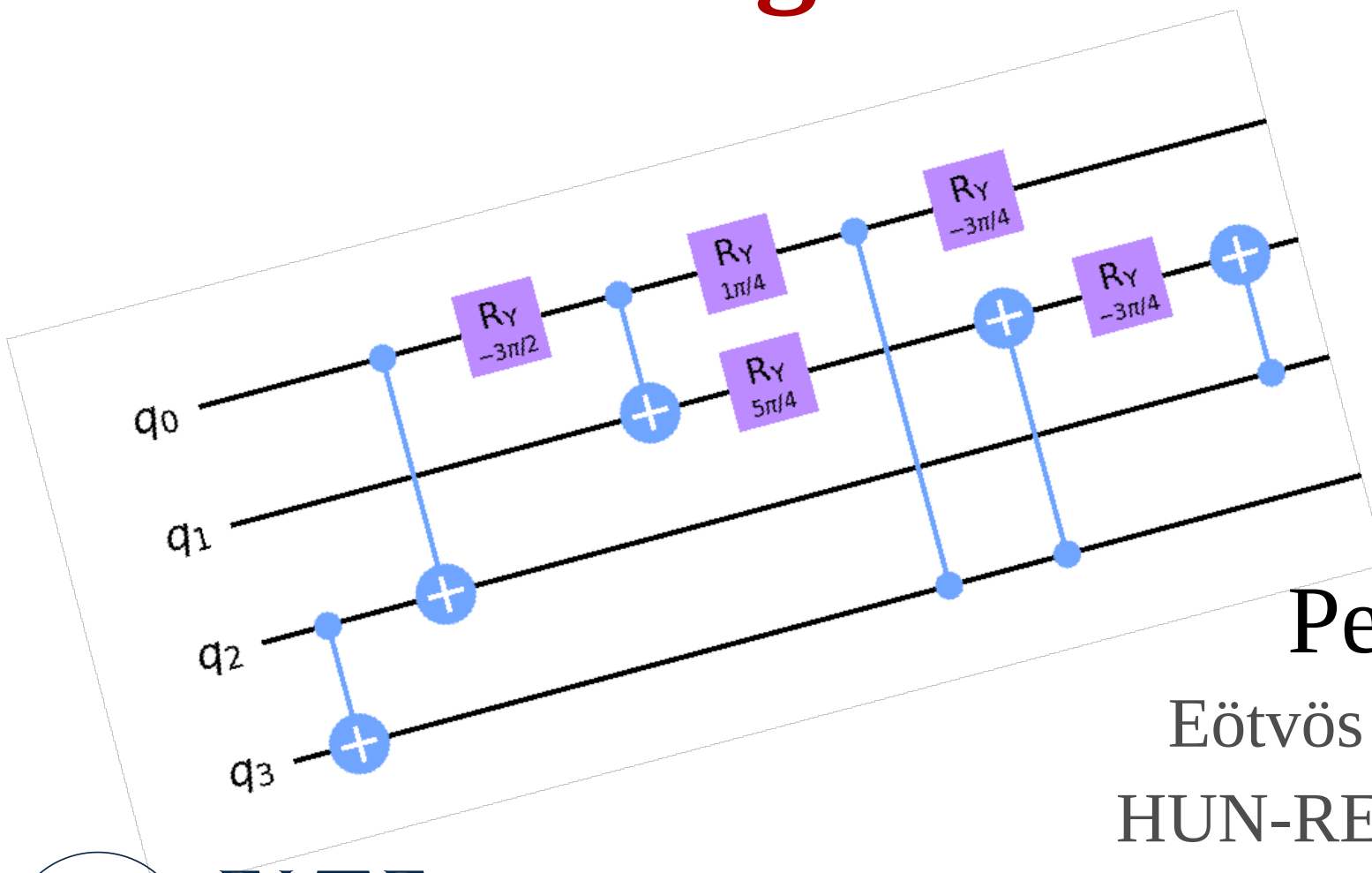


Quantum ML at Scale: Unlocking New Frontiers



Peter Rakyta

Eötvös Loránd University
HUN-REN Wigner Research
Centre for Physics

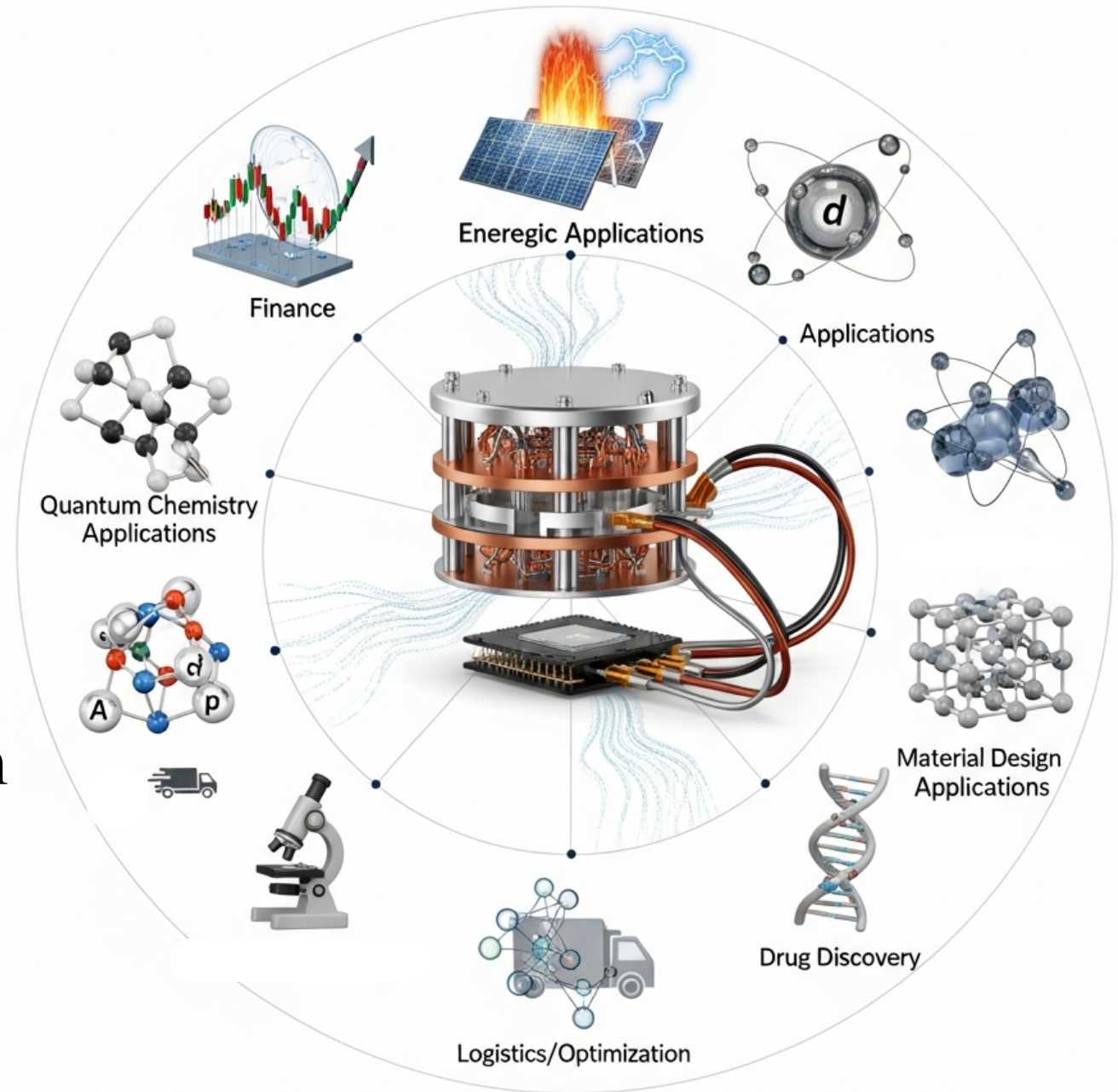


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Quantum Machine Learning

- Hybrid quantum-classical platforms
- Training quantum circuits on classical hardware
- Inference on quantum hardware

