More in-depth look: Zero-noise extrapolation
- SQMS, Open-source software, Unitary Fund & Mitiq
- Conclusions

Quantum Error Mitigation: Outline

- Introduction to noise in quantum computing
- Motivation & overview of quantum error mitigation
- **More in-depth look: Zero-noise extrapolation & Mitiq**
- Unitary Fund, Open-source software, SQMS
- Conclusions

Noisy quantum evolution

noise scale factor
[dimensionless real number]

Markovian master equation: $\partial_t \rho = -i[K(t), \rho] + \lambda \mathcal{L}[\rho]$

noiseless
Hamiltonian

noise operator

Noiseless evolution: $\lambda = 0$

Hardware dynamics: $\lambda = 1$

Noisy quantum evolution

noise scale factor
[dimensionless real number]

Markovian master equation: $$\partial_t \rho = -i[K(t), \rho] + \lambda \mathcal{L}[\rho]$$

noiseless
Hamiltonian

noise operator

Noiseless evolution: $\lambda = 0$

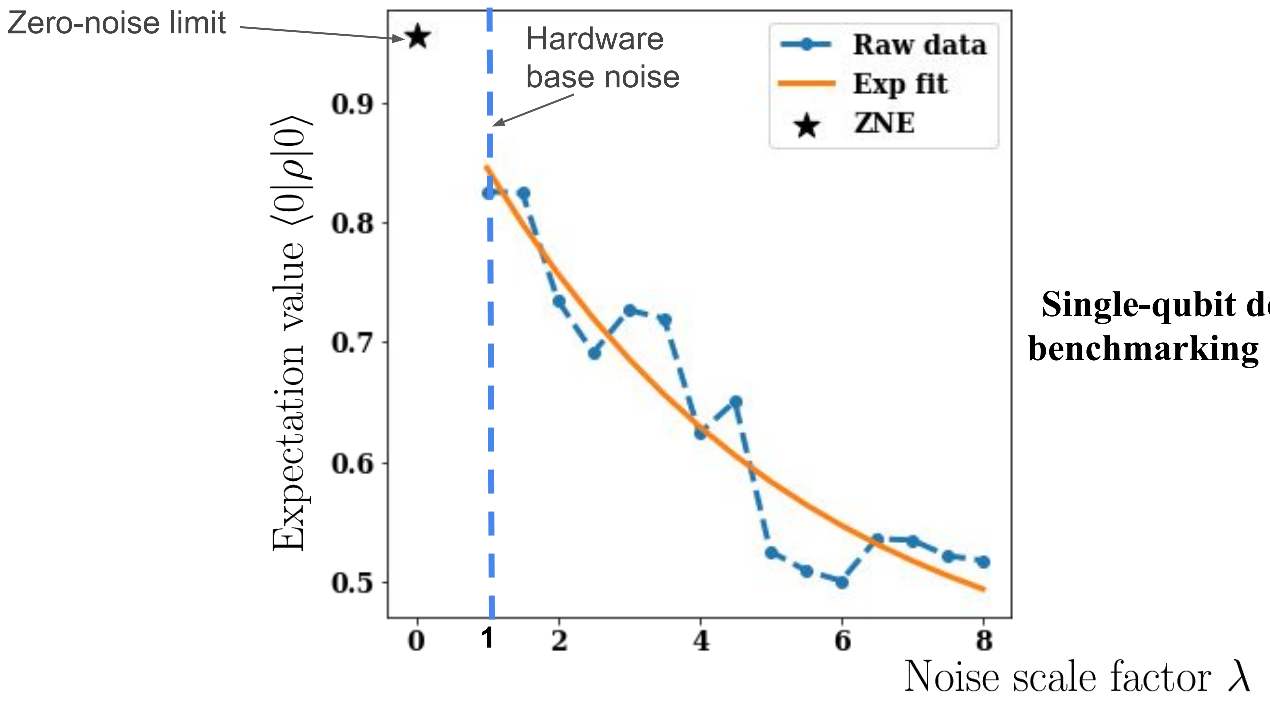
Hardware dynamics: $\lambda = 1$

Increase noise: $\lambda = 2$

K. Temme, S. Bravyi, and J. M. Gambetta,
“Error Mitigation for Short Depth Quantum Circuits,”
Physical Review Letters,. **119**, 180509 (2017)

Zero-noise extrapolation (ZNE): increasing noise… and back

Markovian master equation: $$\partial_t \rho = -i[K(t), \rho] + \lambda \mathcal{L}[\rho]$$



Single-qubit depth *d = 200* randomized benchmarking circuit on IBMQ Armonk

Noise scaling by pulse stretching

noise scale factor
[dimensionless real number]

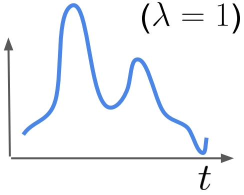
Markovian master equation: $\partial_t \rho = -i[K(t), \rho] + \lambda \mathcal{L}[\rho]$

noiseless
Hamiltonian

noise operator

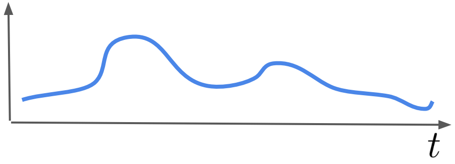
Experimentally:

$(\lambda = 1)$



In practice, all the physical
control pulses must be **stretched**

$(\lambda = 2)$



K. Temme, S. Bravyi, and J. M. Gambetta, "Error Mitigation for Short Depth Quantum Circuits," Physical Review Letters,. **119**, 180509,(017).

A. Kandala, *et al.* "Error mitigation extends the computational reach of a noisy quantum processor" Nature **567**, 491 (2019)

Zero-noise extrapolation (ZNE) by pulse stretching

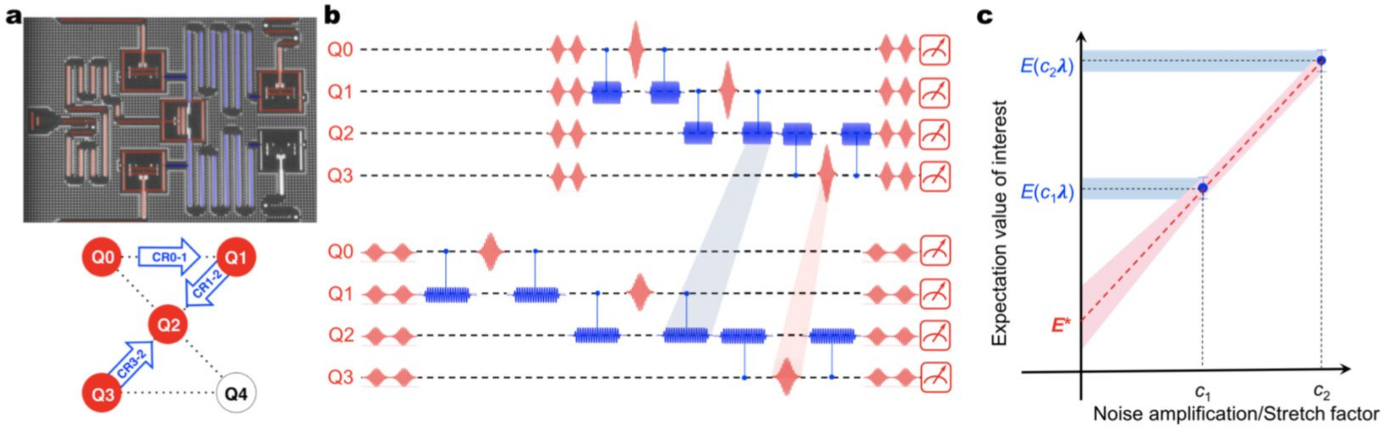


FIG. 1. **Device and experimental protocol a** False-colored optical micrograph (top) of the superconducting quantum processor and schematic (bottom) of the qubits and gates utilized in the experiment. The device is composed of 5 transmon qubits, with the coupling provided by 2 superconducting CPW resonators, in blue. **b** A measurement of the expectation value after rescaled state preparation is equivalent to a measurement under an amplified noise strength, if the noise is time-translation invariant. **c** An illustration of the error mitigation method, shown here for a first-order Richardson extrapolation to the zero-noise limit, highlights that the variance of the mitigated estimate E^* is crucially dependent on the variance of the unmitigated measurements, and the stretch factors c_i.

A. Kandala, *et al.* “Error mitigation extends the computational reach of a noisy quantum processor” Nature **567**, 491 (2019)

Zero-noise extrapolation (ZNE) by pulse stretching

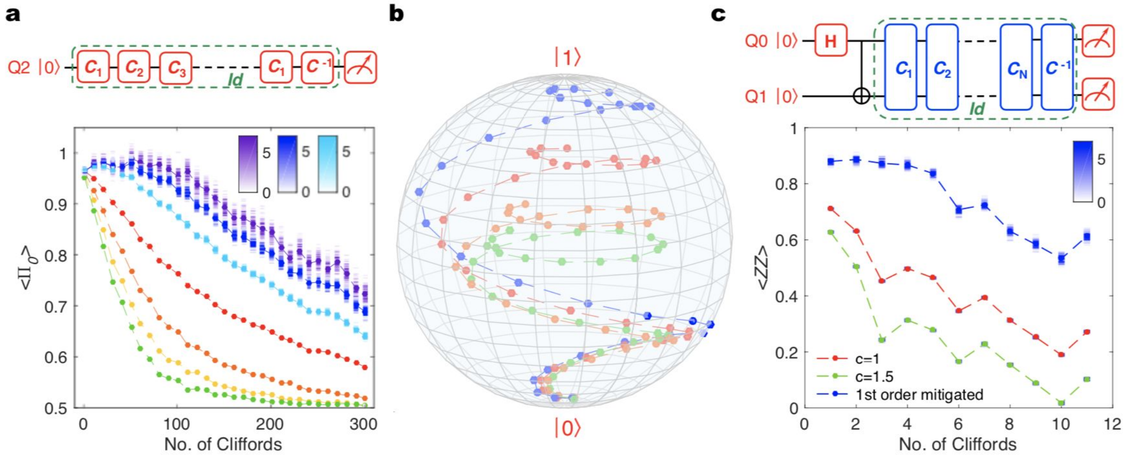


FIG. 2. **Error mitigation of random single-qubit and two-qubit circuits a** Expectation value of the ground state projector for identity equivalent single-qubit Clifford sequences for stretch factors $c = 1$ (red), 2 (orange), 3 (yellow), 4 (green) and the corresponding Richardson extrapolations to first (light blue), second (dark blue) and third order (violet). **b** Experimental implementation of trajectories described by Eq. 3, represented on a Bloch sphere for stretch factors $c = 1$ (red), 2 (orange), 3 (green) and the and the corresponding first-order Richardson extrapolation (blue). The ideal theoretical trajectory is one that takes the qubit from its ground state to its excited state along the surface of the Bloch sphere. **c** Expectation value of the ZZ parity for identity equivalent two-qubit Clifford sequences applied on a Bell State for stretch factors $c = 1$ (red), 1.5 (green) and the corresponding 1st order Richardson extrapolations (dark blue). The color density plots of **a, c** represent histograms of outcomes of 100 numerical experiments obtained by bootstrapping of each experimental data point.

