Enabling High Performance Debugging for Variational Quantum Algorithms using Compressed Sensing

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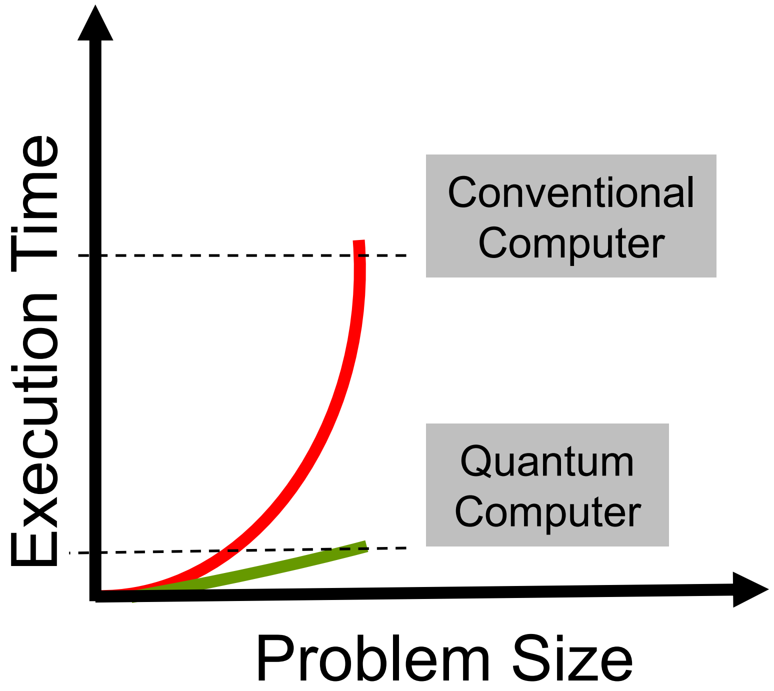
Quantum Computing

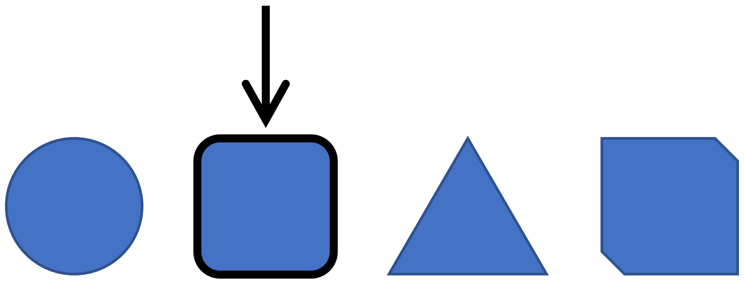
Provide speed up using
properties of qubits