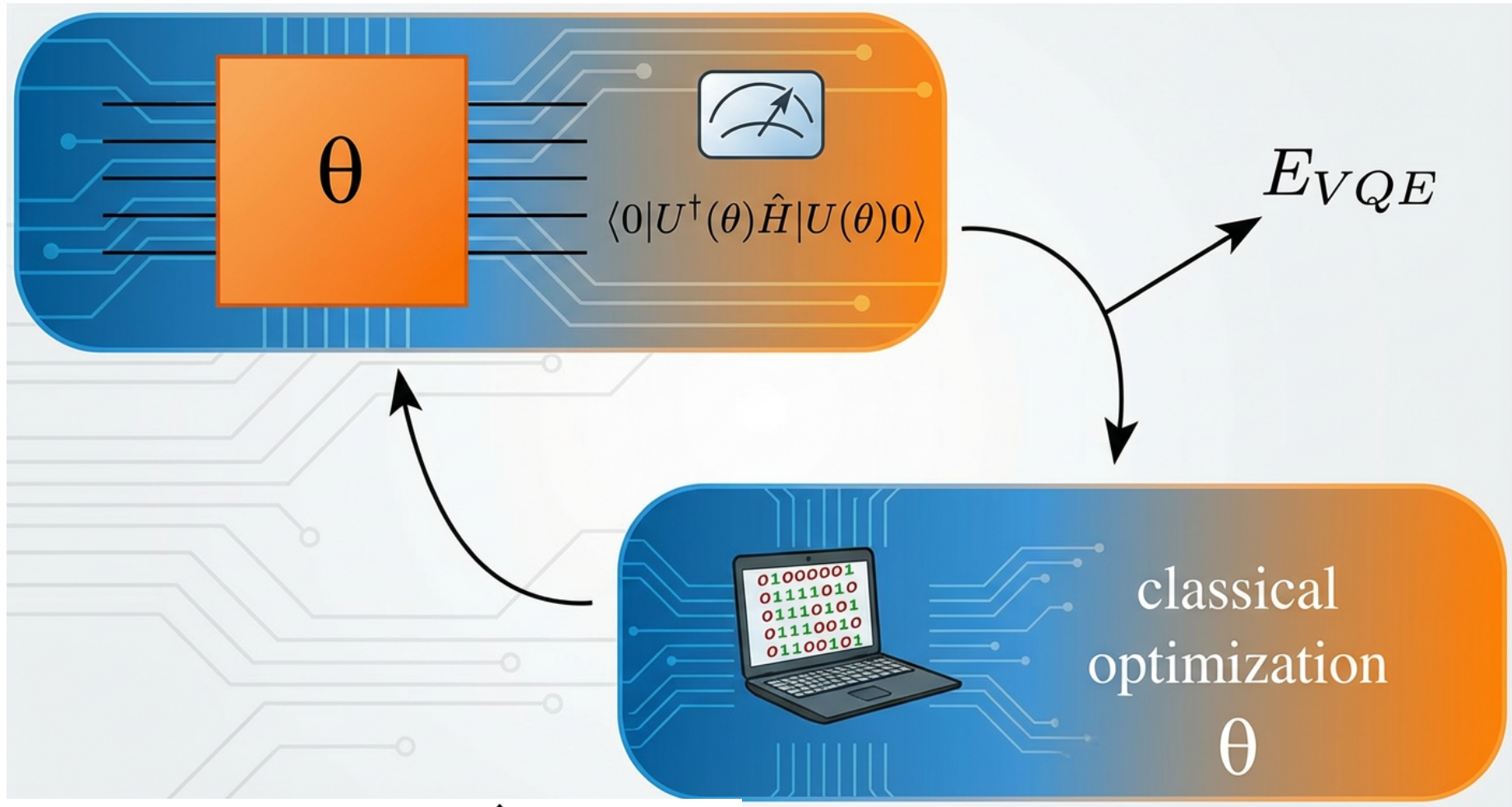


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National Laboratory
HUNGARY

Variational quantum eigensolver

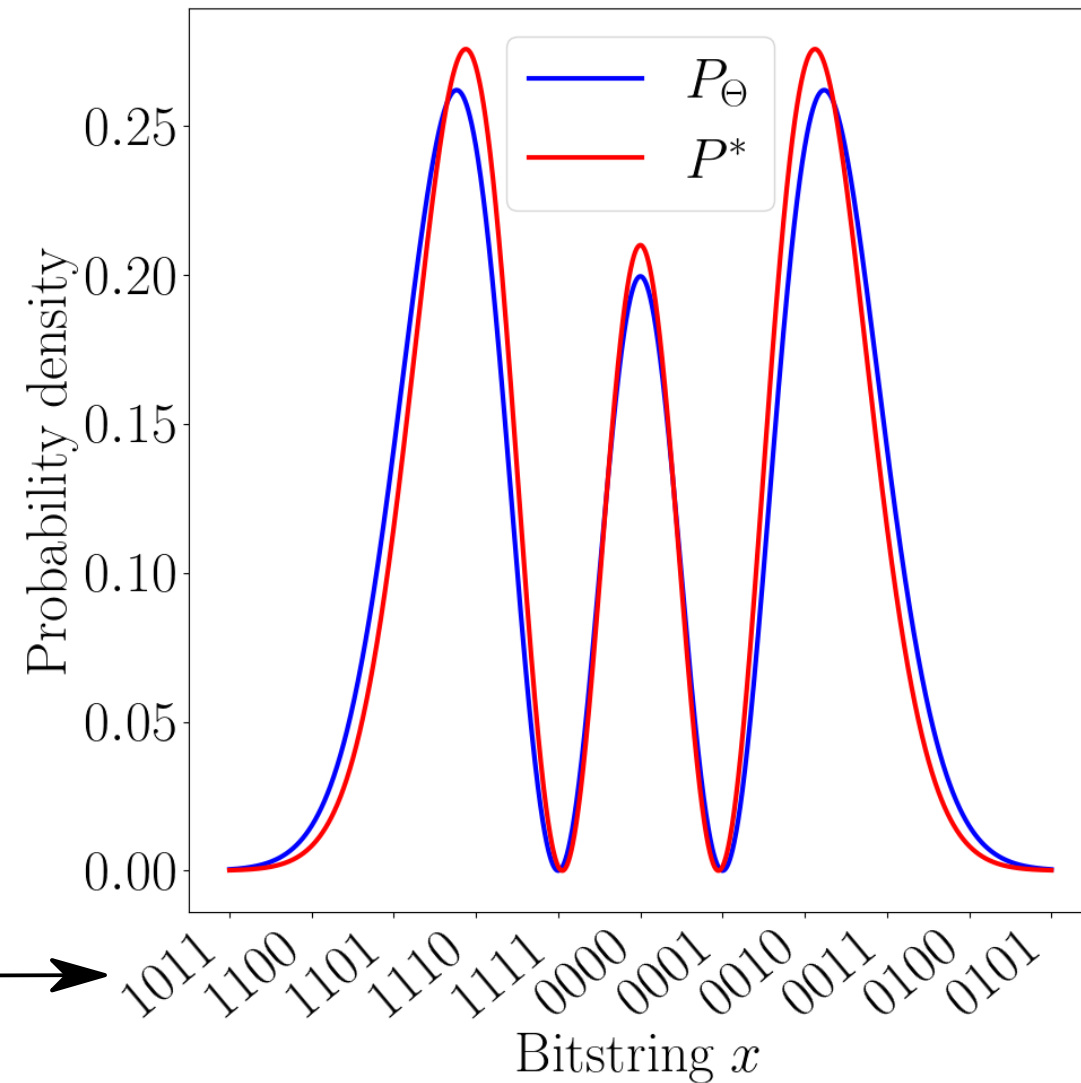
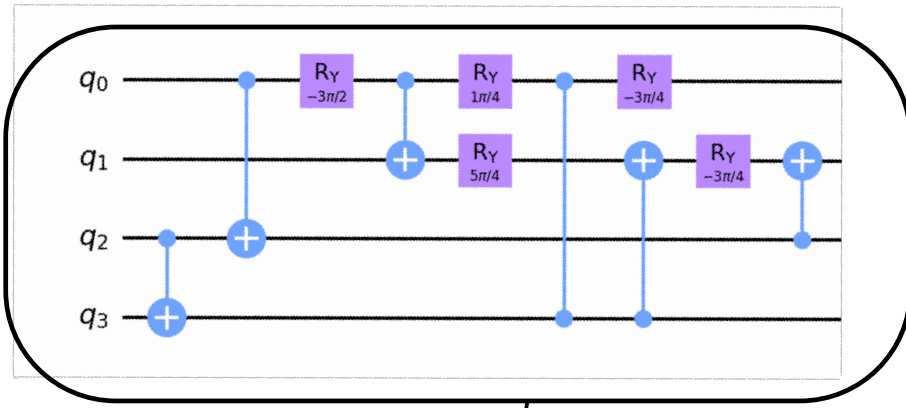


$$E_{VQE} = \min_{\theta} \langle \mathbf{0} | U^\dagger(\theta) \hat{H} | U(\theta) \mathbf{0} \rangle$$

$$\hat{H} = \sum_{\alpha}^{\mathcal{P}} w_{\alpha} \hat{P}_{\alpha}$$

Generating probability distribution

Target distribution: P^*



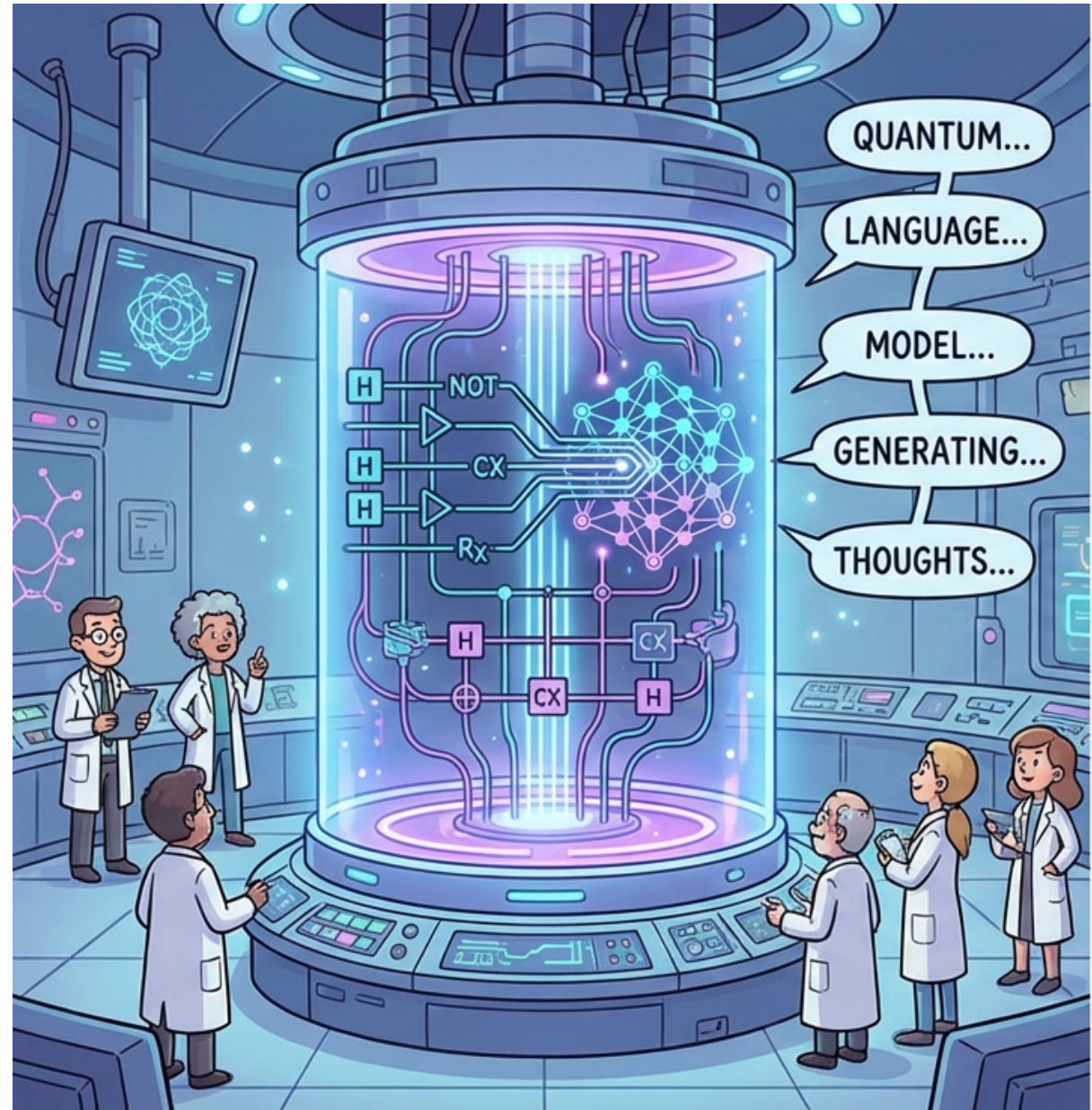
$$P_{\theta}(\mathbf{x}) = |\langle \mathbf{x} | U(\theta) | 0 \rangle|^2$$