A. Kandala, *et al.* “Error mitigation extends the computational reach of a noisy quantum processor” Nature **567**, 491 (2019)

Overview of Mitiq

mitiq.readthedocs.io

`pip install` **`mitiq`**

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

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

Accepted in **Quantum** arxiv.org/abs/2009.04417 (Dated: July 19, 2022)

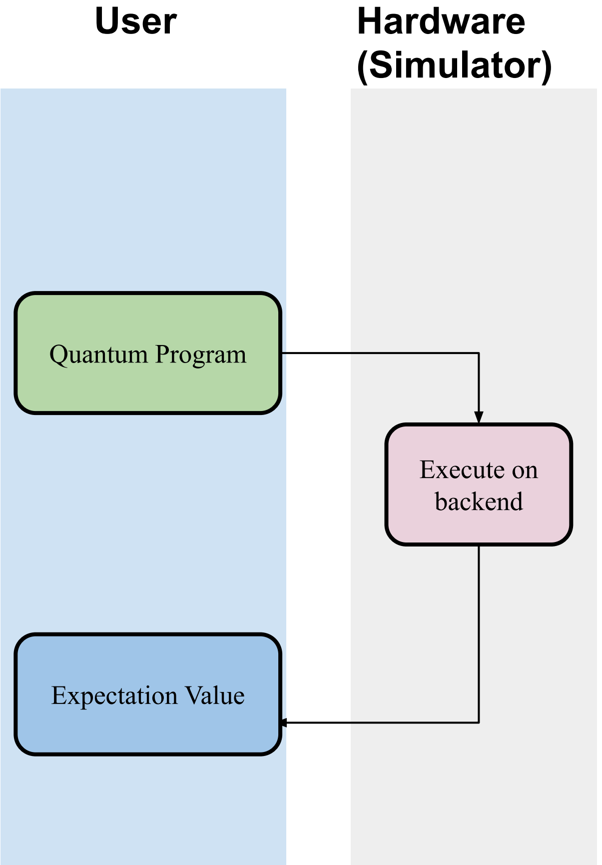
Typical workflow in quantum software

Qiskit

Cirq

rigetti

aws
Amazon Braket



IBM Q

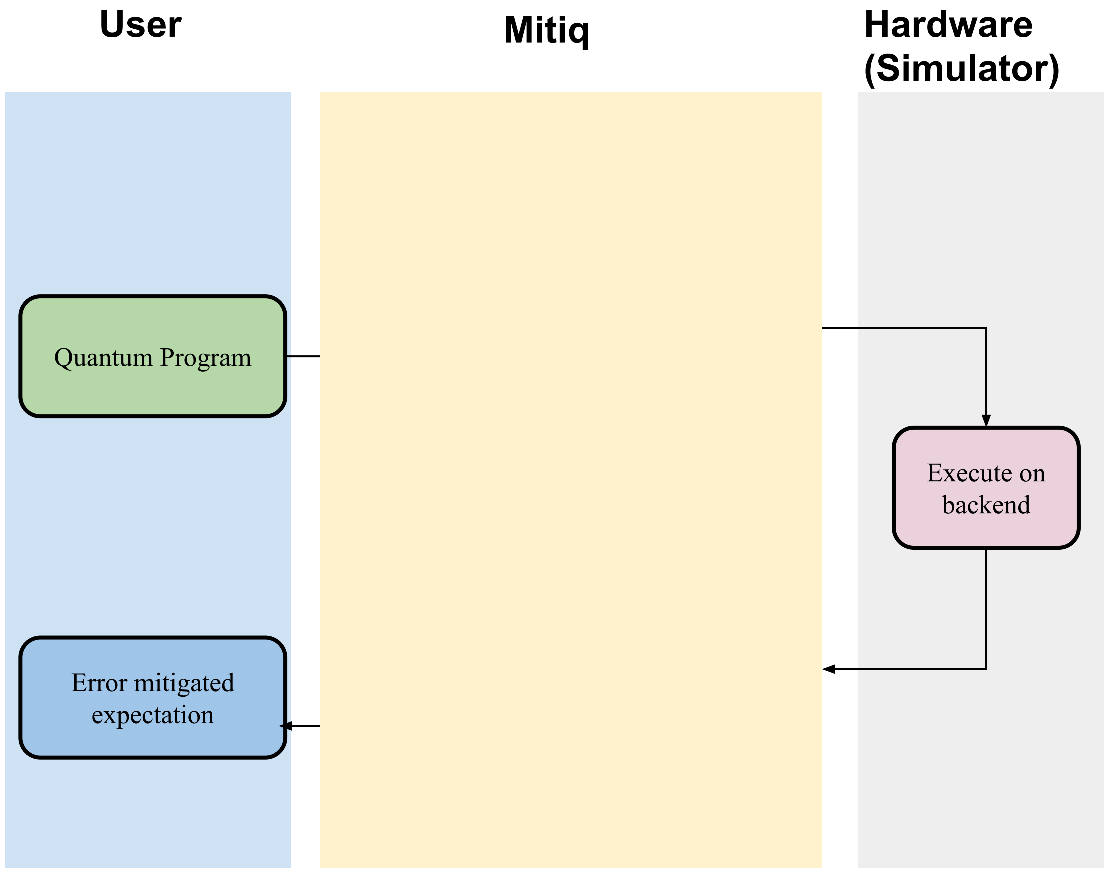
rigetti

aws
Amazon Braket

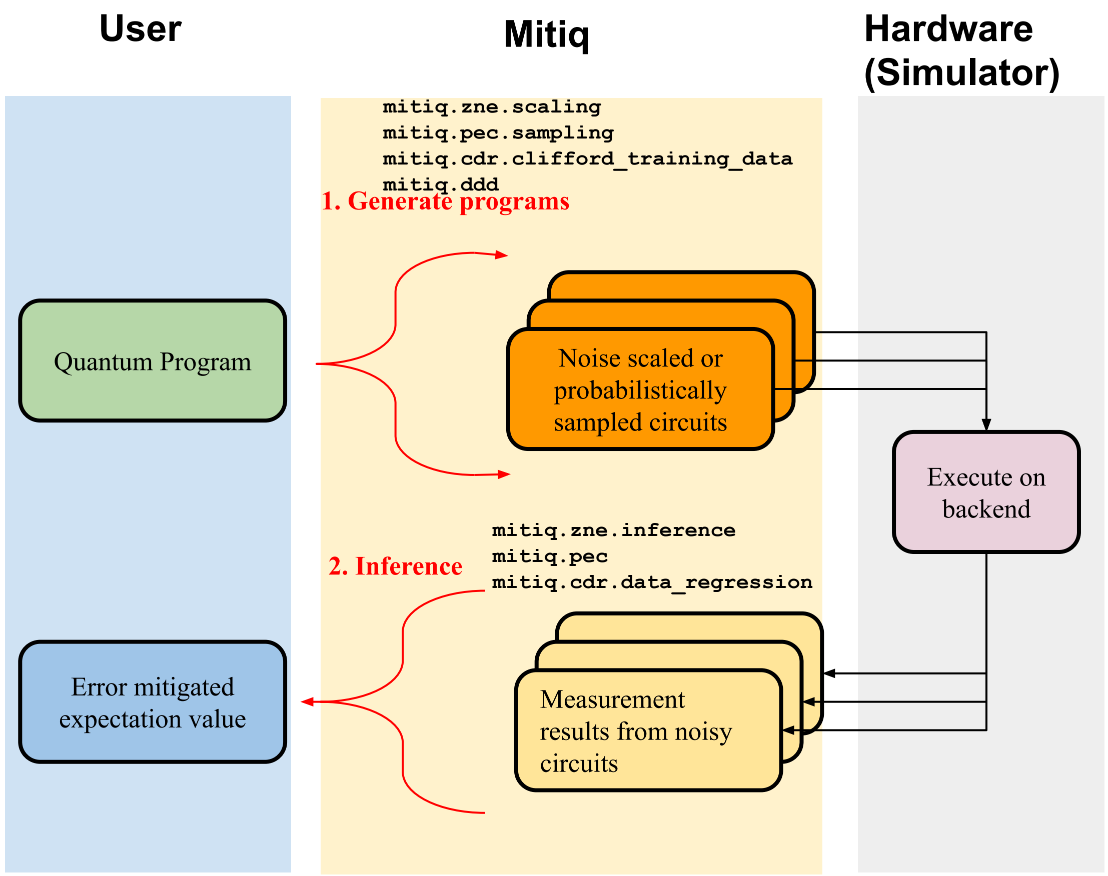
QuTiP
Quantum Toolbox in Python

...

Mitiq: a thin layer between the user and the backend



Mitiq: a thin layer between the user and the backend



Noisy quantum evolution

noise scale factor
[dimensionless real number]

Markovian master equation: $$\partial_t \rho = -i[K(t), \rho] + \lambda \mathcal{L}[\rho]$$

noiseless
Hamiltonian

noise operator

Noiseless evolution: $\lambda = 0$

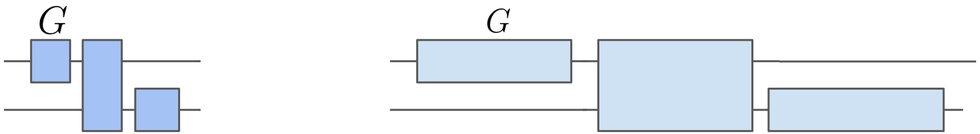
Hardware dynamics: $\lambda = 1$

Increase noise: $\lambda = 2$

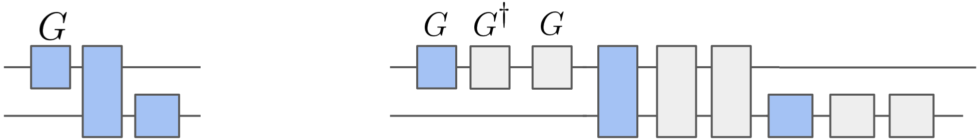
[1] K. Temme, S. Bravyi, and J. M. Gambetta, "Error Mitigation for Short Depth Quantum Circuits," Physical Review Letters,. **119**, 180509,(2017).

Analog and *digital* noise scaling methods for ZNE

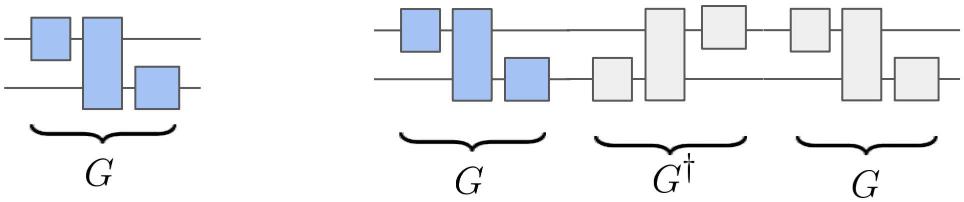
- Pulse stretching



- Local folding



- Global folding

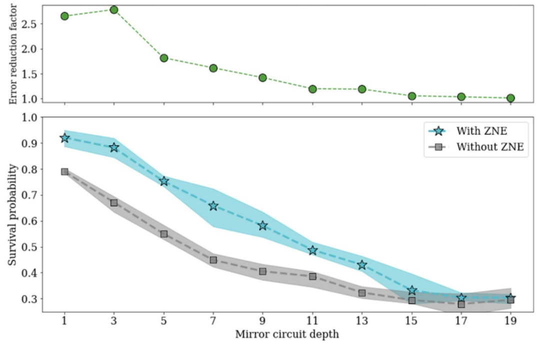


K. Temme, S. Bravyi, and J. M. Gambetta, "Error Mitigation for Short Depth Quantum Circuits," Physical Review Letters, vol. 119, p. 180509, 11 2017.