15 = 3 x 5

Find prime factors

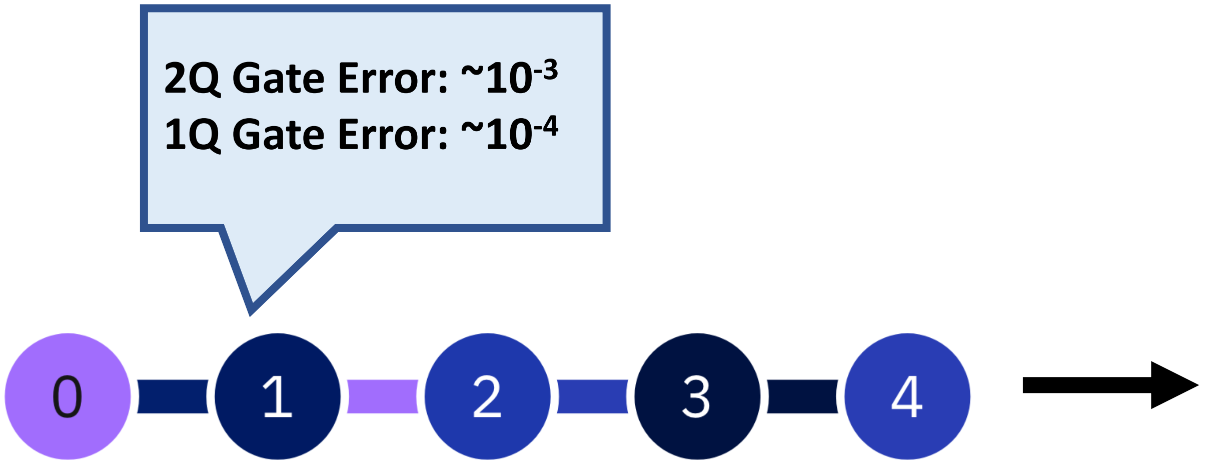
exponential speedup



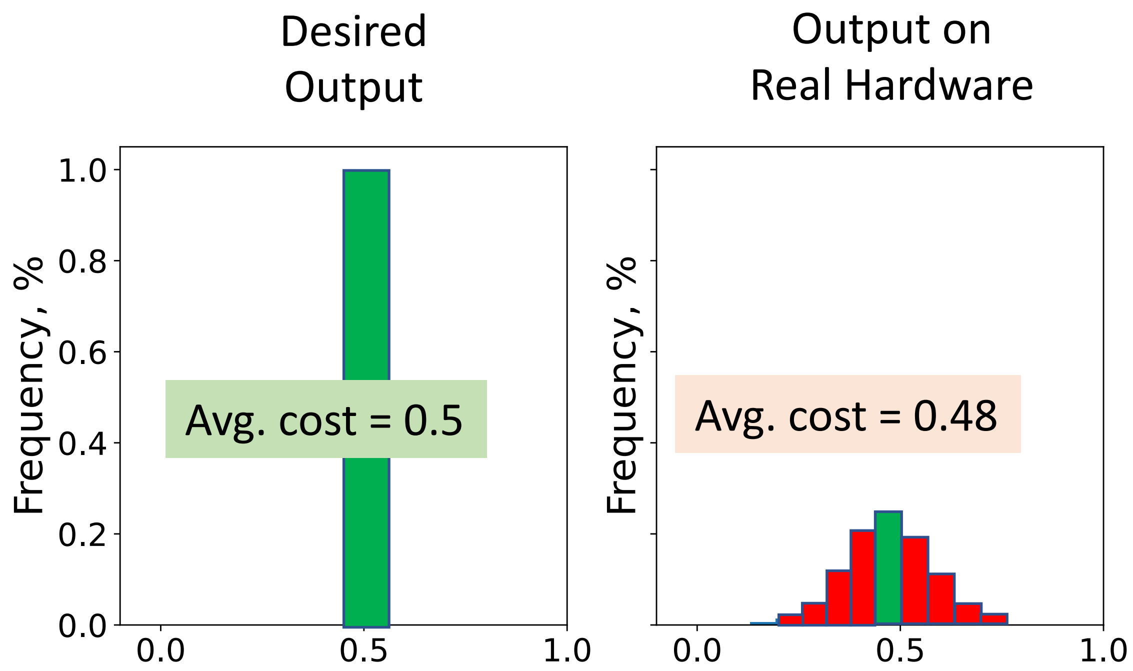
Unstructured search

quadratic speedup

Noisy and limited in number of qubits



A quantum computer with 5 qubits

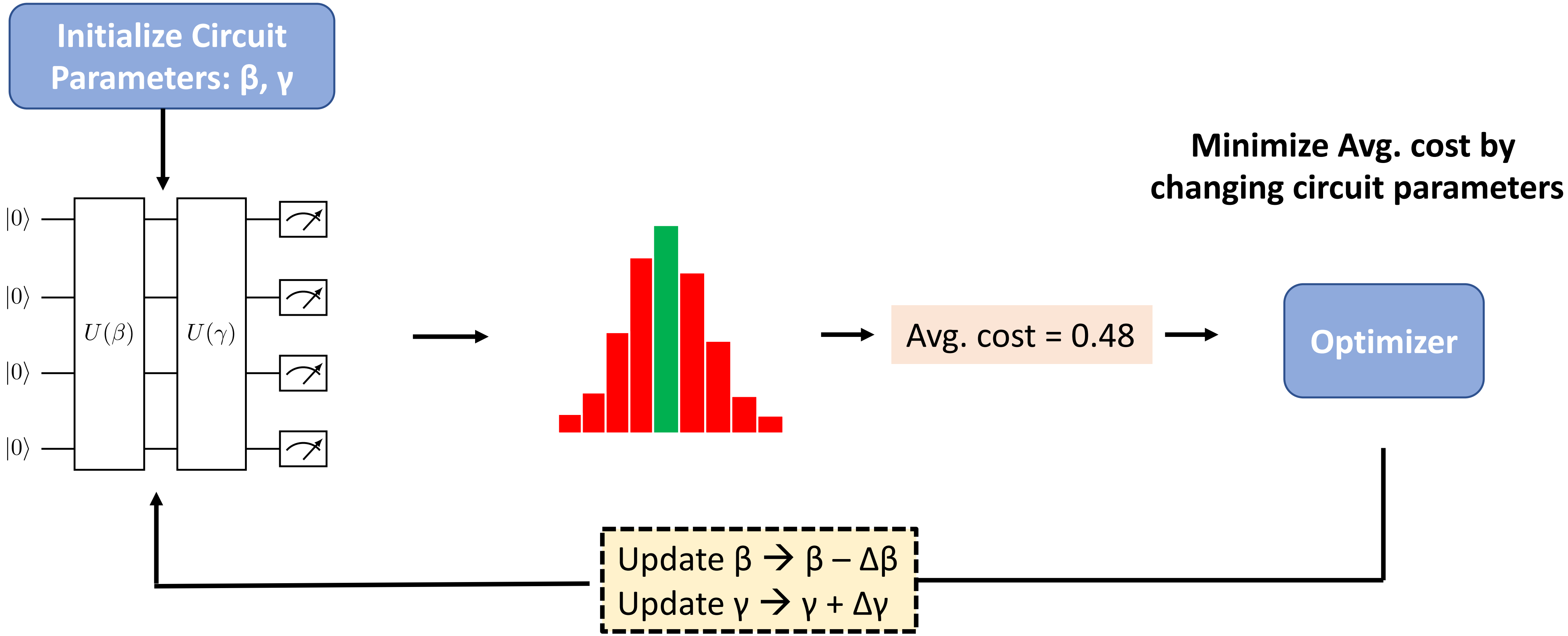


Noisy Intermediate Scale Quantum Computers (NISQ)

→ No Error Correction, learn to live with errors

Variational Quantum Algorithms (VQAs)

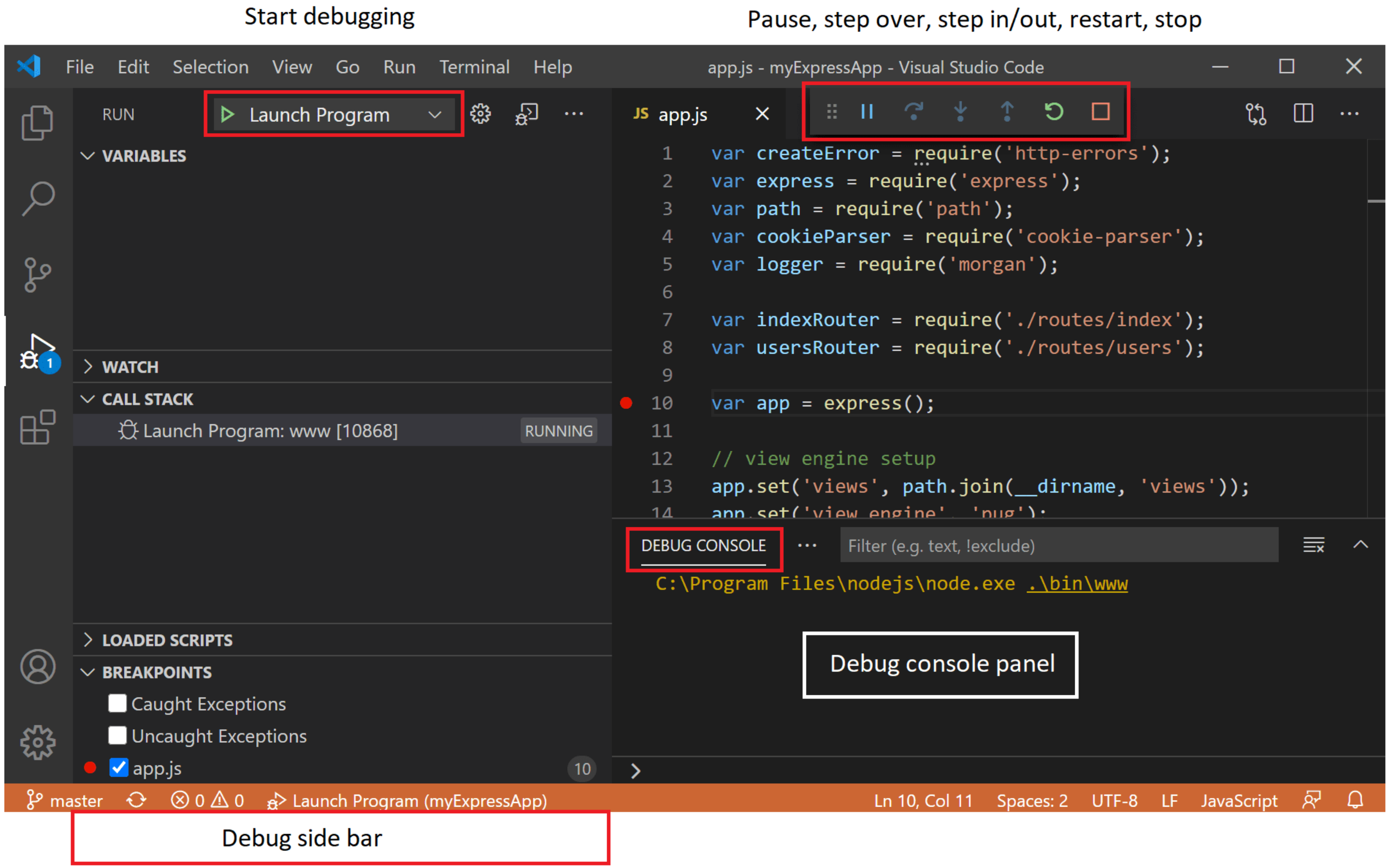
VQAs use parametric quantum circuits to calculate average cost and use optimization loop to tune the circuit parameters



Debugging Classical Programs

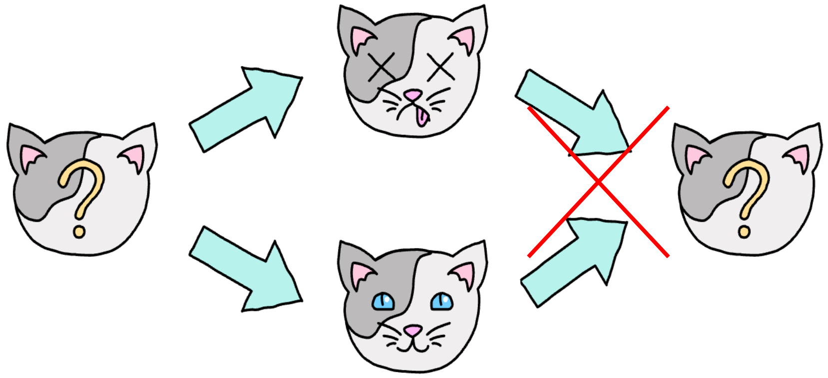
```
variable = ...
print(variable)
...
```

We cannot easily transfer these to the quantum world!



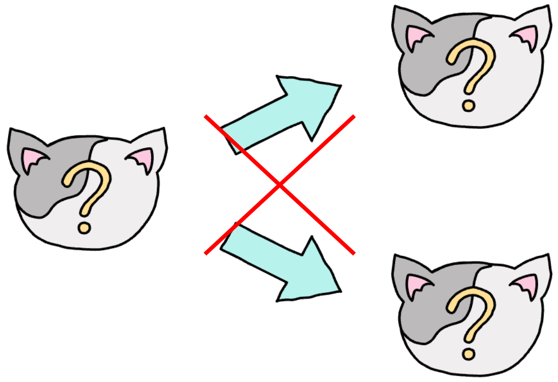
Source: https://code.visualstudio.com/docs/editor/debugging