Bitstrings

$$\mathcal{L}_{\text{MMD}}(P_{\theta}, P^*) = \left\| \sum_{\mathbf{x}} P_{\theta}(\mathbf{x}) \phi(\mathbf{x}) - \sum_{\mathbf{x}} P^*(\mathbf{x}) \phi(\mathbf{x}) \right\|^2$$

Next token prediction task with QLM

- Tokens encoded via the basis in the Hilbert space
- ~20-25 qubits
- Positional encoding via relative phase (also ensures non-linearity)
- Attention mechanism via entanglement



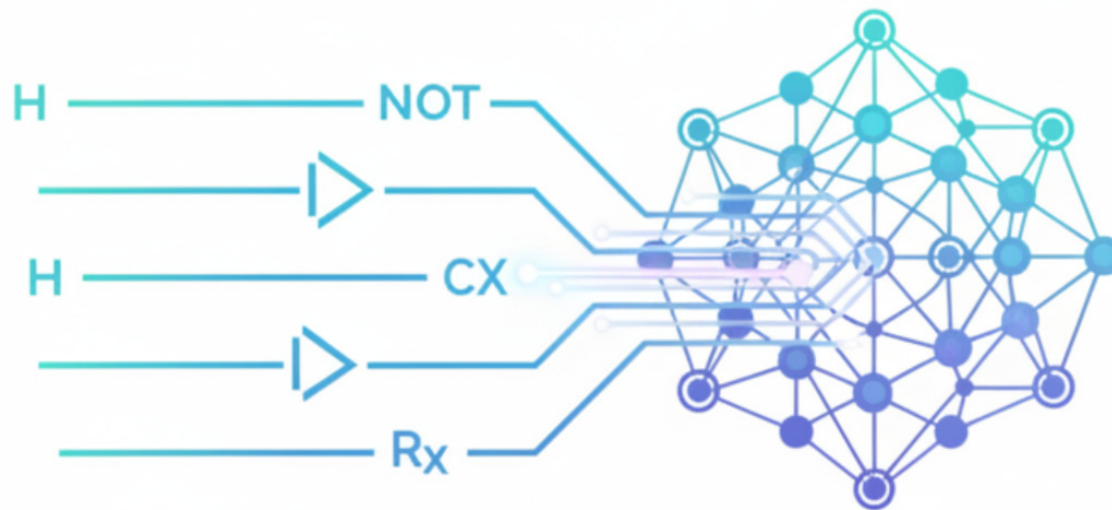
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SQUANDER: toolkit to train quantum circuits

Sequential Quantum Gate Decomposer



High performance
QC simulator

QML

SQUANDER

Quantum Gate
Compilation

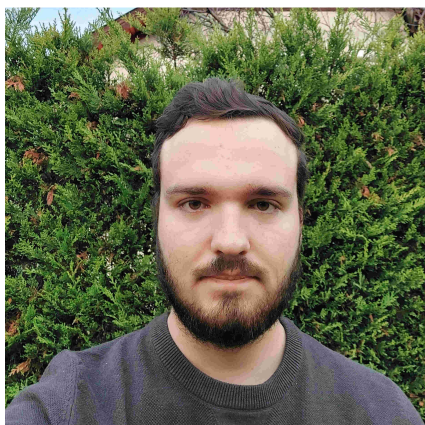
Gradient Descend and
Evolutionary Optimizers



GitHub <https://github.com/rakytap/sequential-quantum-gate-decomposer>

SQUANDER Tech Team

QNL Quantum Information
National Laboratory
HUNGARY



Barna Villám



Gregory Morse
(senior developer)



Zoltán Kégli
(senior developer)