T. Giurgica-Tiron, Y. Hindy, R. LaRose, A. Mari, W. J. Zeng, *Digital zero noise extrapolation for quantum error mitigation*, 2020 IEEE International Conference on Quantum Computing and Engineering (QCE) (2020).

ZNE with Mitiq is used to improve results on hardware *now*

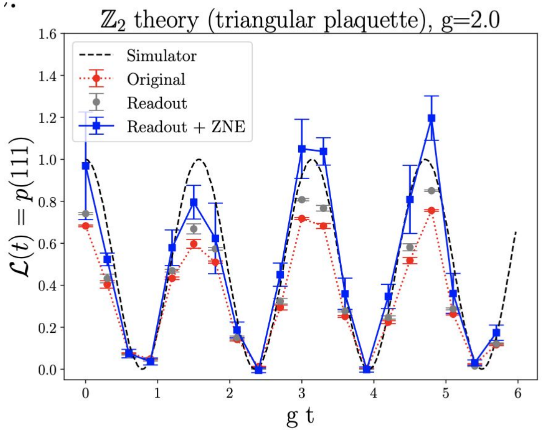
Mirror circuits on Rigetti (verbatim compilation)



(Top panel) Error reduction factors with zero-noise extrapolation (ZNE). (Bottom panel) Survival probability of two-qubit mirror circuits at increasing depths, with and without ZNE. Each marker is the average survival probability of four random mirror circuits, and the color bands mark the minimum and maximum survival probabilities.

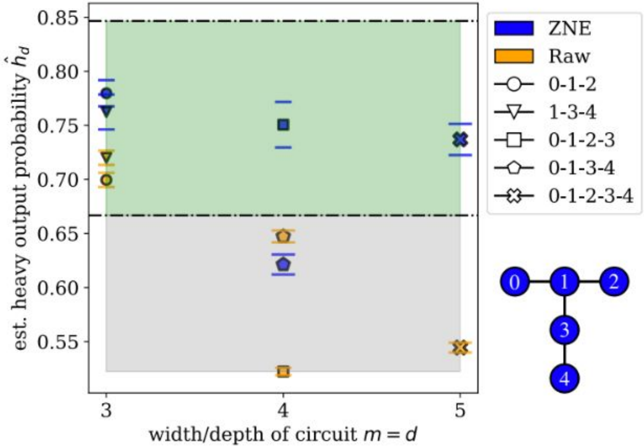
Exploring quantum error mitigation with Mitiq and Amazon Braket aws.amazon.com/blogs/quantum-computing

Quantum field theory models



Real-time dynamics of Plaquette Models using NISQ Hardware, E. Huffman *et al.* arxiv:2109.15065

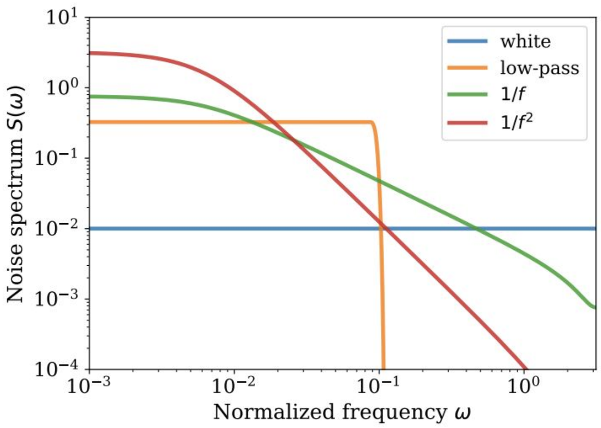
Effective quantum volume increase



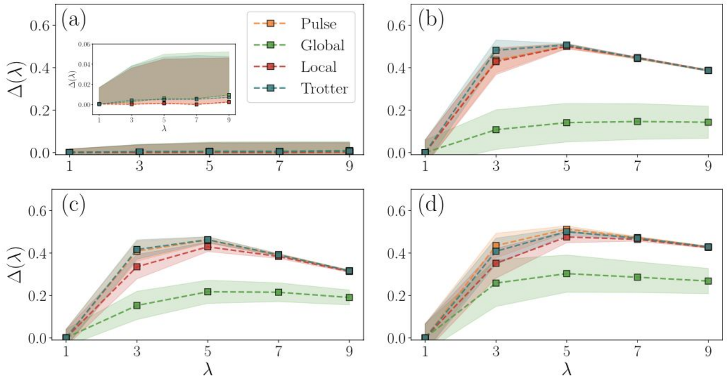
Error mitigation increases the effective quantum volume of quantum computers, R. LaRose *et al.* arxiv:2203.05489

Reducing the impact of time-correlated noise on ZNE

Colored noise spectra



Different noise-scaling methods



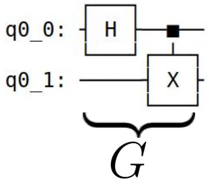
This is the first study testing the **robustness and reliability of ZNE** against **correlated noise** models. We perform a systematic survey with different noise scaling models.

Kevin Schultz, Ryan LaRose, Andrea Mari, Gregory Quiroz, Nathan Shammah, B. David Clader, William J. Zeng
arXiv:2201.11792

Example: noise scaling by *global folding* with Mitiq

```python
import qiskit

qubits = qiskit.QuantumRegister(2)
circuit = qiskit.QuantumCircuit(qubits)
circuit.h(0)
circuit.cnot(0, 1)

print(f"Original circuit: \n{circuit}")
```

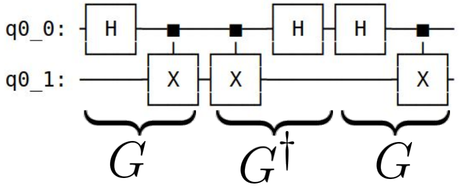
```
Original circuit:
```



$\lambda = 3$

```python
from mitiq.zne.scaling import fold_global

scaled_circuit = fold_global(circuit, scale_factor=3)

print(f"Globally scaled circuit: \n{scaled_circuit}")
```

```
Globally scaled circuit:
```

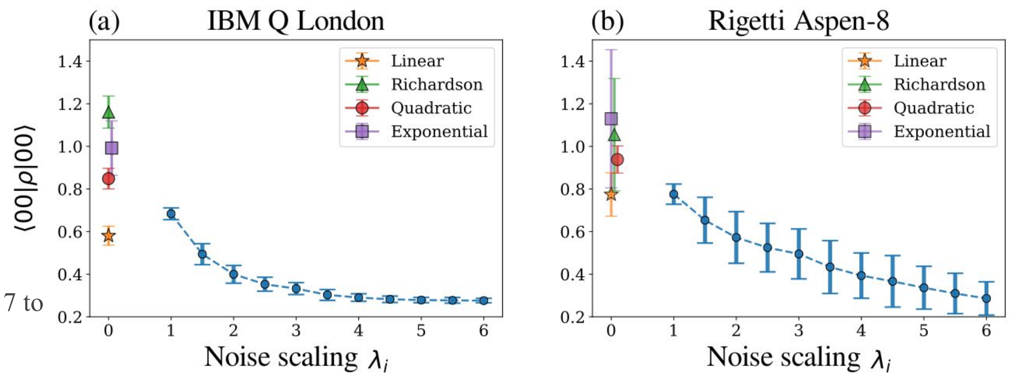


Example: Different extrapolation methods with `Factories`

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).

Quantum Error Mitigation: Outline

- Introduction to noise in quantum computing
- Motivation & overview of quantum error mitigation
- **More in-depth look: Zero-noise extrapolation & Mitiq**
- Unitary Fund, Open-source software, SQMS
- Conclusions

Quantum Error Mitigation: Outline

- Introduction to noise in quantum computing
- Motivation & overview of quantum error mitigation
- More in-depth look: Zero-noise extrapolation & Mitiq
- **Unitary Fund, Open-source software, SQMS**
- Conclusions

Unitary Fund

Unitary Fund is a 501(c)(3) non-profit helping create a quantum technology ecosystem that benefits the most people.

UF Microgrants

54 microgrants ($4k, no strings attached + mentorship) to awardees

- 22 countries
- 16 publications
- 30+ libraries w/ 1200+ stars, 50+ contributors, ~6k commits
- 2 startups, 1 non-profit

mitiq

Python toolkit for quantum error mitigation

Focus of this talk

metriq

Community-driven quantum computing benchmarks, **metriq.info**

The importance of benchmarking to test QEM technique effectiveness & characterize hardware

Workload

- GHZ circuits
- Randomized Benchmarking circuits
- Mirror circuits
- Quantum volume circuits
- …

Apply QEM Technique

- ZNE
- PEC
- CDR
- Dynamical Decoupling
- …

Apply to Backend

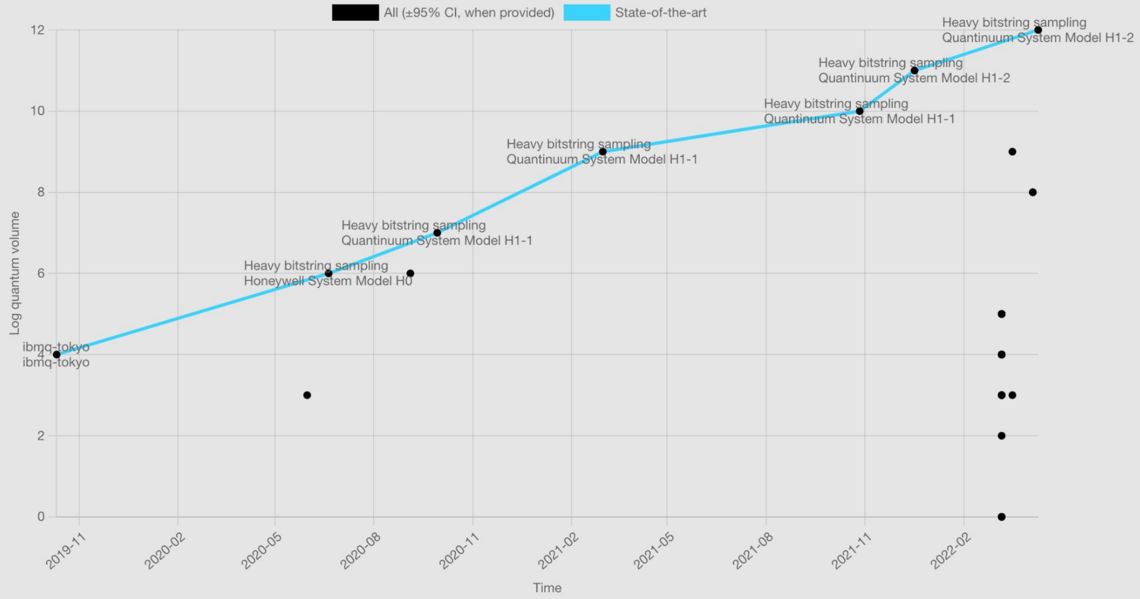
- IBM-Q QPU
- Rigetti QPU
- IonQ QPU
- Quantinuum QPU
- …

We could benefit from reproducible benchmarks, public/open-source (standard) datasets/codee, maintained QPUs