Challenges in Debugging Quantum Circuits



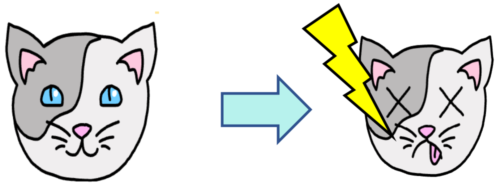
Destructive reads

Reading qubit destroys the state



No cloning theorem

Copying qubit state not allowed

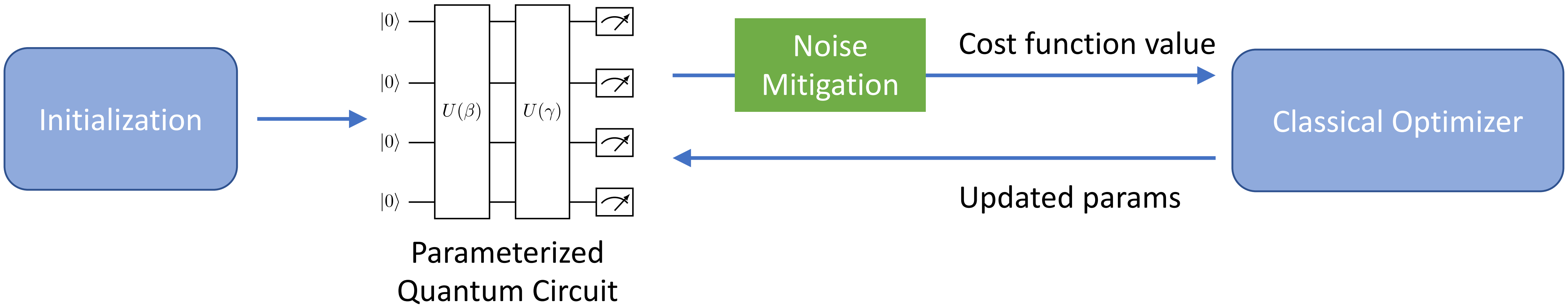


Hardware errors

Hardware errors introduce uncertainty

Source: https://pennylane.ai/images/qml/whatisqml/quantum_computing_neural_network.svg, modified

Challenges in debugging VQA workflows



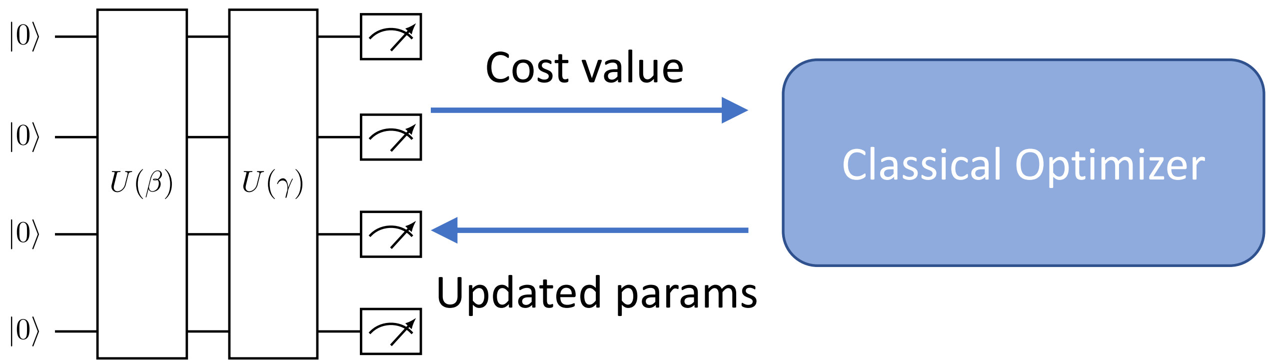
For a successful VQA run, we need:

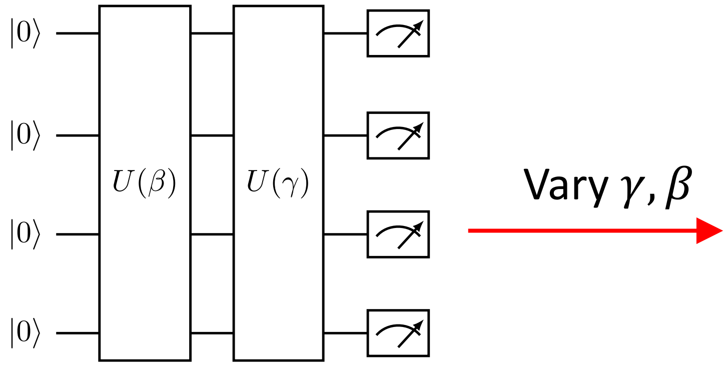
1. Right initialization for circuit parameters
2. Appropriate noise mitigation methods
3. Suitable classical optimizer configurations

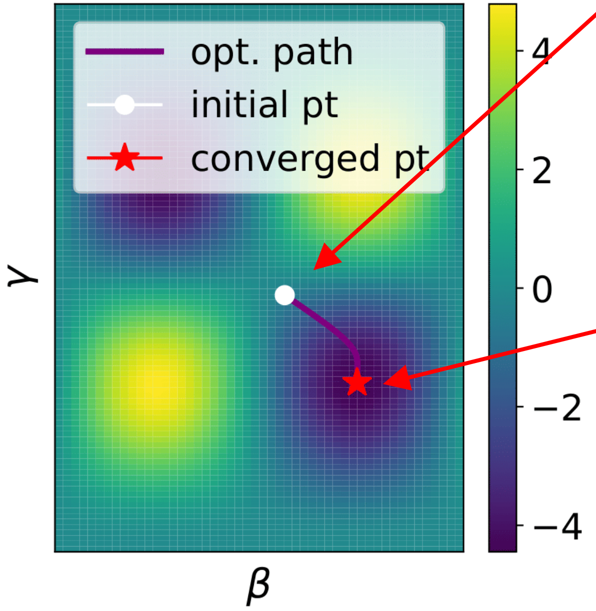
So, if there is a problem, it is hard to know the cause.

What's worse, debugging VQAs is challenging due to its quantum nature.

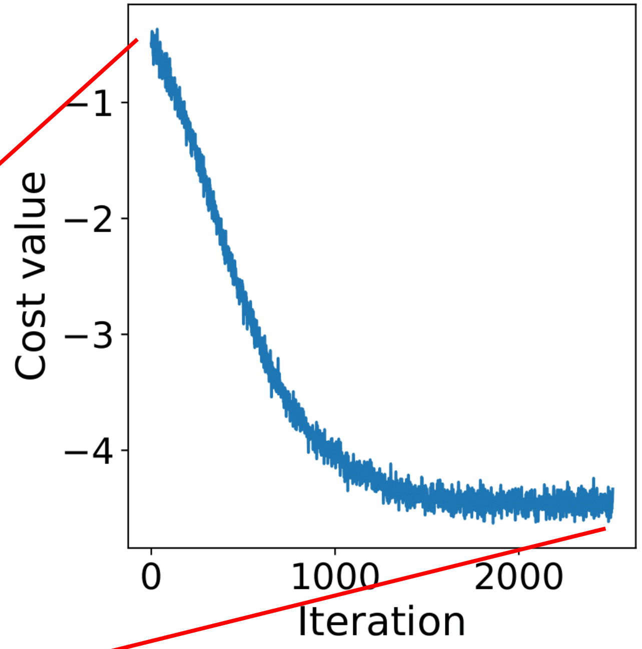
VQA cost landscapes can help





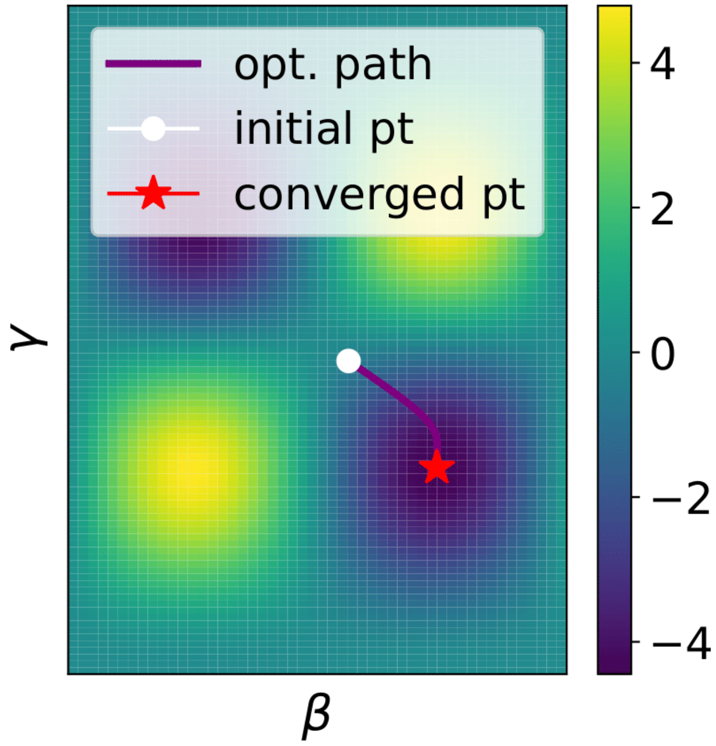


Landscape



- Little information
- Want to have a **bird's eye view** instead of just the **optimization path**