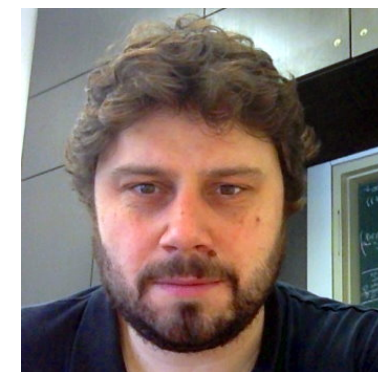
Muhammad Al Farizi



László Hajas



Jakab Nátori

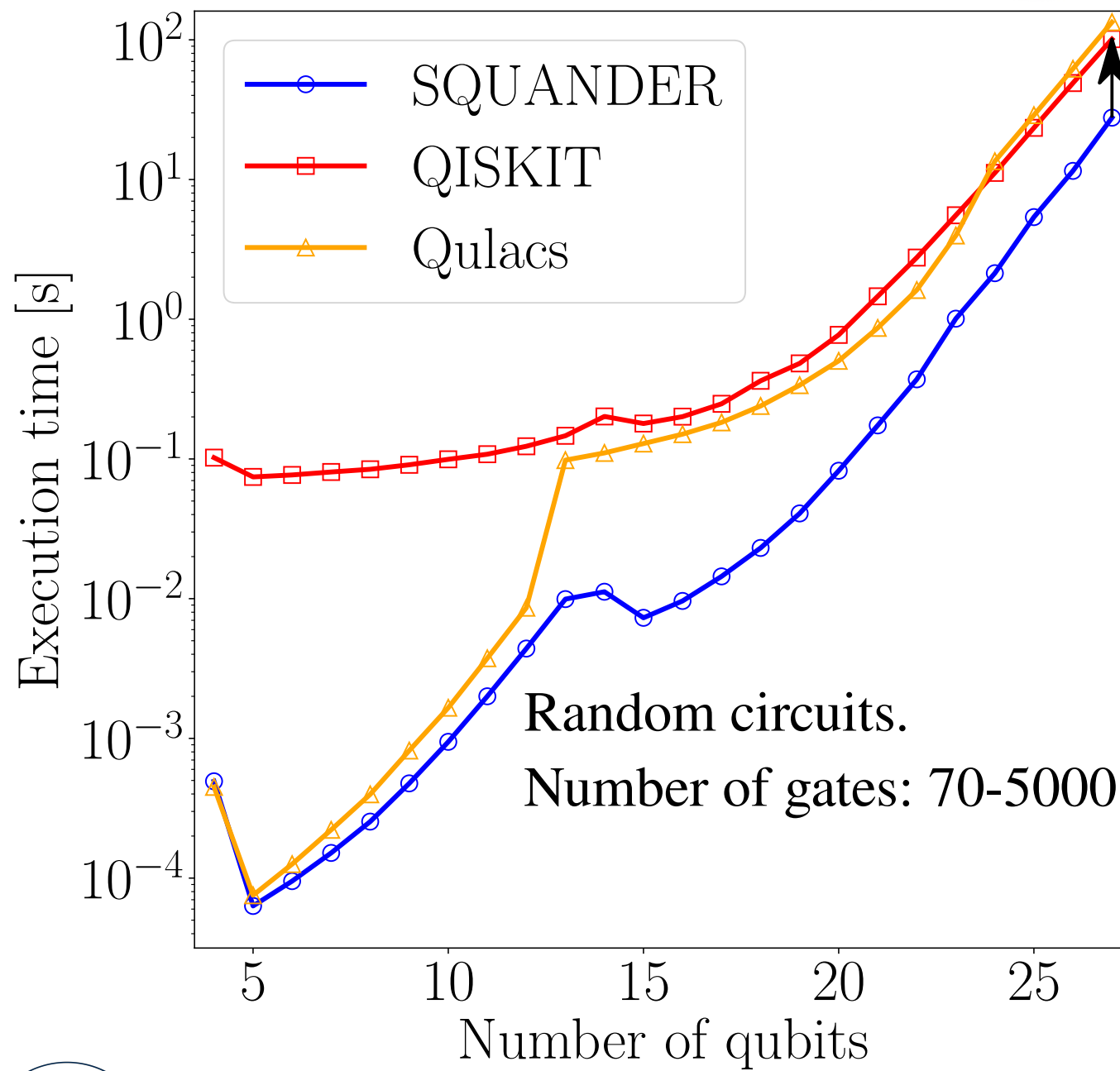


Zoltán Zimborás
(consultant)



<https://github.com/rakytap/sequential-quantum-gate-decomposer>

QC simulation with SQUANDER



5x speedup

Optimal circuit partitioning

$$\min_{U \subset S} \left[\sum_{i \in U} (\mathcal{A}_i + \mathcal{IO}) \right]$$

$$\sum_{i \in U} i = \text{Circuit}$$

$\mathcal{S}$ Set of all partitions

$\mathcal{IO}$ IO overhead

$\mathcal{A}_i$ Number of Arithmetic operations of partition "i"



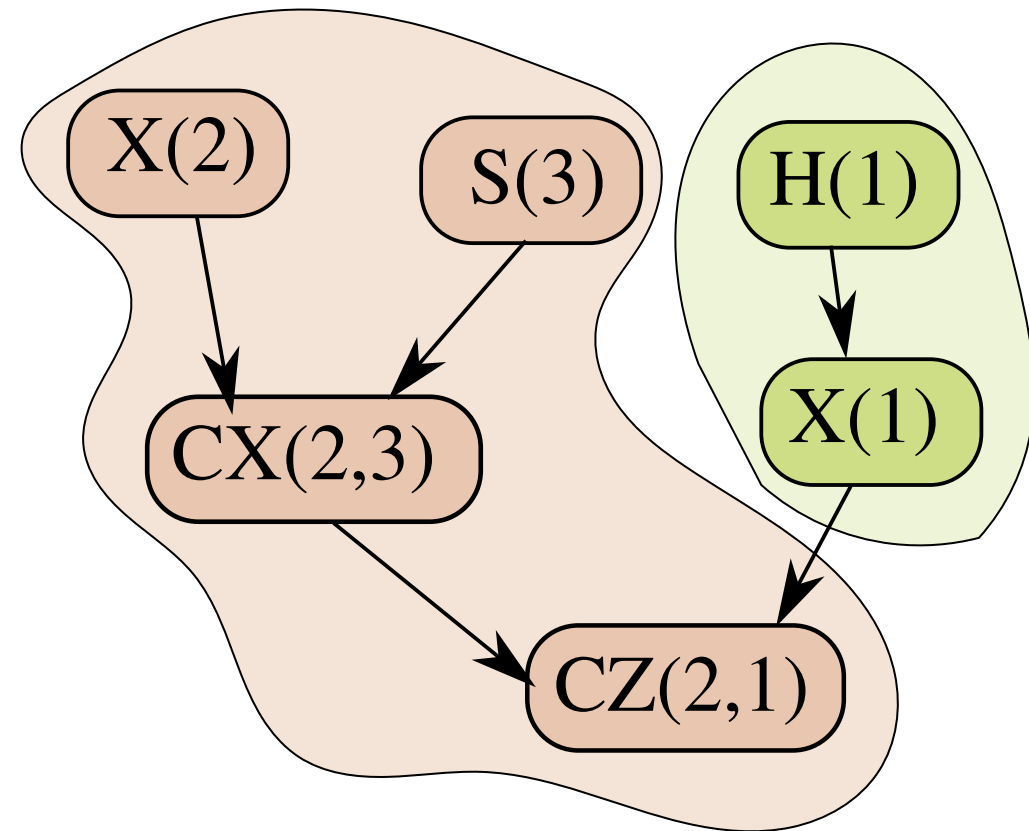
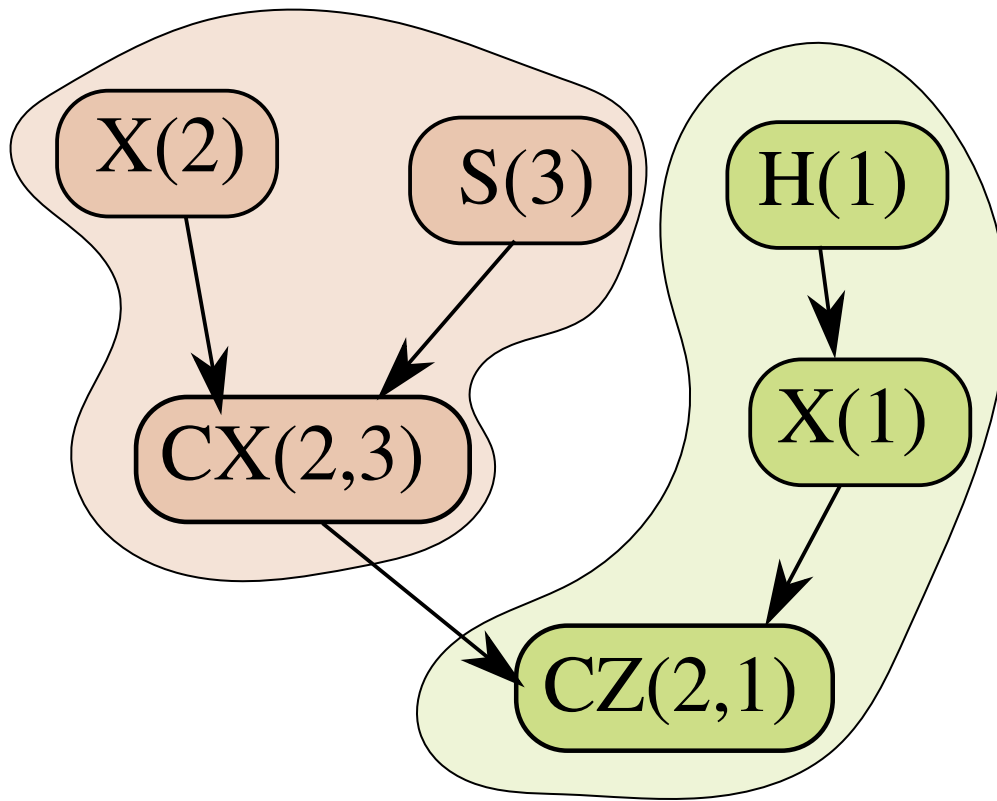
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ILP based cover set problem

Directed Acyclic Graph of gate operations

- Use Integer Linear Programming solver to find the optimal circuit partitioning



- 4 example partitions
- two pairs of them adding up to the whole circuit



SQUANDER

Graphical User Interface

Qubitkit by SQUANDER Test

Gates

Search gates...