Community-driven quantum computing benchmarks, **metriq.info**

Chart Metric: Log quantum volume

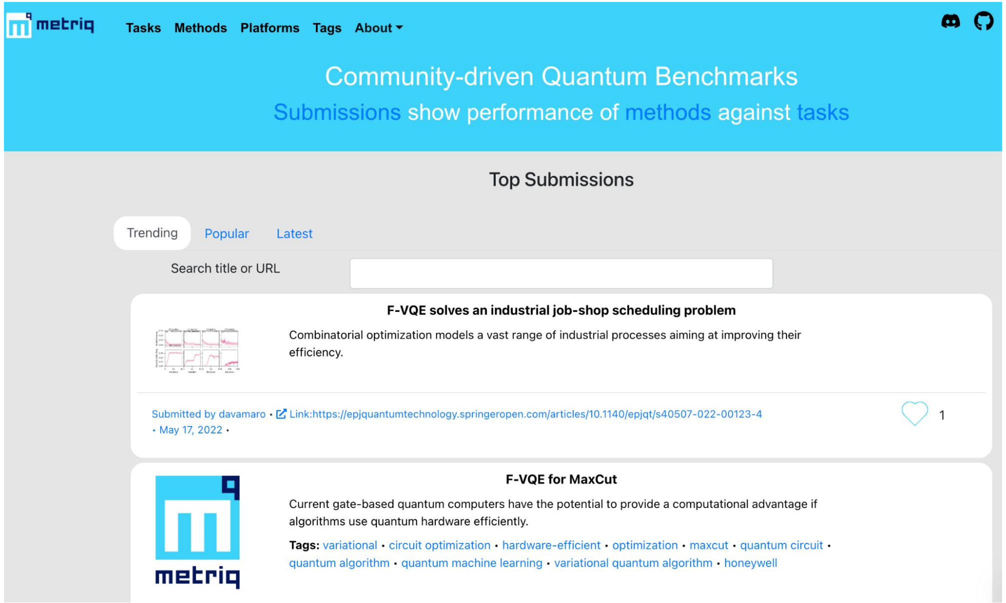
Logarithmic:

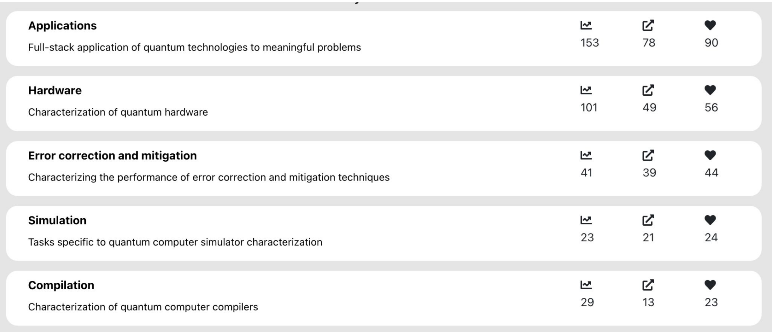


Quantum volume

Quantum volume (QV) is a benchmark for quantum computing hardware. It expresses the maximum size (quantum circuit depth n times number of qubits n) of square quantum circuits that can be implemented successfully by a quantum computer. Here the plotted value is n, also called log2(QV), since QV is given by 2^n.

Community-driven quantum computing benchmarks, **metriq.info**





Unitary Fund

Unitary Fund is a 501(c)(3) non-profit helping create a quantum technology ecosystem that benefits the most people.

QuTiP *10 years on!*
Quantum Toolbox in Python

Quantum simulation and simulation of QC circuits and devices (qutip-qip). More than 700,000 downloads qutip.org

Hackathon for open source quantum projects, over 30 participating projects, 66 bounties. unitaryhack.dev

Weekly community calls for OSS projects: Mitiq, QIR Alliance, QuTiP. Anyone can join. **discord.unitary.fund**

Unitary Fund Team

Team

Will Zeng, PhD
President. Head of Quantum Research at Goldman Sachs. Fmr. product/sw lead at **Rigetti**. Oxford quantum algorithms PhD.

Andrea Mari, PhD
Member of the technical staff
> 40 peer reviewed scientific publications. Contributor to **Pennylane**. Fmr. researcher at Xanadu. Univ. of Potsdam PhD in quantum information.

Dan Strano
Member of the technical staff
working on Metriq. Full stack web engineer. Lead developer on the **qrack** quantum simulator.

Nathan Shammah, PhD
CTO. Lead developer at **QuTiP**. Visiting scientist at RIKEN. PhD in quantum physics from Univ. of Southampton.

Misty Wahl
Member of the technical staff
working on Mitiq. Unitary Fund Ambassador. Fmr. SWE Proj. Leader at ASML.
MSc in Mech. Eng., Cornell.

Vincent Russo, PhD
Member of the technical staff
working on Metriq & Mitiq. Post-quantum security developer at ISARA. Lead dev on **toqito** quantum info package. PhD from UWaterloo.

Nate Stemen
Member of the technical staff
working on Mitiq. MSc in QC from U. Waterloo. Fmr. SWE @ Overleaf.

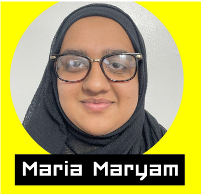
Frances Poblete
UI/UX Designer

Alowina Yap
Marketing specialist

Interns

QUBIT X QUBIT

B.A. student, CUNY



B.Sc. student, U of Maryland

Alumni

Sarah Kaiser, PhD
Microsoft.

Ryan LaRose, PhD
Postdoc at EPFL

Peter Karalekas
AWS Quantum

Unitary Fund Community

Ambassadors

ANDRE ALVES

MISTY WAHL

AARON ROBERTSON

PURVA THAKRE

Awardees Community

60+ grantees

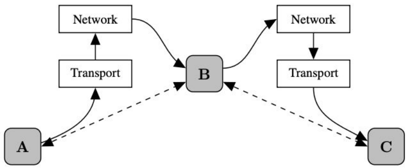
23 countries

Advisory Board

15 volunteer experts in quantum systems & software from:

QuNetSim

To Stephen DiAdamo to develop the first full featured software stack for quantum network protocols.



Stephen DiAdamo

Stephen is a research scientist at Cisco working on quantum networks and attends TU Munich for his PhD, as well as a former microgrant recipient for QuNetSim and Interlin-q.

Unitary Fund Supporters & Collaborators

Collaborators

Stanford University

Lawrence Livermore National Laboratory

APL The Johns Hopkins University APPLIED PHYSICS LABORATORY

DARTMOUTH

University of Maryland 1856

THE UNIVERSITY OF CHICAGO

Fermilab | SQMS

Supporters

iqt LABS

Core Members

IBM accenture

Supporting Members

BCG XANADU IONQ QM

PASQAL DoraHacks agnostiq

Other Supporters

rigetti Microsoft ZAPATA

PLOS CQC Cambridge Quantum Computing STRANGE WORKS EeroQ Quantum Hardware

QuTiP Community

Board Members

Anton Frisk Kockum

Chalmers University of Technology

Daniel Burgarth

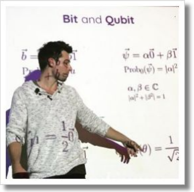
Macquarie University

Franco Nori

RIKEN / University of Michigan

Rob Johansson

Rakuten



Will Zeng

Unitary Fund

Admins

Neill Lambert, RIKEN

Alex Pitchford
Aberystwyth U.

Nathan Shammah
Unitary Fund

Eric Giguere
Sherbrooke U / Calcul Quebec

Shahnawaz Ahmed
Chalmers

Boxi Li, Jülich

Jake Lishman, IBM

Simon Cross, RIKEN

And other 100+ contributors on GitHub

Support

日本学術振興会 Japan Society for the Promotion of Science

JST Japan Science and Technology Agency

RIKEN

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

Unitary Fund

NUMFOCUS OPEN CODE = BETTER SCIENCE

Google Summer of Code

UNIVERSITÉ DE SHERBROOKE

PRIFYSGOL ABERYSTWYTH UNIVERSITY

Great open source software tools accelerate SQMS research

QIS Ecosystem

Maintaining OSS is hard, time consuming, and requires specific skills beyond research. The academic incentives are not yet aligned with this collaborative (vs. competitive) endeavor. Example: QuTiP.

Clear **request from open-source community for Unitary Fund**: Step-up the support of development of open source software.

SQMS Collaboration

Need to **share software internally – efficiently, written with best practices** – and will want to **maximize the impact of its results** have on the wider QIS community.

Researchers **need to build some computational and simulation tools from the ground up** and would benefit from tailored tools.

In the Quantum Information Science ecosystem, open-source software (OSS) for science plays a major role.

The SQMS collaboration is pioneering several new paths in QIS, such as multi-mode superconducting cavities.

Quantum Error Mitigation: Outline

- Introduction to noise in quantum computing
- Motivation & overview of quantum error mitigation
- More in-depth look: Zero-noise extrapolation & Mitiq
- **Unitary Fund, Open-source software, SQMS**
- Conclusions

Quantum Error Mitigation: Outline

- Introduction to noise in quantum computing
- Motivation & overview of quantum error mitigation
- More in-depth look: Zero-noise extrapolation & Mitiq
- Unitary Fund, Open-source software, SQMS
- **Conclusions**

Conclusions

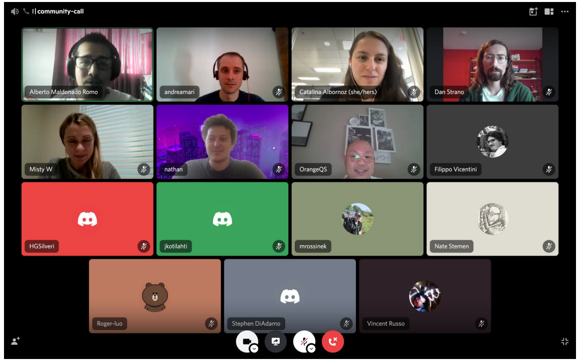
- Quantum error mitigation (**QEM**) can improve the **performance** of quantum programs *now*
- Quantum error mitigation will be a **critical** component in benchmarking for years to come
- Very **dynamic space** borrowing concepts from adjacent fields & testing new ideas
- A continuous bridge between QEM and quantum error correction, **NISQ & beyond**
- Cutting-edge QEM techniques need to be available to **non-experts** for fair **benchmarks**
- **Mitiq** is an open source software (OSS) with state-of-the-art QEM techniques
- **Unitary Fund** (SQMS) is supporting the growth of a quantum OSS ecosystem

Join the Unitary Fund & Mitiq community online

discord.unitary.fund Weekly community calls:

Mitiq Community Call: **Fridays**, 6pm CET / 12pm ET / 9am PT

Quantum Group Meeting: **Wednesdays**, 6:30pm CET/12:30pm ET

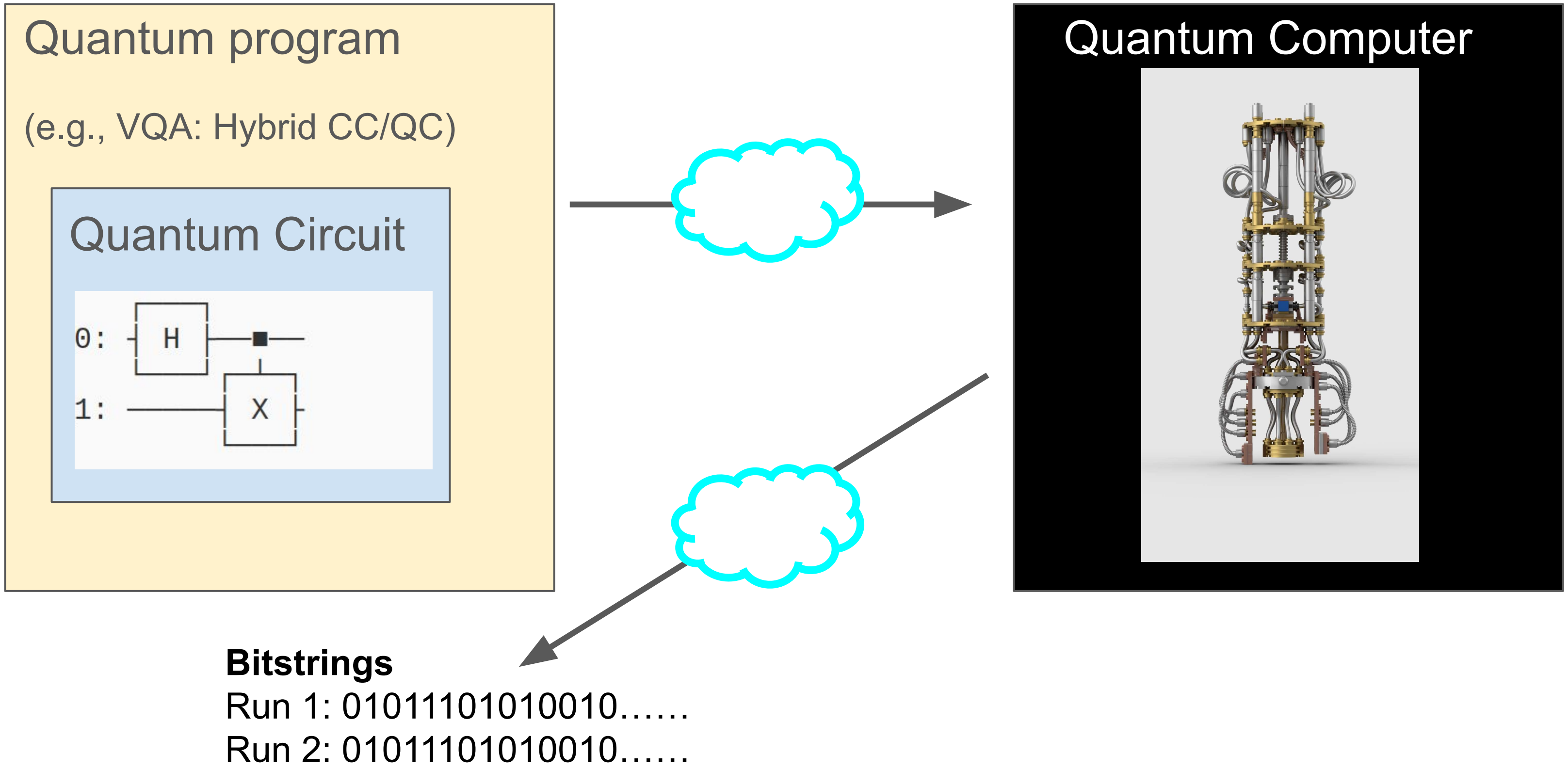


Nathan Shammah

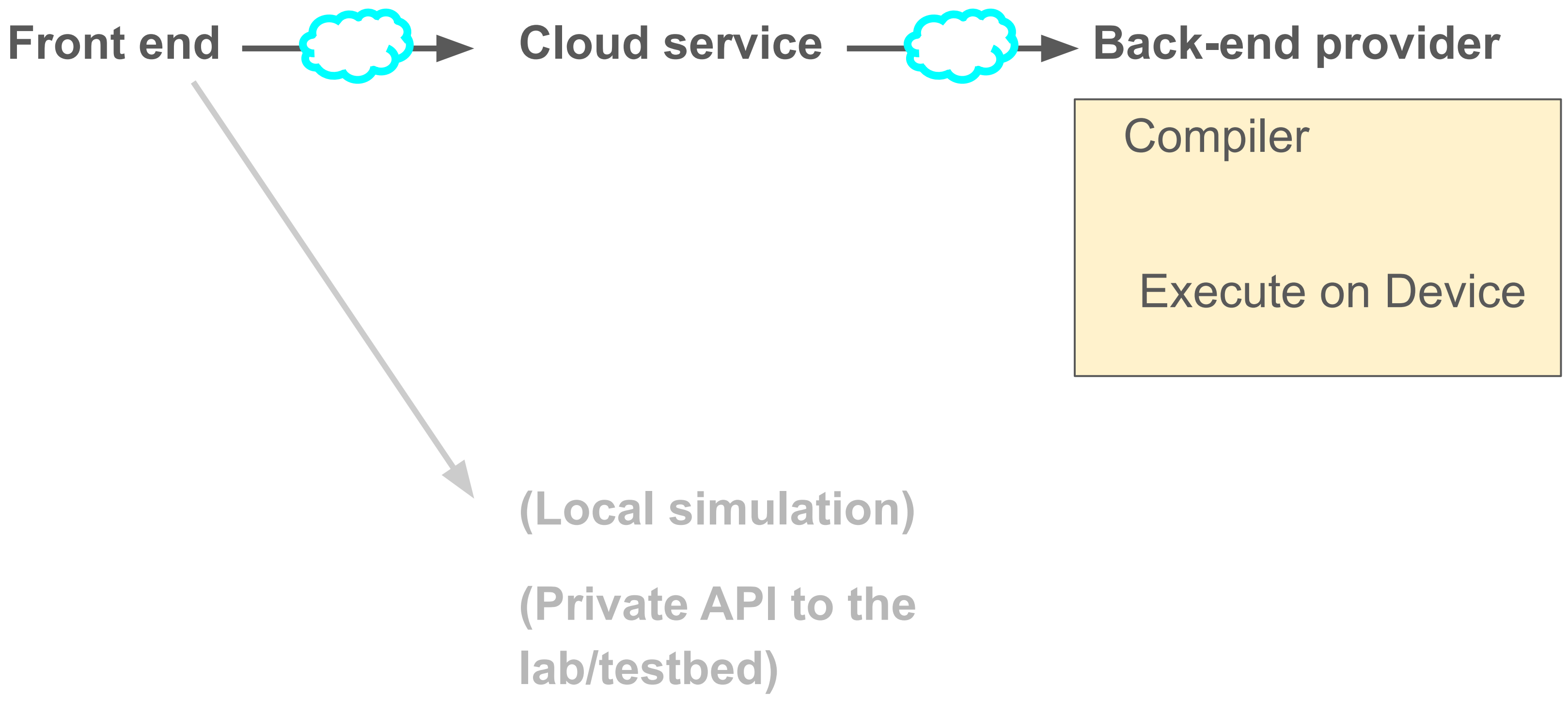
nathan@unitary.fund

Appendix

Running programs on quantum computers (or simulators)



Running programs on quantum computers (or simulators)



Quantum error mitigation: References

Summary of papers (not exhaustive)

Mitiq: A software package for error mitigation on noisy quantum computers Ryan LaRose, arxiv:2009.04417 accepted in Quantum (2022)

A. Mari, N. Shammah, and W. J. Zeng. Extending quantum probabilistic error cancellation by noise scaling. *Phys. Rev. A* 104, 052607, (2021)

A. Lowe et al., Unified approach to data-driven quantum error mitigation. *Phys. Rev. Res.* 3, 033098 (2021).

Y. Li and S.C. Benjamin. Efficient variational quantum simulator incorporating active error minimization. *Phys. Rev. X* 7, 021050 (2017).

K. Temme, S. Bravyi, and J. M. Gambetta. Error mitigation for short-depth quantum circuits. *Phys. Rev. Lett.* (2017).

A. Kandala, et al., Error mitigation extends the computational reach of a noisy quantum processor. *Nature*, 567, 491 (2019).

T. Giurgica-Tiron et al., Digital zero noise extrapolation for quantum error mitigation. (2020). arXiv:2005.10921.

Jinzhao Sun, et al, Mitigating realistic noise in practical noisy intermediate-scale quantum devices. *Phys. Rev. Appl.* 15, 034026 (2021).

R. Takagi. Optimal resource cost for error mitigation. *Phys. Rev. Res.*, (2021)

S. Zhang, et al., Error-mitigated quantum gates exceeding physical fidelities in a trapped-ion system. *Nature Communications*, (2020)

P. Czarnik et al., Error mitigation with Clifford quantum-circuit data. *Quantum* 5, 592, (2021)

L. Viola, E. Knill, and S. Lloyd. Dynamical decoupling of open quantum systems. *Phys. Rev. Lett.* 82, 2417 (1999)

L. Viola and S. Lloyd. Dynamical suppression of decoherence in two-state quantum systems. *Phys. Rev. A* 58, 2733 , (1998).

J. Zhang, *et al.,* Protected quantum computing: interleaving gate operations with dynamical decoupling sequences. *Phys. Rev. Lett.*, 112:050502, (2014)

J. J. Wallman and Joseph Emerson. Noise tailoring for scalable quantum computation via randomized compiling. *Phys. Rev. A* 94, 052325, (2016).

B. Pokharel et al., Demonstration of fidelity improvement using dynamical decoupling with superconducting qubits. *Phys. Rev. Lett.*, 121:220502, (2018).

Chen *et al.*, Exponential suppression of bit or phase errors with cyclic error correction. *Nature*, 595 383, (2021)

K. N. Smith et al., Error Mitigation in Quantum Computers through Instruction Scheduling. (2021). arXiv:2105.01760.

P. Das *et al.* Adapt: mitigating idling errors in qubits via adaptive dynamical decoupling., MICRO '21, 950 (2021).

R. M. Parrish, *et al.*. Quantum computation of electronic transitions using a variational quantum eigensolver. *Phys. Rev. Lett.* **122**, 230401, (2019)

P. J. J. O'Malley, *et al.,* Scalable quantum simulation of molecular energies. *Phys. Rev. X* **6**, 031007 (2016).

T. Proctor et al.. Measuring the capabilities of quantum computers. *Nature Physics*, 18, 75 (2021).

A. Strikis, *et al.*. Learning-based quantum error mitigation. *PRX Quantum*, (2021).

S. Endo *et al.,* Hybrid quantum-classical algorithms and quantum error mitigation. *J. Phys. Soc. Japan*, 90, 032001, (2021)

E. Knill. Quantum computing with realistically noisy devices. *Nature*, 434(7029):39–44, (2005)

S. Endo et al.. Practical quantum error mitigation for near-future applications. *Phys. Rev. X* 8, 031027, (2018)

S. Zhang, *et al.,* Error-mitigated quantum gates exceeding physical fidelities in a trapped-ion system. *Nature Commun.*, (2020)

J. R. McClean, *et al.*. Hybrid quantum-classical hierarchy for mitigation of decoherence and determination of excited states. *Phys. Rev. A* **95**, 042308, (2017)

X. Bonet-Monroig, *et al*. Low-cost error mitigation by symmetry verification. *Phys. Rev. A* **98**, 062339, (2018)

J. R. McClean, et al., Decoding quantum errors with subspace expansions. *Nature Communications*, (2020).

R. Sagastizabal, *et al.,*. Experimental error mitigation via symmetry verification in a variational quantum eigensolver. *Phys. Rev. A*, 100:010302, (2019)

Loock. Approximate quantum error correction for generalized amplitude-damping errors. *Phys. Rev. A* 89, 022316, (2014)

Probabilistic Error Cancellation

Typical step of many quantum algorithms: **estimating expectation values**.