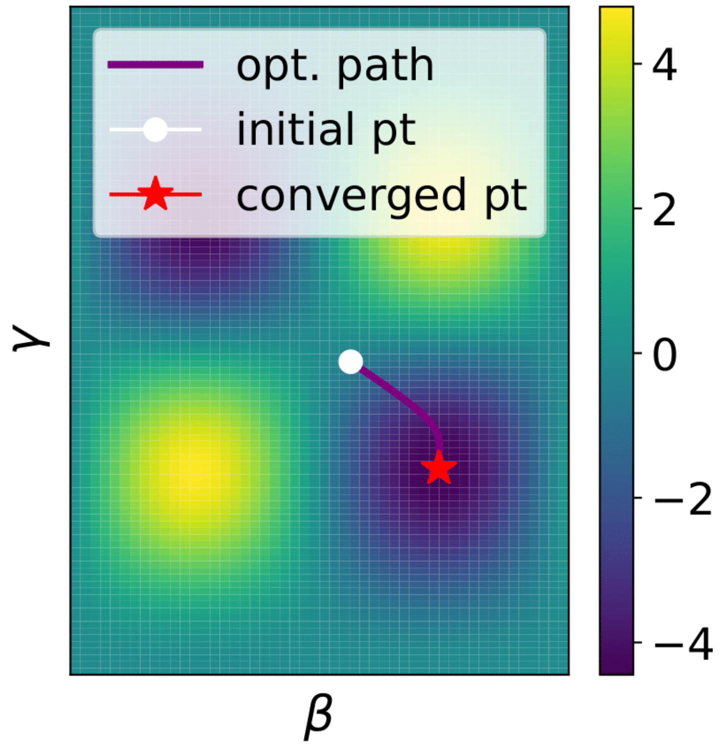
Landscape: A bird’s eye view



Find the bugs **visually and numerically**

- Error mitigation performance
- Initial point settings
- Optimizer configurations
- …

Deriving landscapes is **inefficient**

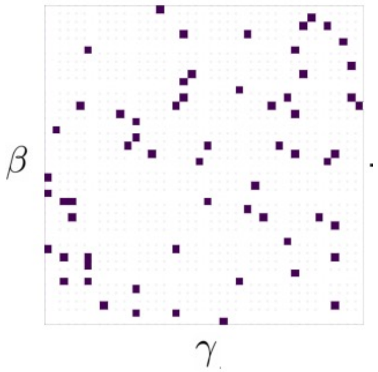


- For **every** point on the landscape, we need to execute the quantum circuit thousands of times
- Executing quantum circuits is slow and expensive
- Grid has 10^4 pixels → 10^7 runs → \$1000*

* Assuming IBM's pay as you go pricing of \$1/sec

Can we debug VQAs
by efficiently reconstructing VQA landscapes?

OSCAR: cOmpressed Sensing based Cost lAndscape Reconstruction

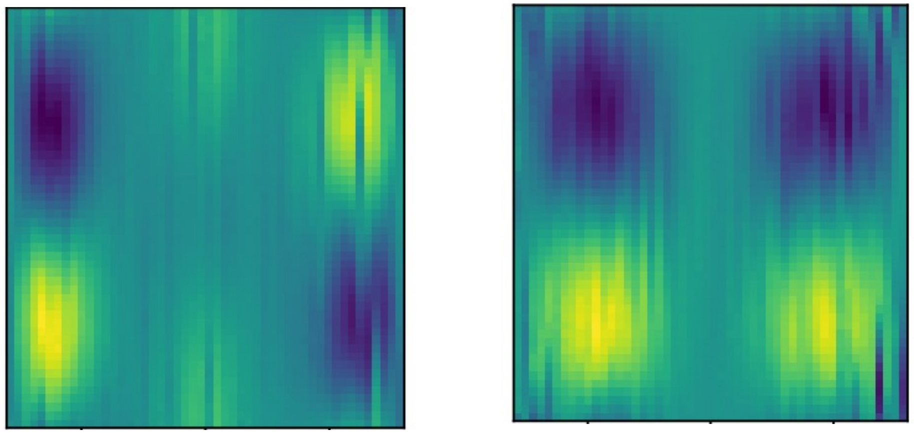


Random Parameters

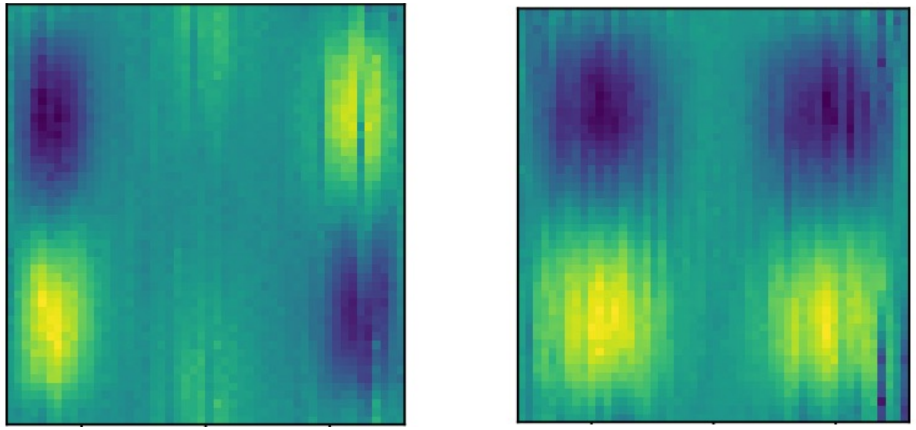
With 5%-10% of cost values on the parameters, we could reconstruct the full landscape.

Reconstruct Landscapes on Google's Device[1]

Original landscapes:

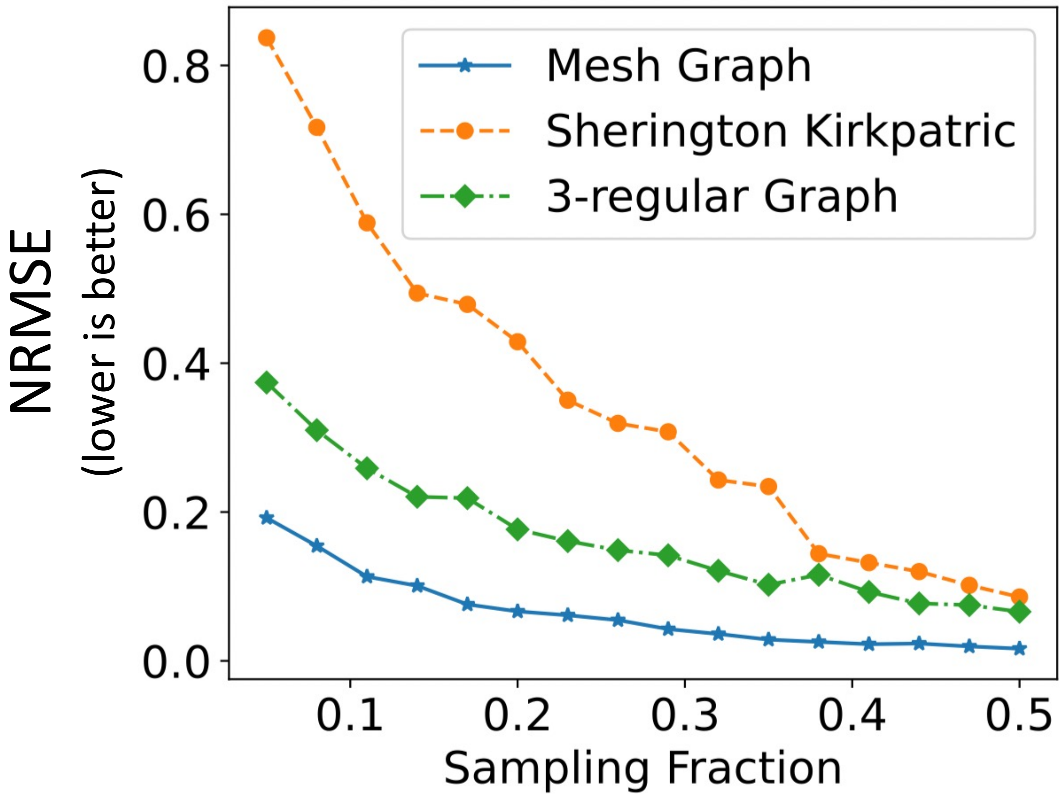


Reconstructed landscapes:



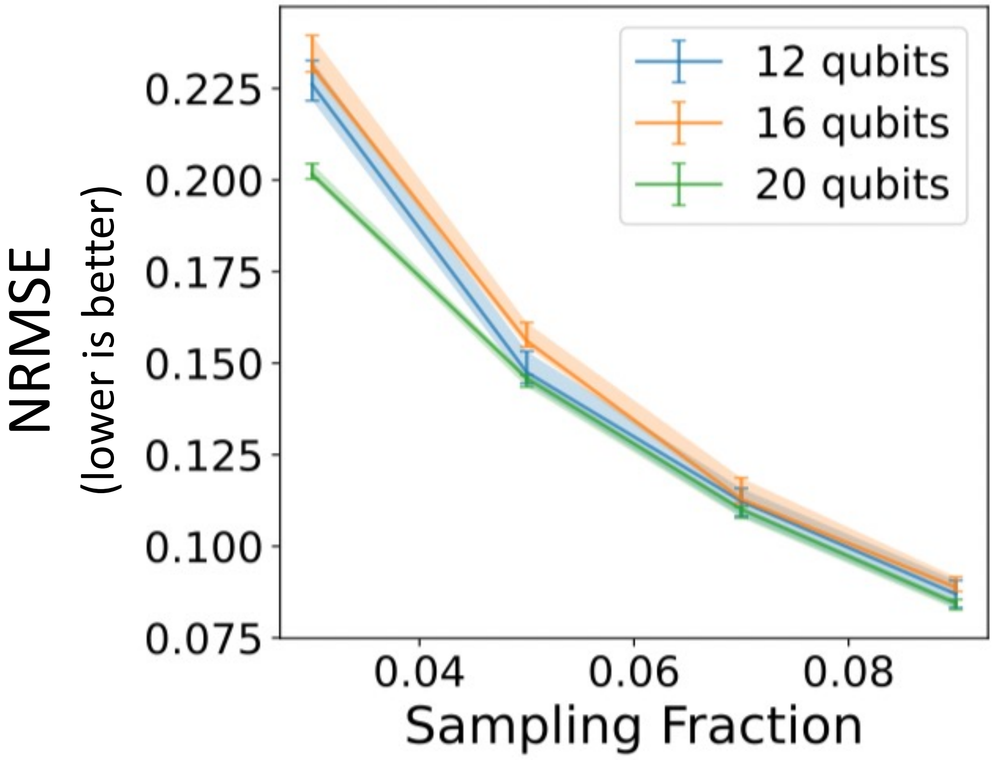
[1] Harrigan, et. al. "Quantum approximate optimization of non-planar graph problems on a planar superconducting processor"

Figure of merit

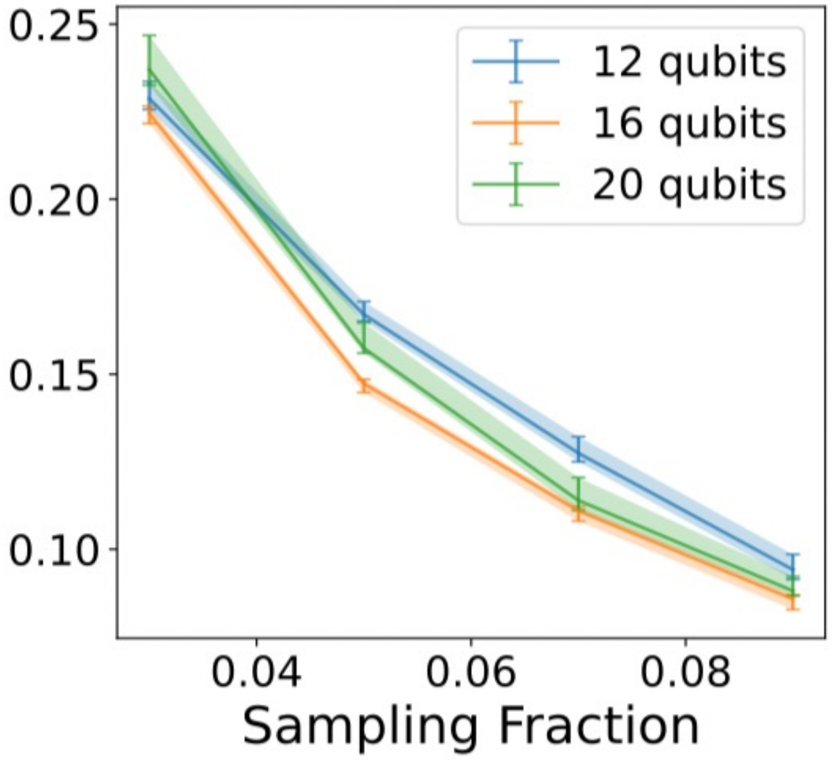


- **Sampling fraction:** fraction of random points to perform compressed sensing
- **NRMSE:** Normalized Reduced Mean Square Error; measure the difference between the original and the reconstructed landscapes