Single-Qubit Gates

U1 U2 U3 X
Y Z S Sdg
T Tdg H RX
RY RZ R SX

Two-Qubit Gates

CH CNOT CZ CP
CRX CRY CRZ CR
CROT CU SWAP SYC

Multi-Qubit Gates

CCX CSWAP

Quantum Circuit

Circuit Circuit 1

Backend SQUANDER Strategy Kahn Qubits 4 Timeout 0 s

q[0] U3 CZ U3 CZ U3
q[1] U3 CZ U3 CNOT U3 CNOT U3 CNOT U3 CNOT U3
q[2] U3 U3 U3 CZ U3 U3 U3
q[3] U3 U3 U3 U3
q[4] U3 U3 U3

Imported: mod5d1_63.qasm

Simulation Results

shots: 10,000 • strategy: kahn • max partition size: 3 qubits

Circuit Fidelity
100.00%

Gate Properties

T Gate
n/8 gate

Single-Qubit Gates
T: 1, C: 0

DESCRIPTION

The T gate applies a $\pi/4$ phase shift (45 degrees) to the $|1\rangle$ state. It is a fundamental gate in fault-tolerant quantum computing and is the fourth root of the Pauli-Z gate.

TRANSFORMATIONS

$|0\rangle \rightarrow |0\rangle$
 $|1\rangle \rightarrow e^{i\pi/4}|1\rangle$

MATRIX

$$\begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix}$$

QASM Code

```
4 qreg q[5];
5 creg c[5];
6
7 cz q[2], q[0];
8 cz q[3], q[1];
9 cx q[2], q[1];
10 cx q[2], q[1];
11 cz q[4], q[0];
12 cz q[4], q[2];
13 cx q[2], q[1];
14 cx q[2], q[1];
```

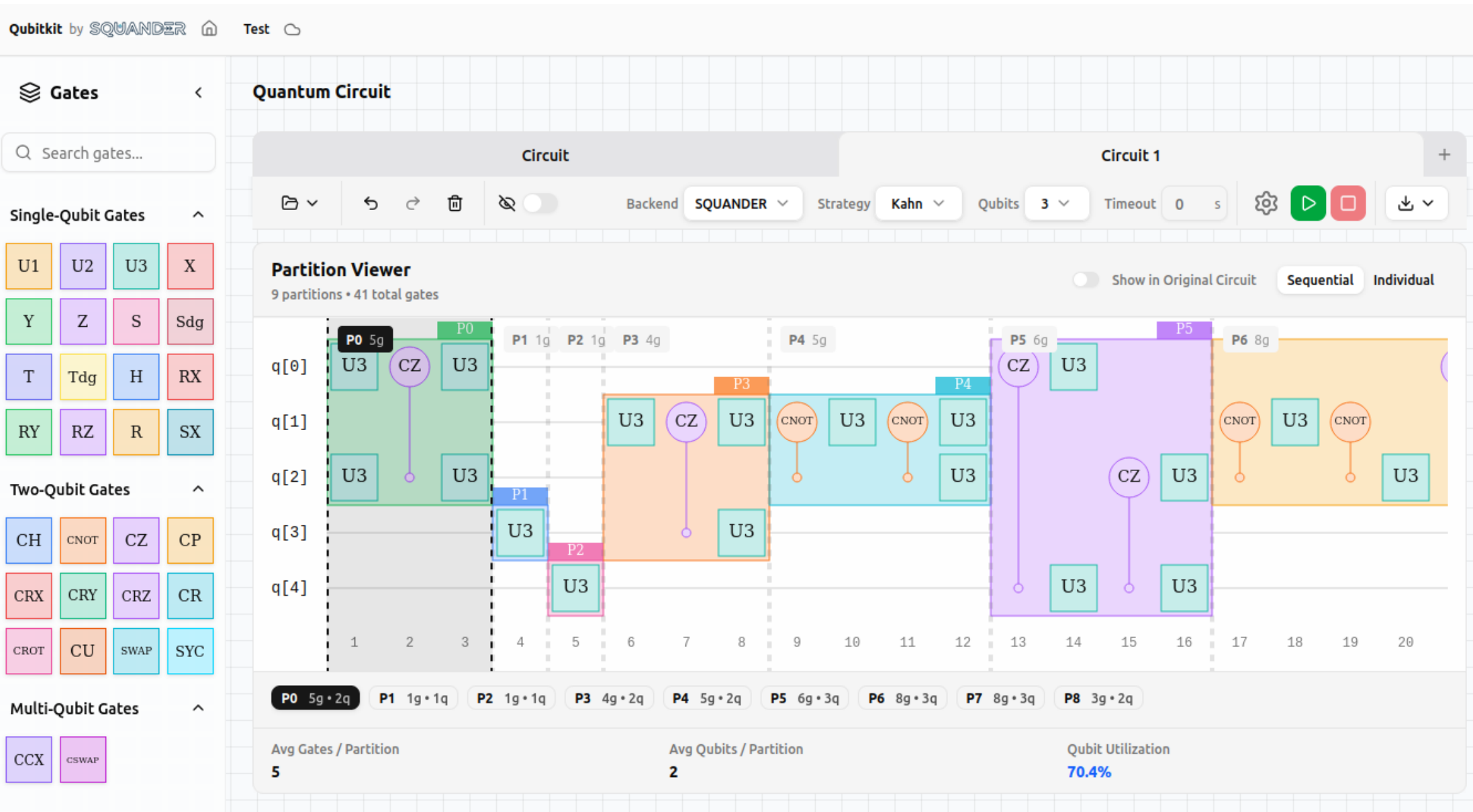


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Visual Inspection of Partitions