Ideal expectation value

Observable

Initial state

$$\langle A \rangle_{\text{ideal}} = \text{tr}[A\mathcal{U}(\rho_0)],$$

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

Ideal gates (local unitary operations)

Unfortunately, we cannot apply an ideal gate with a NISQ device, but...
we can **represent** it as a linear combination of noisy gates!

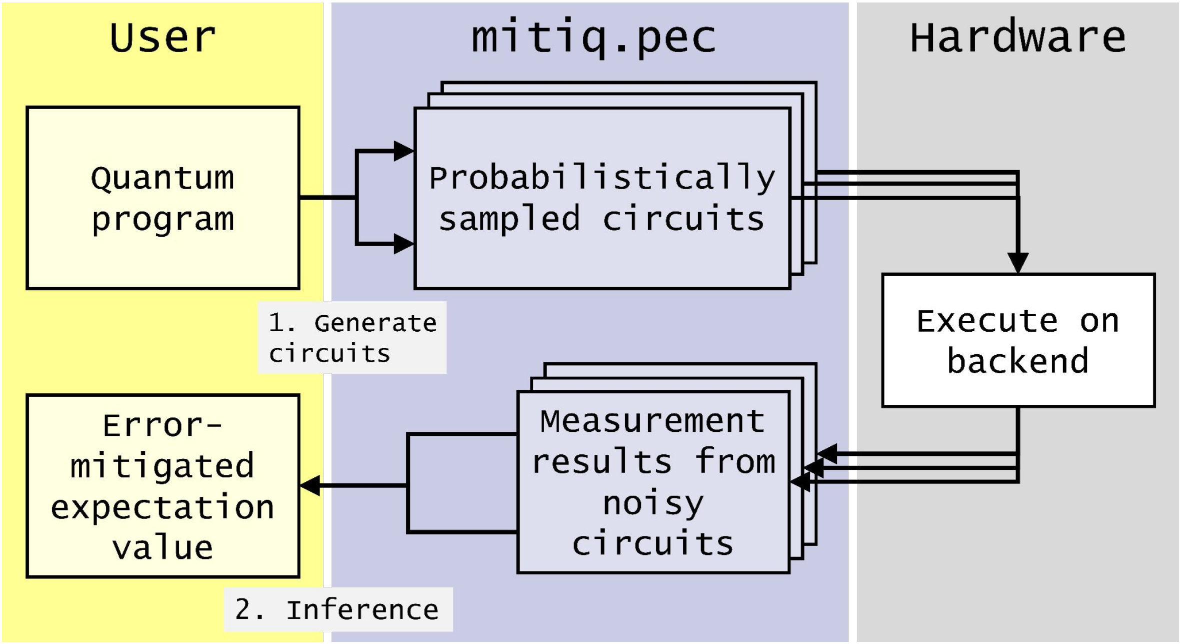
$$\mathcal{G}_i = \sum_\alpha \eta_{i,\alpha} \mathcal{O}_{i,\alpha},$$

Quasi-probability (can have negative values)

Implementable noisy gates

K. Temme, S. Bravyi, and J. M. Gambetta, "Error Mitigation for Short Depth Quantum Circuits," Phys. Rev. Lett. **119**, 180509 (2017).

Probabilistic Error Cancellation workflow with Mitiq



Probabilistic Error Cancellation with Mitiq

Defining `mitiq.OperationRepresentation` objects:

```
import qiskit

ideal_operation = qiskit.QuantumCircuit(1)
ideal_operation.h(0)

print(f"Ideal operation: \n{circuit}")
```

```
Ideal operation:
     ┌───┐
q_0: ┤ H ├
     └───┘
```

$\mathcal{G}_i$

```
from mitiq.pec.representations import represent_operation_with_local_depolarizing_noise

rep = represent_operation_with_local_depolarizing_noise(ideal_operation, noise_level=0.1)

print(rep)
```

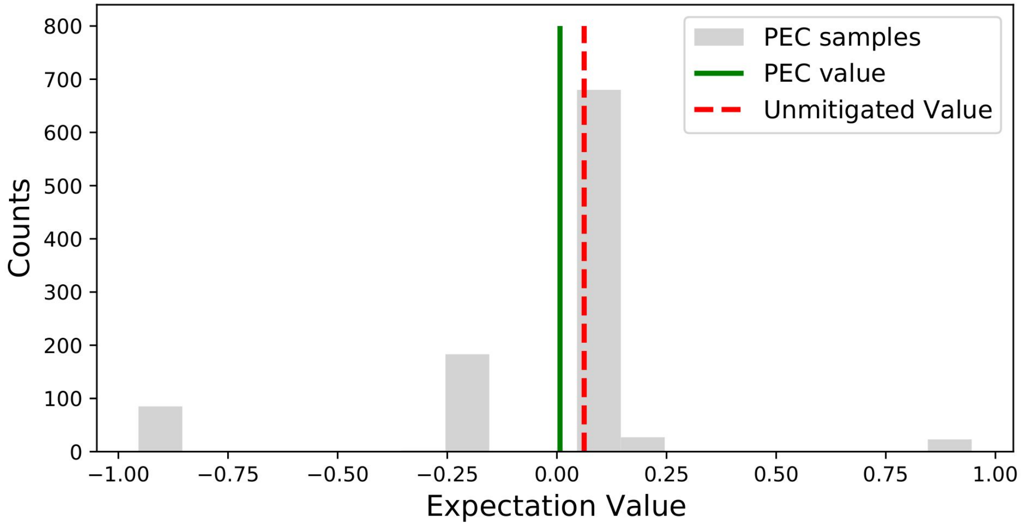
```
q_0: ──H── = 1.115*(q_0: ──H──)-0.038*(q_0: ──H──X──)-0.038*(q_0: ──H──Y──)-0.038*(q_0: ──H──Z──)
```

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

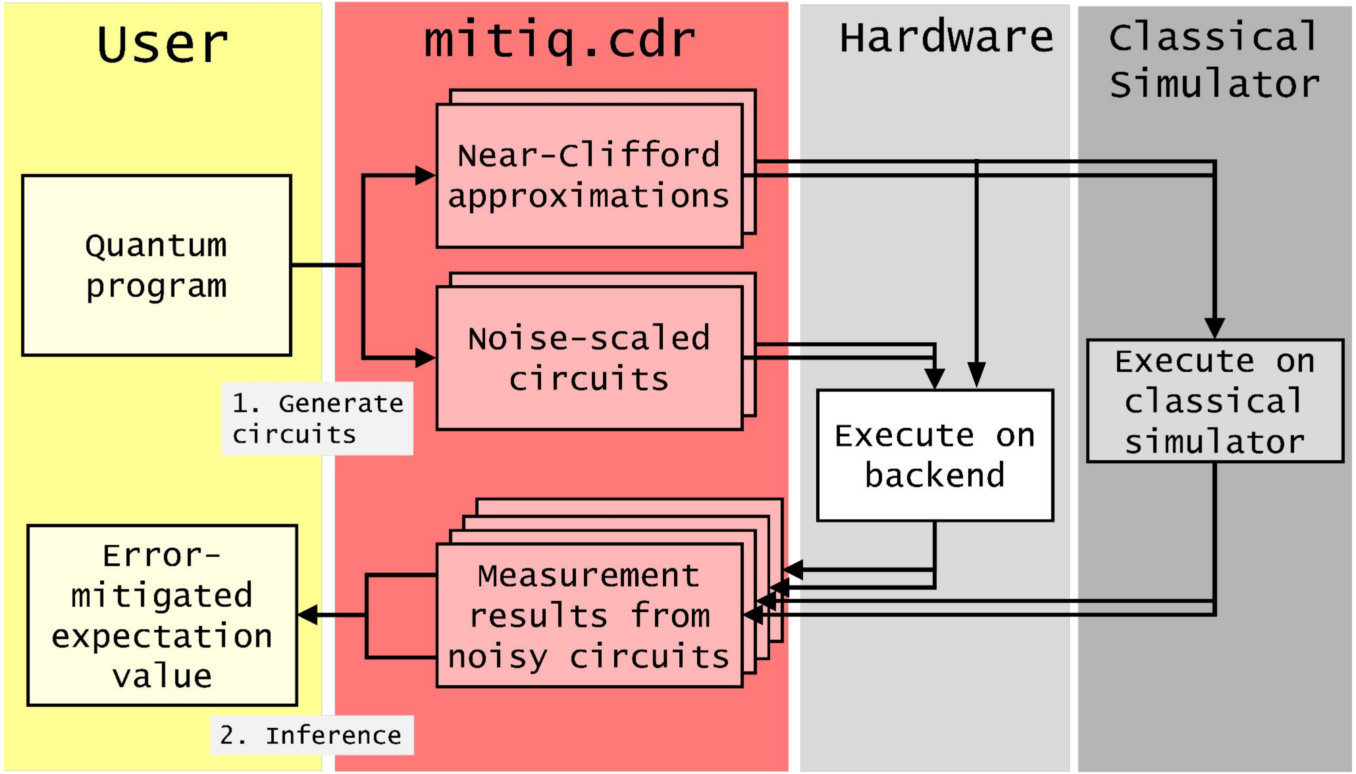
Probabilistic Error Cancellation with Mitiq

Beyond expectation values: analysis of **raw data**

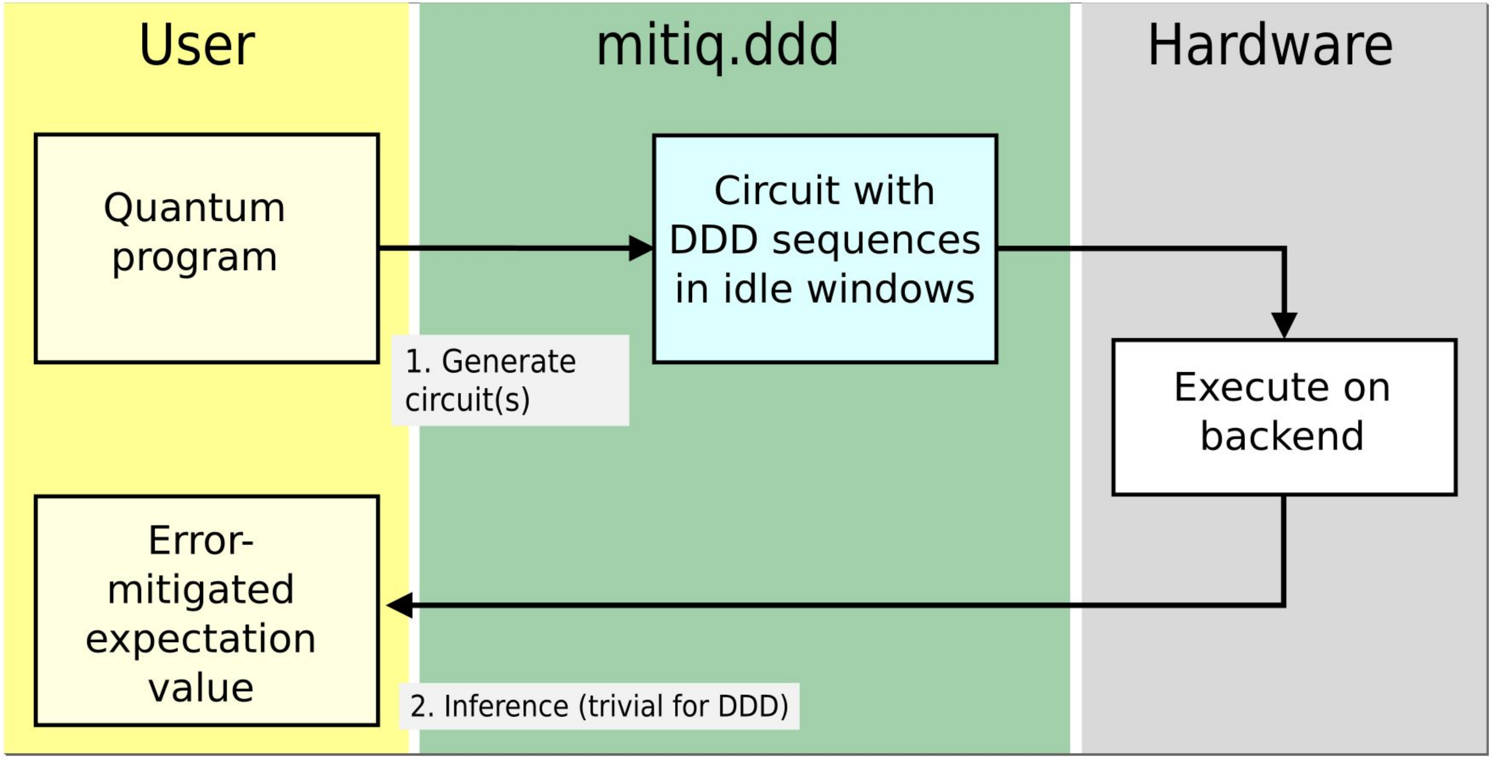
```
from mitiq.pec import execute_with_pec

pec_value, pec_data = execute_with_pec(ideal_circuit, noisy_executor, representations, full_output=True)
```