Reconstruct simulation landscapes



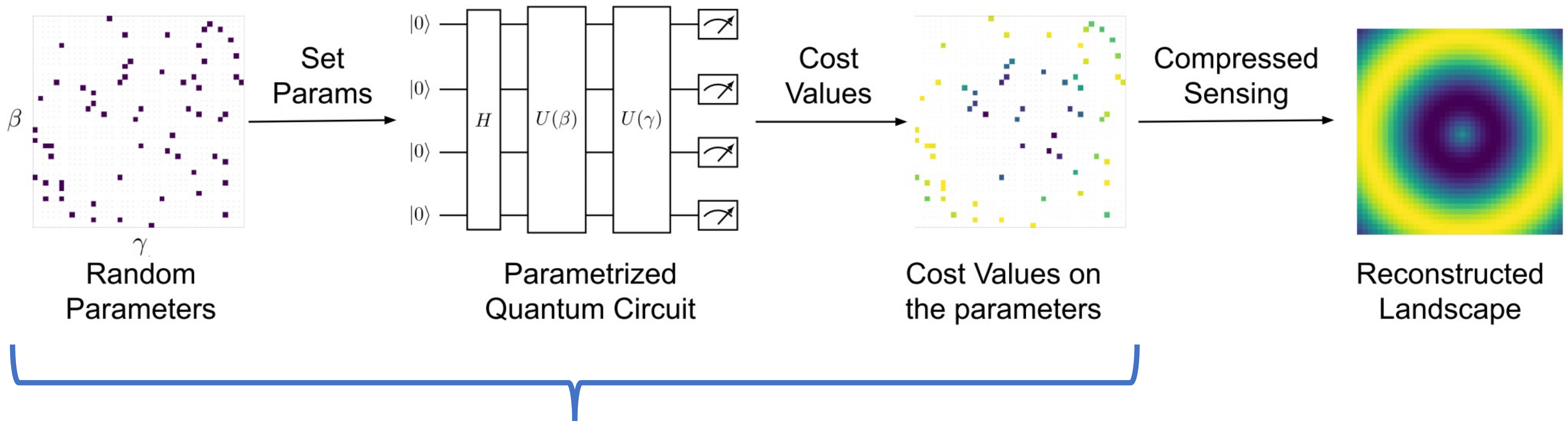
Ideal simulation



Noisy simulation

- Simulate circuits with 4 parameters

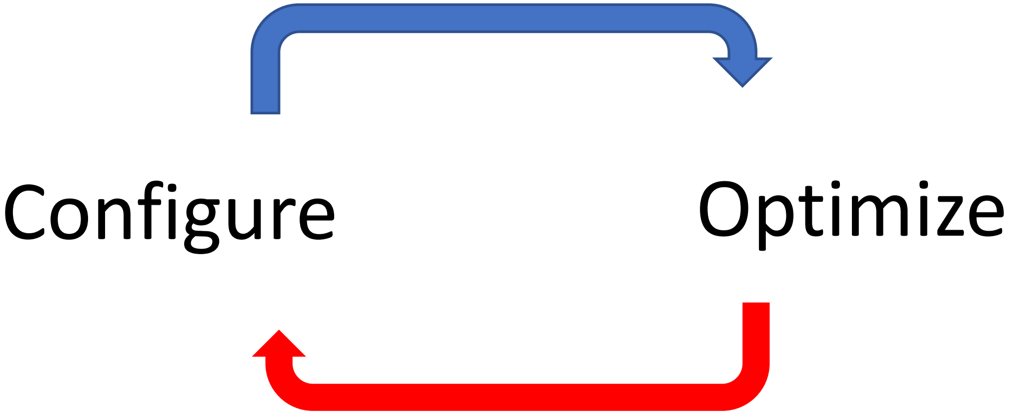
Parallel Reconstruction of Landscape



Random parameters are independent → Embarrassingly Parallelizable

Use Case 1: Configure Optimizers

Which optimizer?
Learning rate
Other hyperparameters
…

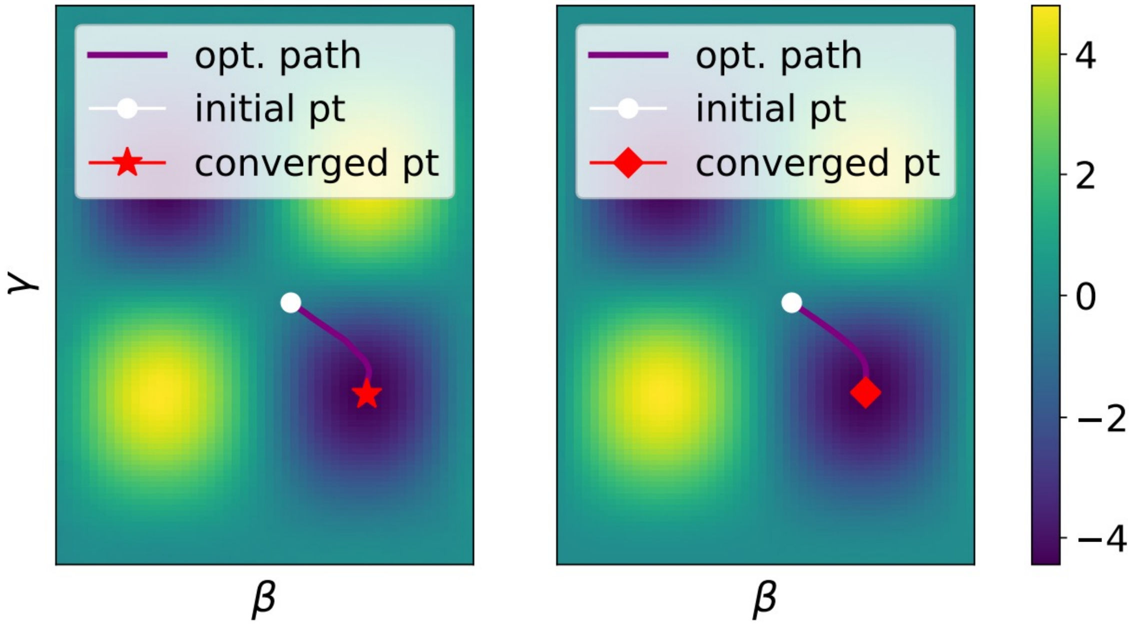


Takes a long time

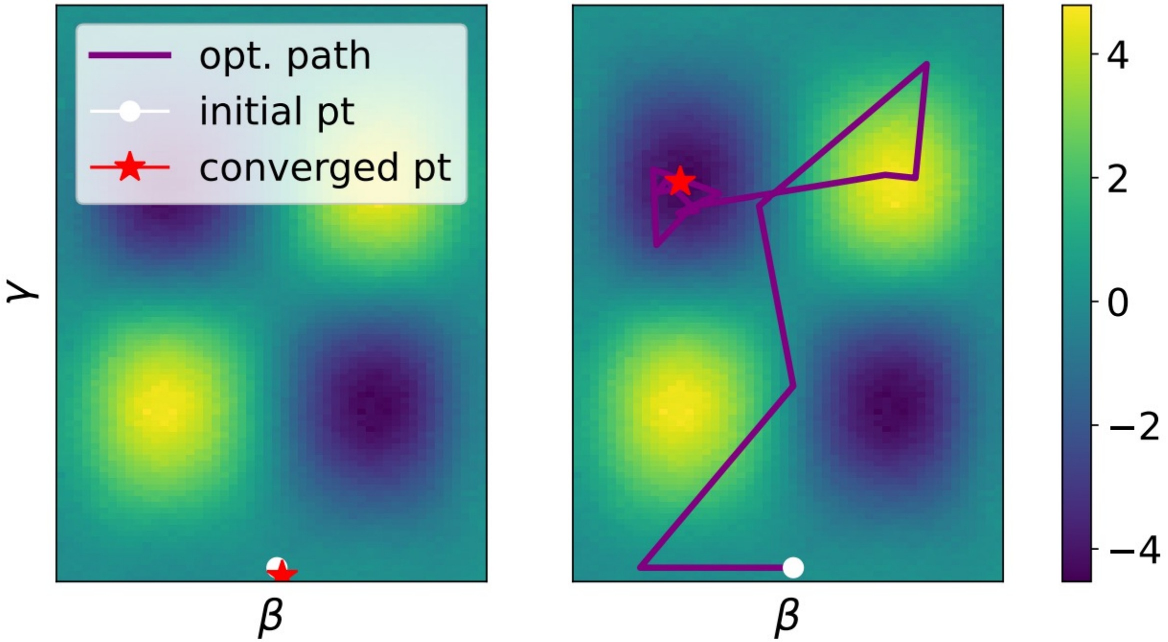
Once fail, change config and start over

We can reduce the cost of configuration with reconstructed landscapes!

Optimize on interpolated, reconstructed landscapes



(A) Interpolation (B) Circuit simulation

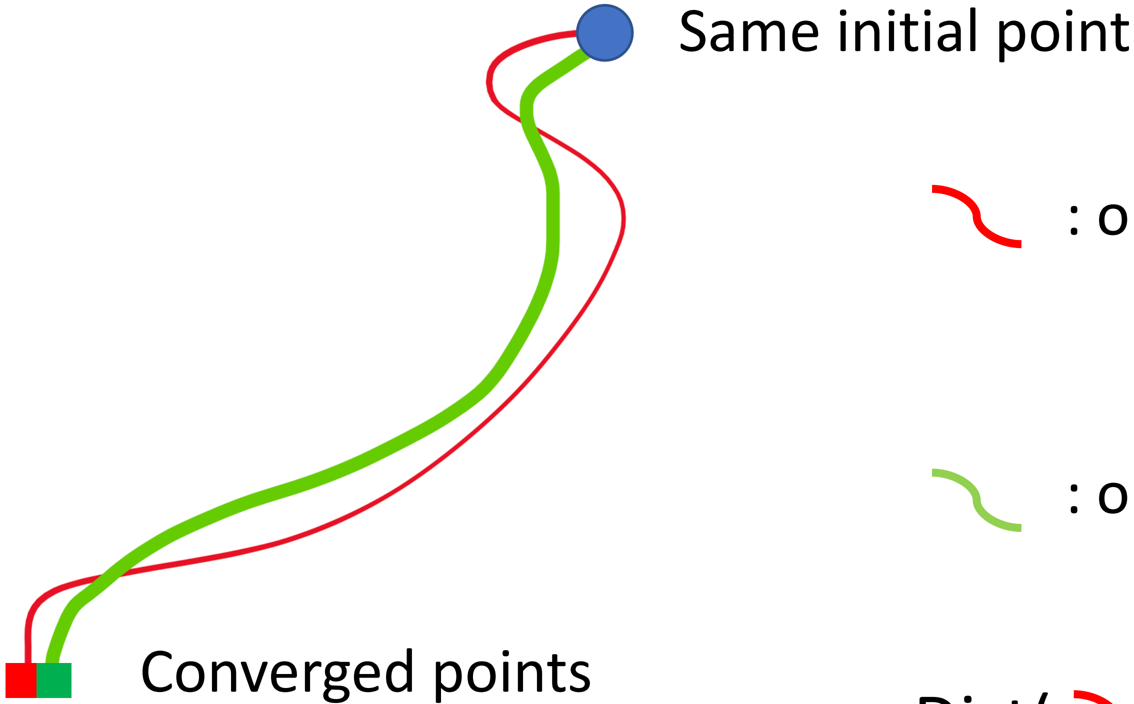


(A) ADAM (B) COBYLA

(A) Optimize on the reconstructed landscape by ADAM. (B) Optimize by circuit simulation by ADAM.

Optimize on the reconstructed landscape by ADAM and COBYLA.