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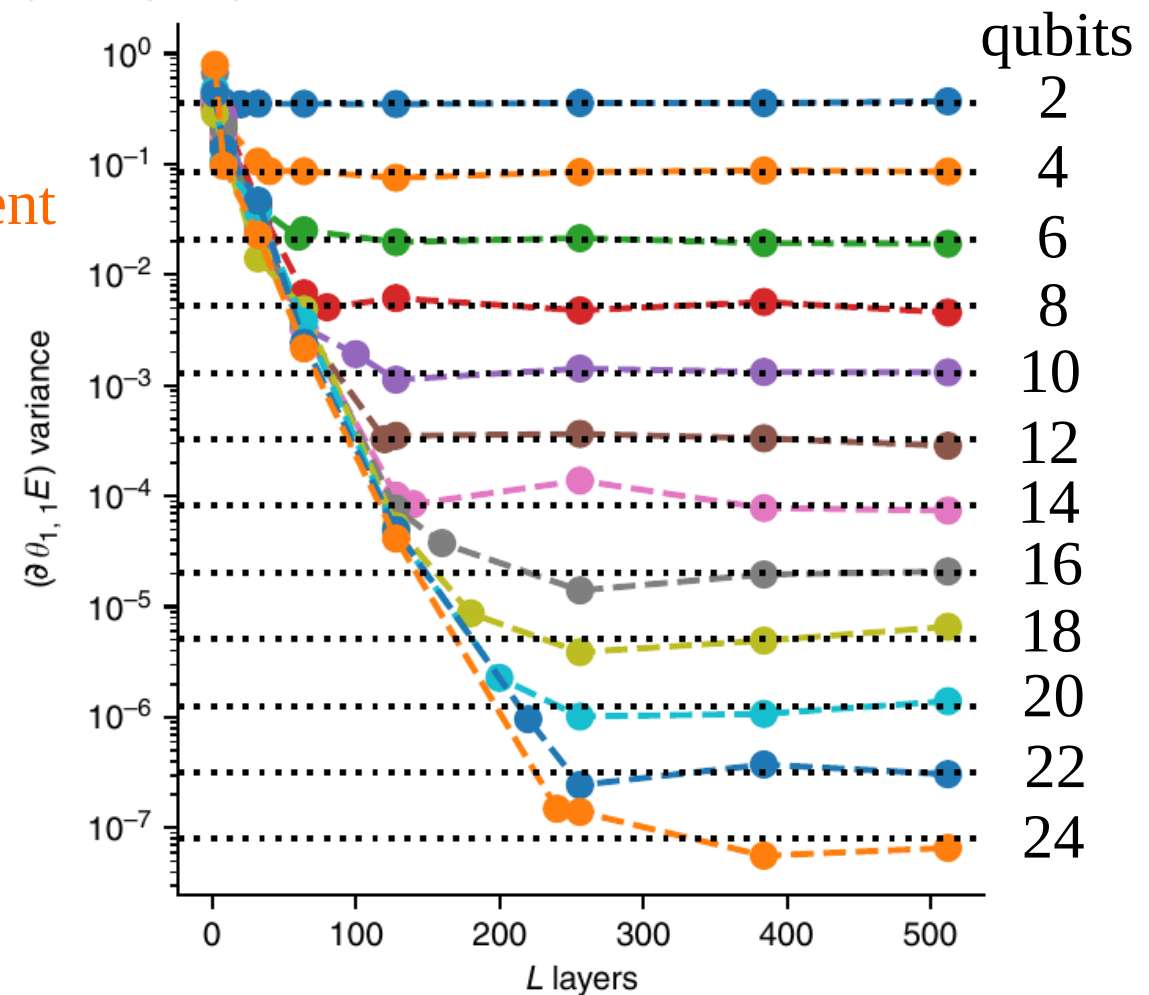


Barren plateaus in quantum neural network training landscapes

Jarrold R. McClean¹, Sergio Boixo¹, Vadim N. Smelyanskiy¹, Ryan Babbush¹ & Hartmut Neven¹

The variance of the cost function gradient
(and consequently its typical value)
vanishes exponentially
in the qubit number N

$$\text{Var}[\partial_{i,l} E(\boldsymbol{\theta})] \sim \mathcal{O}\left(\frac{1}{2^{2N}}\right)$$



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Barren plateau & entanglement entropy

controlling entanglement
to mitigate BP?

Second Rényi entropy

$$S_2 = -\ln \text{Tr} \rho_A^2$$

subsystem

Entanglement-Induced Barren Plateaus

Carlos Ortiz Marrero, Mária Kieferová,
and Nathan Wiebe

PRX Quantum 2, 040316

Entanglement devised barren plateau
mitigation

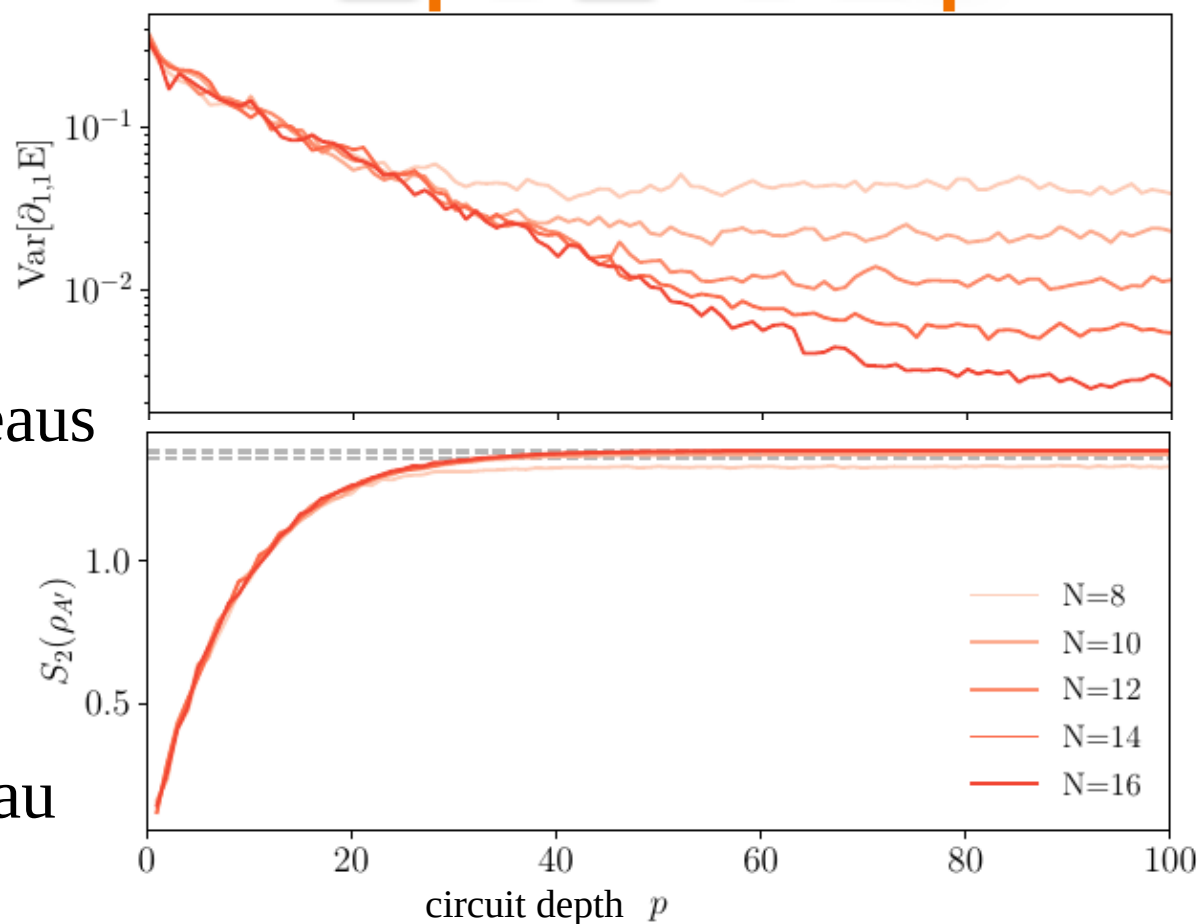
Taylor L. Patti, Khadijeh Najafi, Xun Gao, and Susanne F. Yelin
Phys. Rev. Research 3, 033090