(Variable-noise) Clifford Data Regression workflow with Mitiq



Digital Dynamical Decoupling workflow in Mitiq



Clifford Data Regression

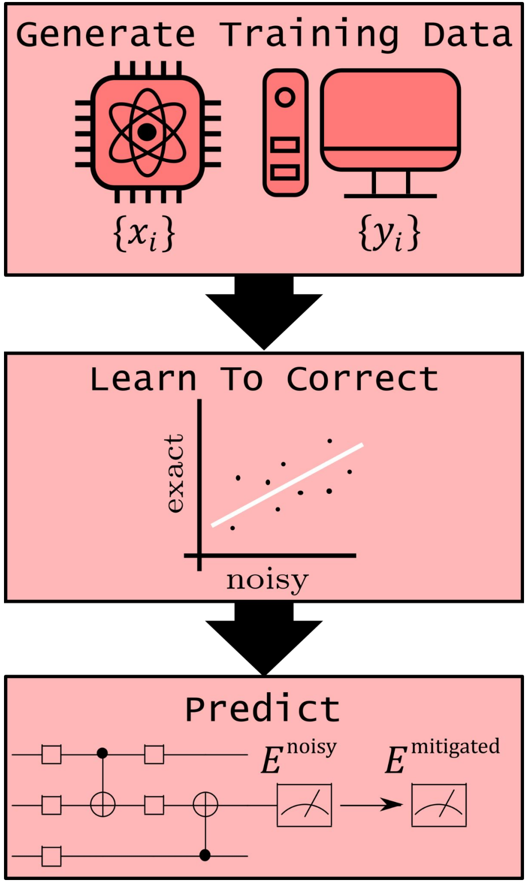
1. Construct the training circuits corresponding to states $\{\rho_i^{\text{train}}, i = 1, \ldots, n_{train}\}$ by replacing non-Clifford gates in the circuit of interest by Clifford gates.

2. For each training circuit ρ_i^{train} evaluate classically a noiseless expectation value E, $y_i = \mathrm{Tr}\rho_i E$, and its noisy expectation value x_i using a quantum computer.

3. Fit exact and noisy expectation values of the training circuits $\{(x_i, y_i)\}$ with a linear model $y = ax+b$.

4. Use the fitted model to correct $\langle E(\gamma_0)\rangle$

$$\langle E\rangle^{\text{mitigated}} = a\langle E(\gamma_0)\rangle + b.$$



P. Czarnik, A. Arrasmith, P. J. Coles, L. Cincio, "Error mitigation with Clifford quantum-circuit data", arXiv:2005.10189, (2020).
A. Lowe, M. Hunter Gordon, P. Czarnik, A. Arrasmith, P. J. Coles, . Cincio, "Unified approach to data-driven quantum error mitigation", Phys. Rev. Research 3, 033098 (2021)

Digital Dynamical Decoupling in Mitiq

The circuit mask

A quantum circuit can be visualized as a 2D grid where the horizontal axis represents discrete time steps (often called moments) and the vertical axis represents the qubits of the circuit. Each gate occupies one or more grid cells, depending on the number of qubits it acts on.

This 2D grid is essentially what we get each time we print a circuit out.

```
from cirq import Circuit, X, SWAP, LineQubit

qreg = LineQubit.range(8)
x_layer = Circuit(X.on_each(qreg))
cnots_layer = Circuit(SWAP.on(q, q + 1) for q in qreg[:-1])
circuit = x_layer + cnots_layer + x_layer
circuit
```

```
0: ───X───×───────────────────────────X───
          │
1: ───X───×───×───────────────────────X───
              │
2: ───X───────×───×───────────────────X───
                  │
3: ───X───────────×───×───────────────X───
                      │
4: ───X───────────────×───×───────────X───
                          │
5: ───X───────────────────×───×───────X───
                              │
6: ───X───────────────────────×───×───X───
                                  │
7: ───X───────────────────────────×───X───
```

Inserting DDD sequences

The DDD error mitigation technique consists of filling the slack windows of a circuit with DDD gate sequences. This can be directly achieved via the function `insert_ddd_sequences()` function.

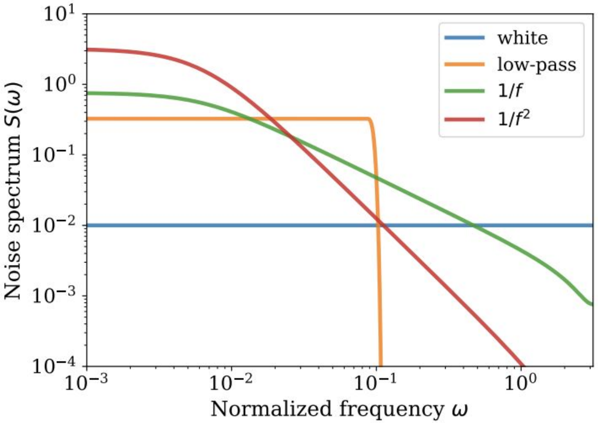
```
xyxy_rule = ddd.rules.xyxy
circuit_with_ddd = ddd.insert_ddd_sequences(circuit, rule=xyxy_rule)
circuit_with_ddd
```

```
0: ───X───×───I───X───Y───X───Y───I───X───
          │
1: ───X───×───×───I───X───Y───X───Y───X───
              │
2: ───X───────×───×───X───Y───X───Y───X───
                  │
3: ───X───────────×───×───────────────X───
                      │
4: ───X───────────────×───×───────────X───
                          │
5: ───X───X───Y───X───Y───×───×───────X───
                              │
6: ───X───I───X───Y───X───Y───×───×───X───
                                  │
7: ───X───I───X───Y───X───Y───I───×───X───
```

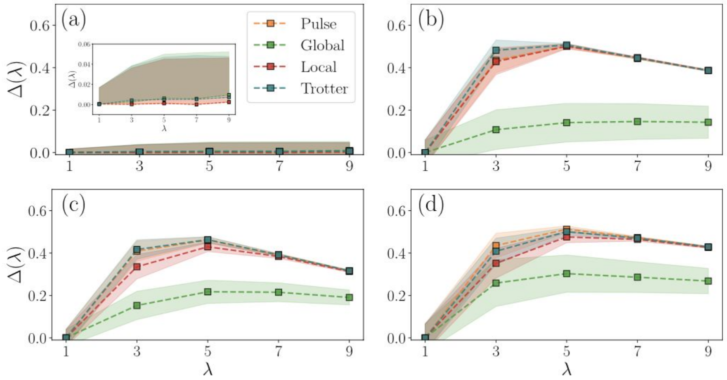
AARON ROBERTSON

Reducing the impact of time-correlated noise on ZNE

Colored noise spectra



Different noise-scaling methods

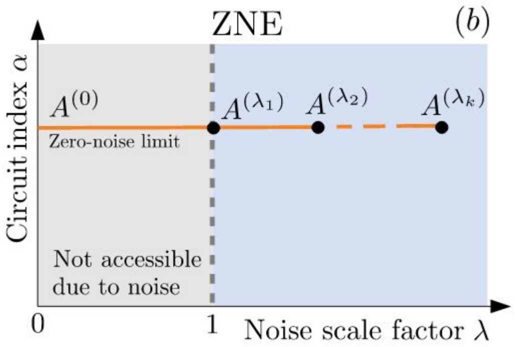


This is the first study testing the **robustness and reliability of ZNE** against **correlated noise** models. We perform a systematic survey with different noise scaling models.

Kevin Schultz, Ryan LaRose, Andrea Mari, Gregory Quiroz, Nathan Shammah, B. David Clader, William J. Zeng
arXiv:2201.11792