Evaluate



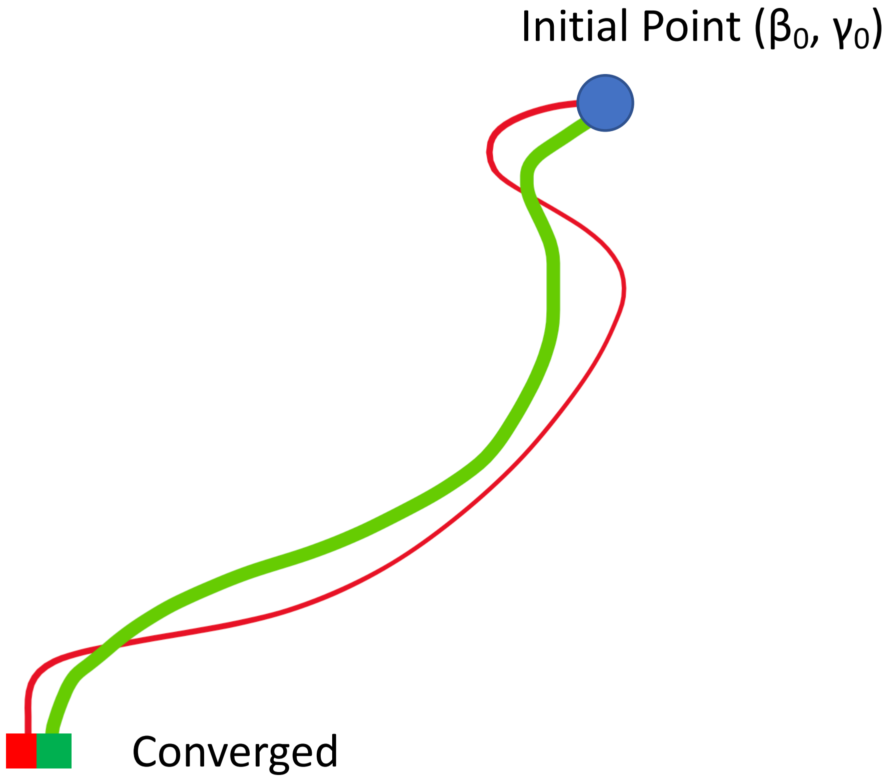
: optimize with **circuit simulation**

Goal: imitate

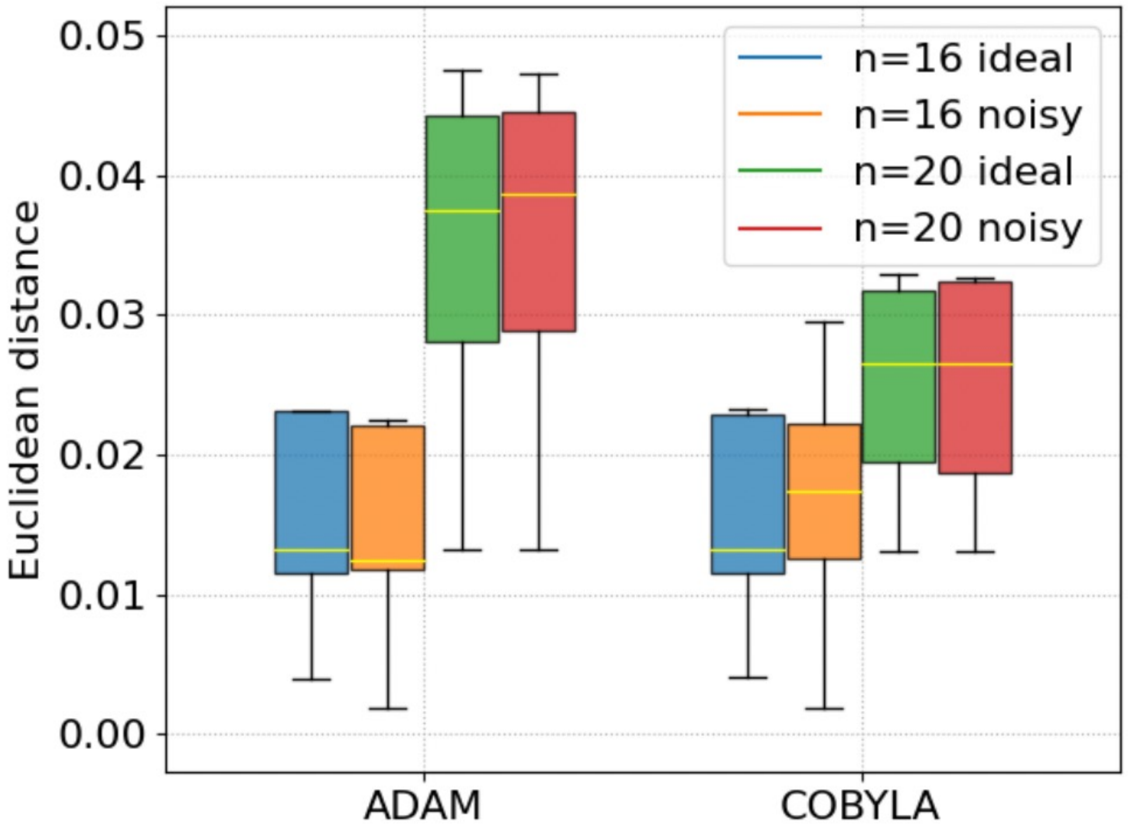
: optimize on **reconstructed landscape**

Dist(,) ≈ Dist(,)

Evaluate



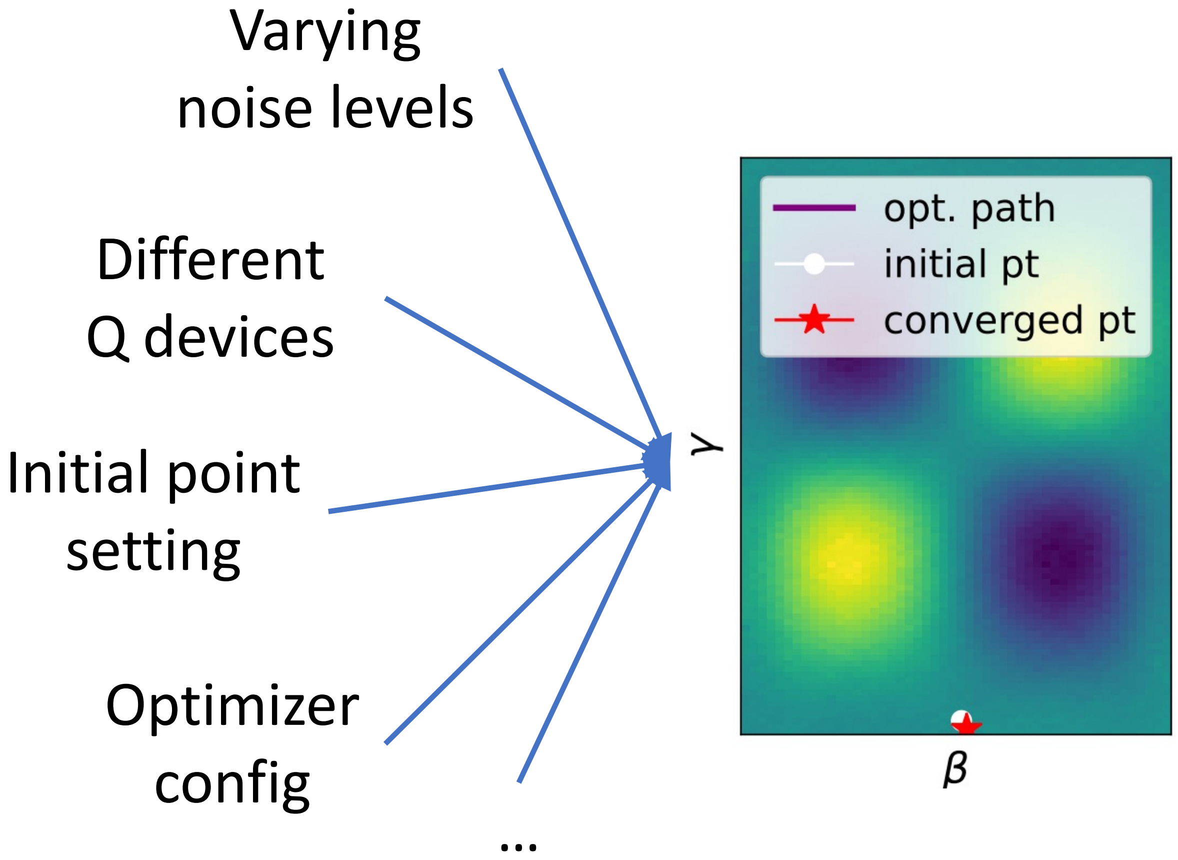
Dist(,) ≈ Dist(,)