ZNE in a general framework

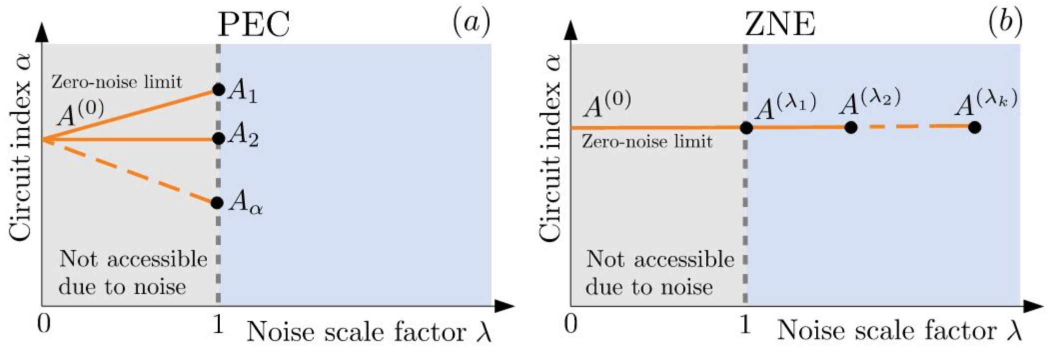
Zero Noise Extrapolation



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

PEC in a general framework

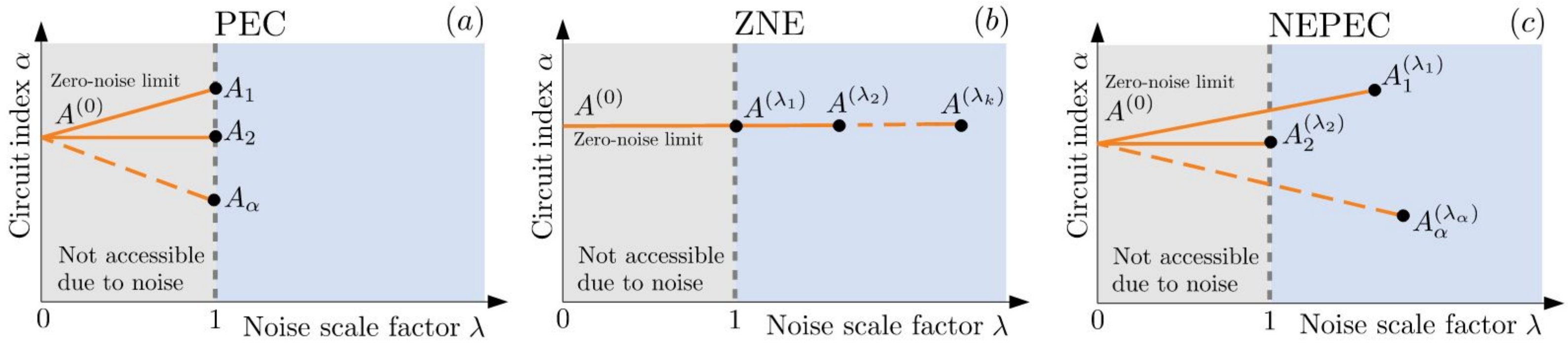
Probabilistic Error Cancellation



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

NEPEC: a general framework for error mitigation

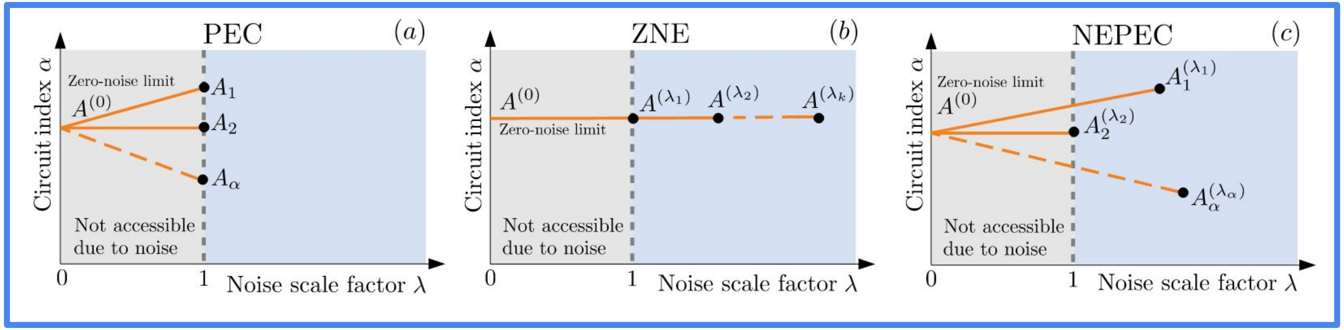
Noise-extended Probabilistic Error Cancellation (NEPEC)



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

NEPEC: a general framework for error mitigation

Noise-extended Probabilistic Error Cancellation (NEPEC)



NEPEC quasi-probability representation

$$\mathcal{G}_i = \sum_{\alpha,\lambda} \eta_{i,\alpha,\lambda} \mathcal{O}_{i,\alpha}^{(\lambda)}, \quad \mathcal{O}_{i,\alpha}^{\lambda} \in \tilde{\mathcal{I}}, \quad \eta_{i,\alpha,\lambda} \in \mathbb{R},$$

Ideal gate

Gate index (PEC-like)

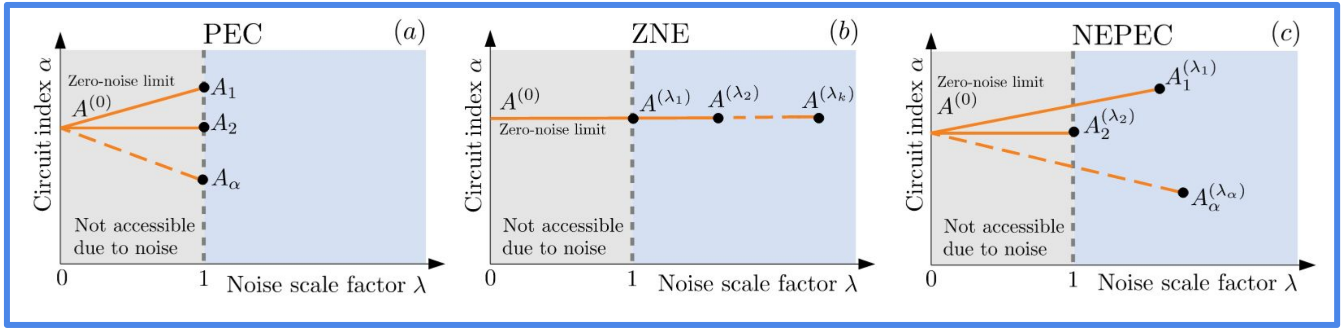
Noise scale factor (ZNE-like)

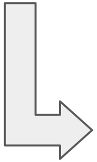
Set of implementable operations extended by noise scaling

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

Applying NEPEC with Mitiq

Research idea





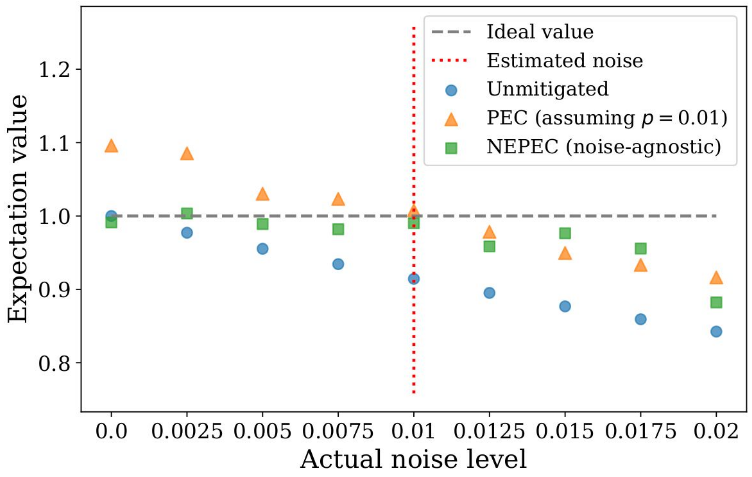
Implementation with Mitiq (for mode details: https://github.com/unitaryfund/research/nepec/)

```
# Examples
q = LineQubit(0)
print(represent_operation_with_nepec(Circuit(X(q)), scale_factors=[1, 3]))
print(represent_operation_with_nepec(Circuit(Y(q)), scale_factors=[1, 7]))
print(represent_operation_with_nepec(Circuit(Z(q)), scale_factors=[1, 3, 5]))
```

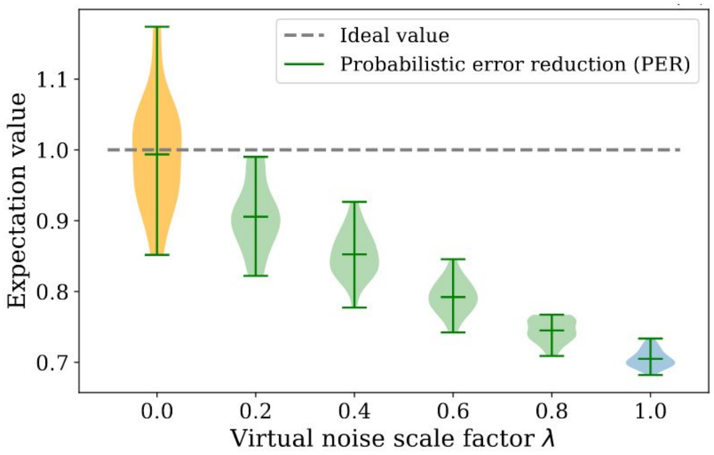
```
0: ───X─── = 1.500*0: ───X───-0.500*0: ───X───X───X───
0: ───Y─── = 1.167*0: ───Y───-0.167*0: ───Y───Y───Y───Y───Y───Y───Y───
0: ───Z─── = 1.875*0: ───Z───-1.250*0: ───Z───Z───Z───+0.375*0: ───Z───Z───Z───Z───Z───
```

NEPEC: Results of different NEPEC techniques

Noise-agnostic PEC



Virtual noise scaling



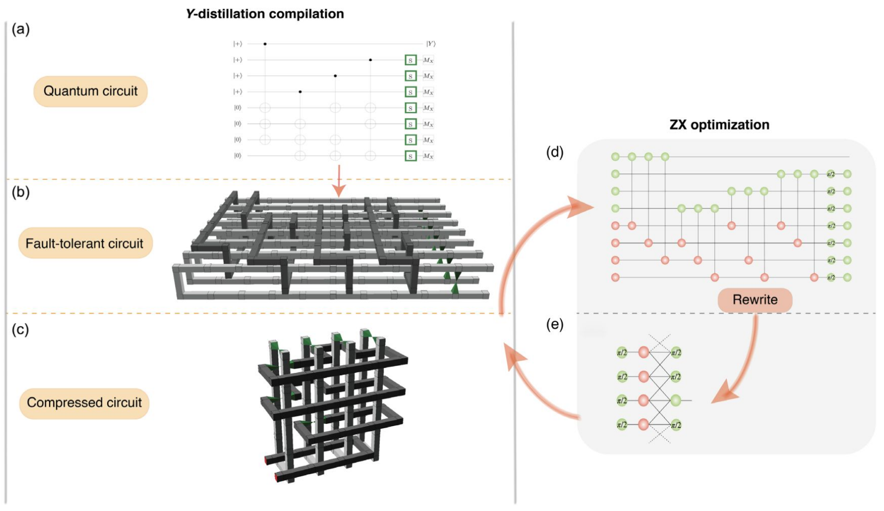
A. Mari, N. Shammah, and W. J. Zeng, Phys. Rev. A 104, 052607 (2021). arXiv:2108.02237

Microgrants: Funded software accelerate research

`PyZX`: compress quantum programs efficiently with ZX calculus

Example of a PRX paper by other authors using PyZX to accelerate their research

EFFECTIVE COMPRESSION OF QUANTUM BRAIDED CIRCUITS … PHYS. REV. X **10,** 041030 (2020)



aided tools. We found it helpful to put several of the larger circuits through an initial round of automated reduction with PyZX, an open source PYTHON library designed to reduce, validate, and visualize ZX-calculus diagrams [36]. PyZX applies a recursive, greedy algorithm [37]. Though the strategy of the PyZX library achieves significant reductions, it does not necessarily take into account the additional gate costs mentioned above (for instance, the reduced graphs of PyZX tend to have many Hadamard gates). Nonetheless, having reduced the overall graph size, it became feasible in isolation to tackle the $\pi/4$, $\pi/8$, and Hadamard gates by hand.

https://journals.aps.org/prx/abstract/10.1103/PhysRevX.10.041030

QuTiP | Google Summer of Code 2022

QuTiP has participated very successfully in Google Summer of Code for the last three years, and we are once again participating in Google Summer of Code 2022.

Check out the exciting projects our students have!

- QuTiP Notebook CI Testing & v5 update | Christian | *https://christian512.github.io*
- QuTiP Benchmarks | Xavier | *https://xspronken.github.io*
- QuTiP-QiP as a Qiskit backend | Shreyas | *https://medium.com/@claretgrace0801/the-qiskit-skeleton-8f228f2d731e*

Mentors: Alex, Boxi, Eric, Jake, Nathan, Neill, Simon
Chat with us on the Unitary Fund Discord server at the #qutip channel.