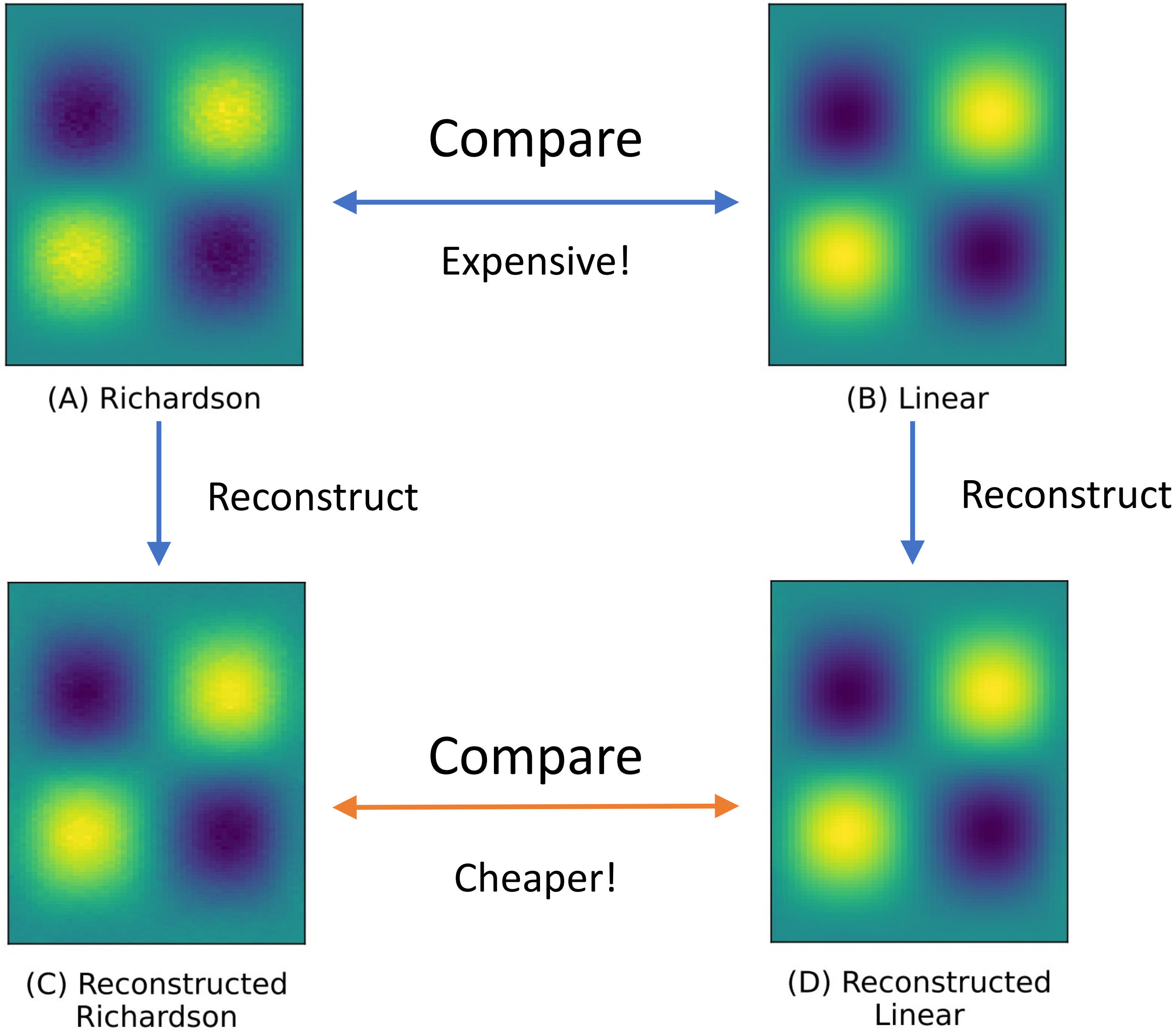
16-qubit and 20-qubit, ideal and noisy optimizations with ADAM and COBYLA

Use Case 2: Benchmark Error Mitigation Methods

- Deciding which mitigation method to use is not straightforward and efficient
- **Reconstructed landscapes can help!**



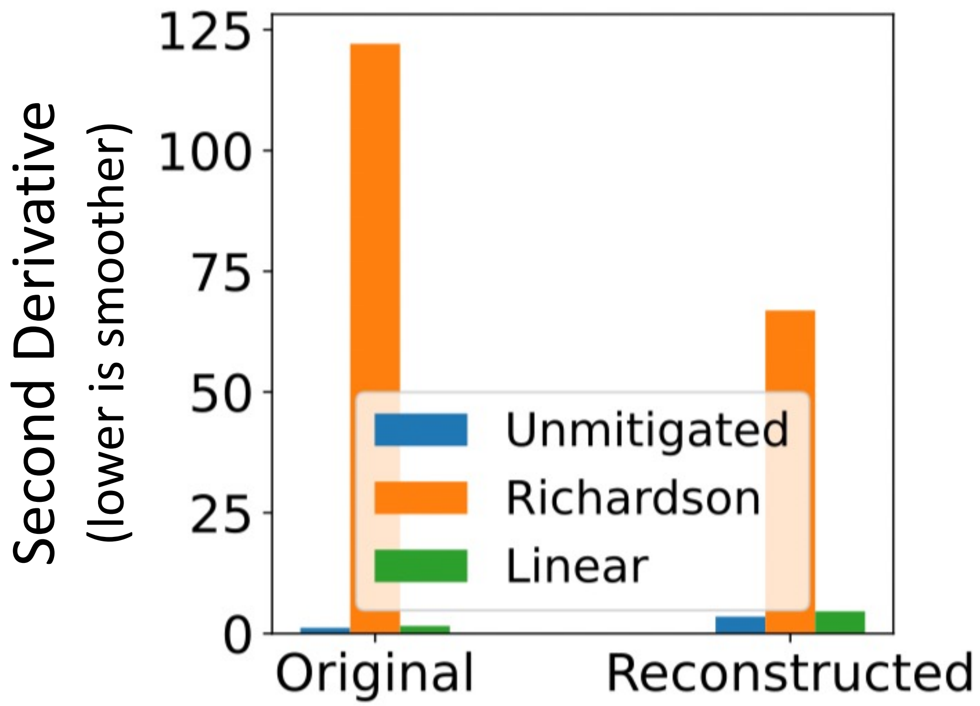
Example

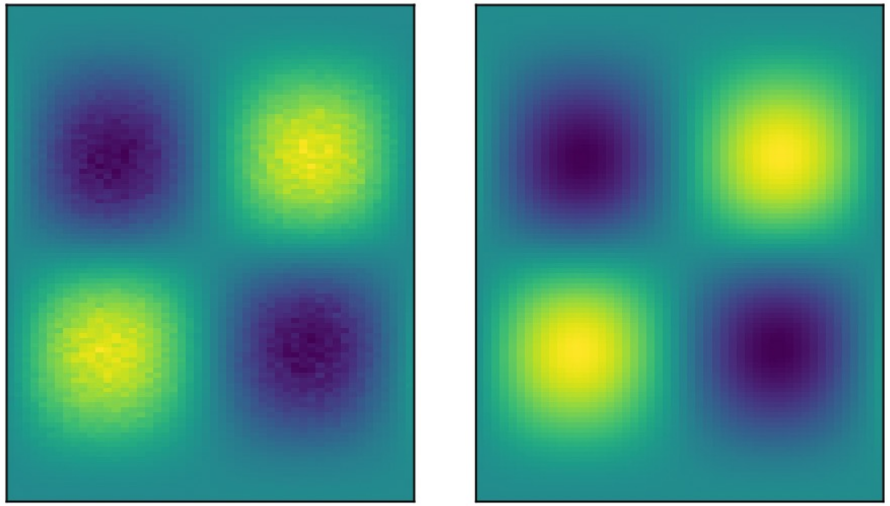


Richardson and Linear: two mitigation methods

Reconstructed landscapes preserve features of the original ones

Recon. landscapes preserve features of the original's





(A) Richardson

(B) Linear

- Share the similar pattern
- Match the actual case

Debugging is time consuming and expensive

It can be exponentially frustrating for quantum programs

OSCAR can help

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