Avoiding Barren Plateaus Using Classical Shadows

Stefan H. Sack, Raimel A. Medina, Alexios A. Michailidis,

Richard Kueng, and Maksym Serbyn

PRX QUANTUM 3, 020365 (2022)



Avoiding Barren Plateaus Using Classical Shadows

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PRX QUANTUM 3, 020365 (2022)

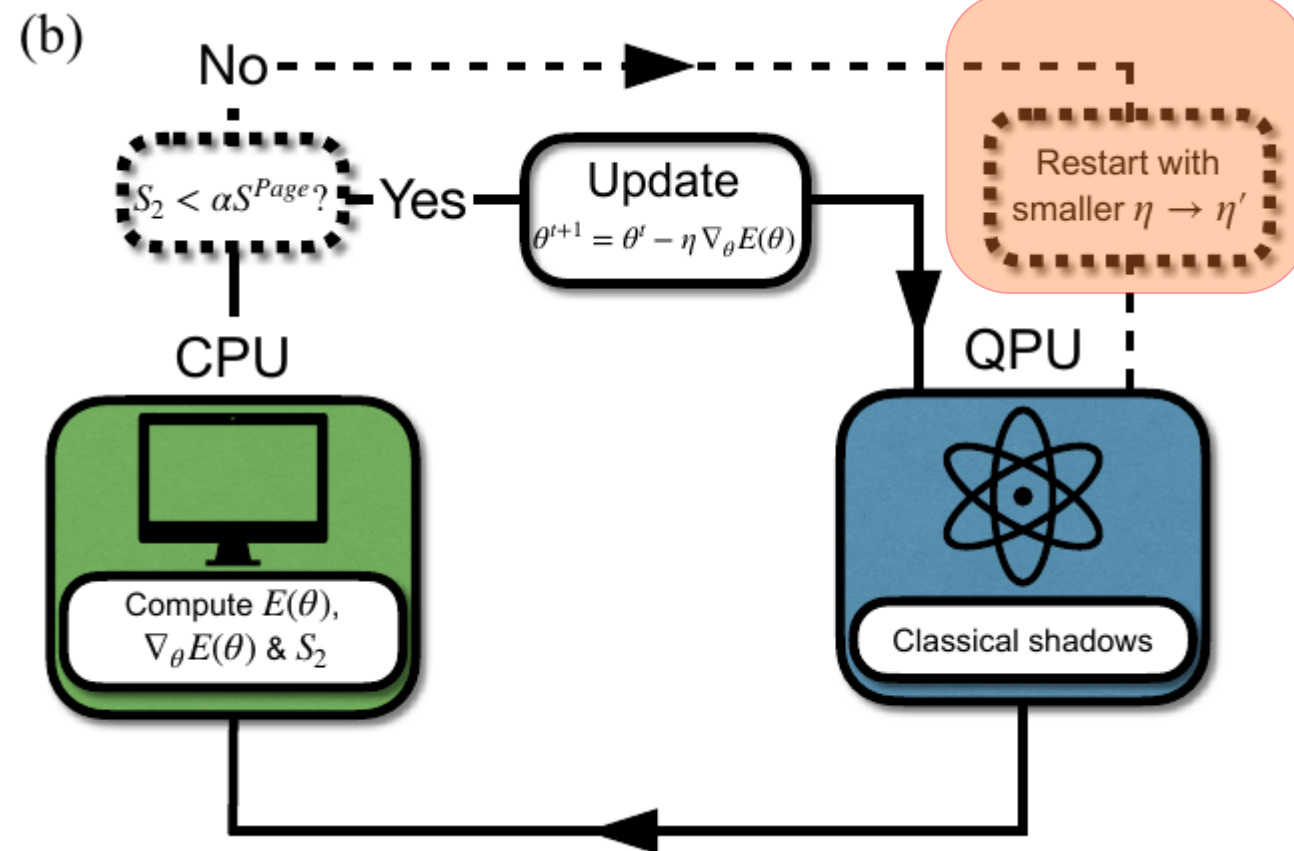
- monitor the entropy and control the learning rate

$$\theta^{t+1} = \theta^t - \eta \nabla_{\theta} E(\theta),$$

Decreasing the learning rate!!

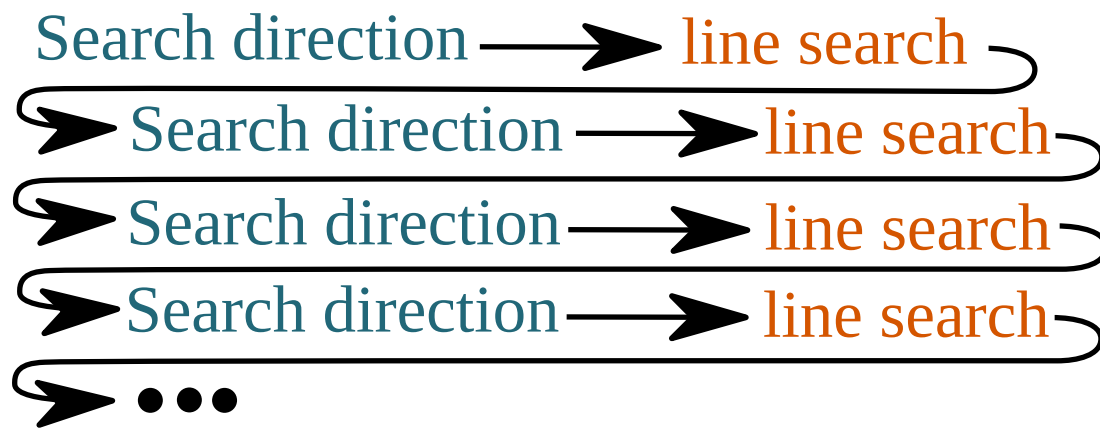
- parameter initialization to low entangling gates
Quantum 3, 214 (2019),
PRX Quantum 3, 010313 (2022)
- use local cost functions
Nature Communications 12, 1791 (2021)
- use matrix product states
PRX Quantum 3, 010313
- layer-by-layer optimization
Quantum Mach. Intell. 3, 5 (2021)

limiting the expressiveness
of the circuit

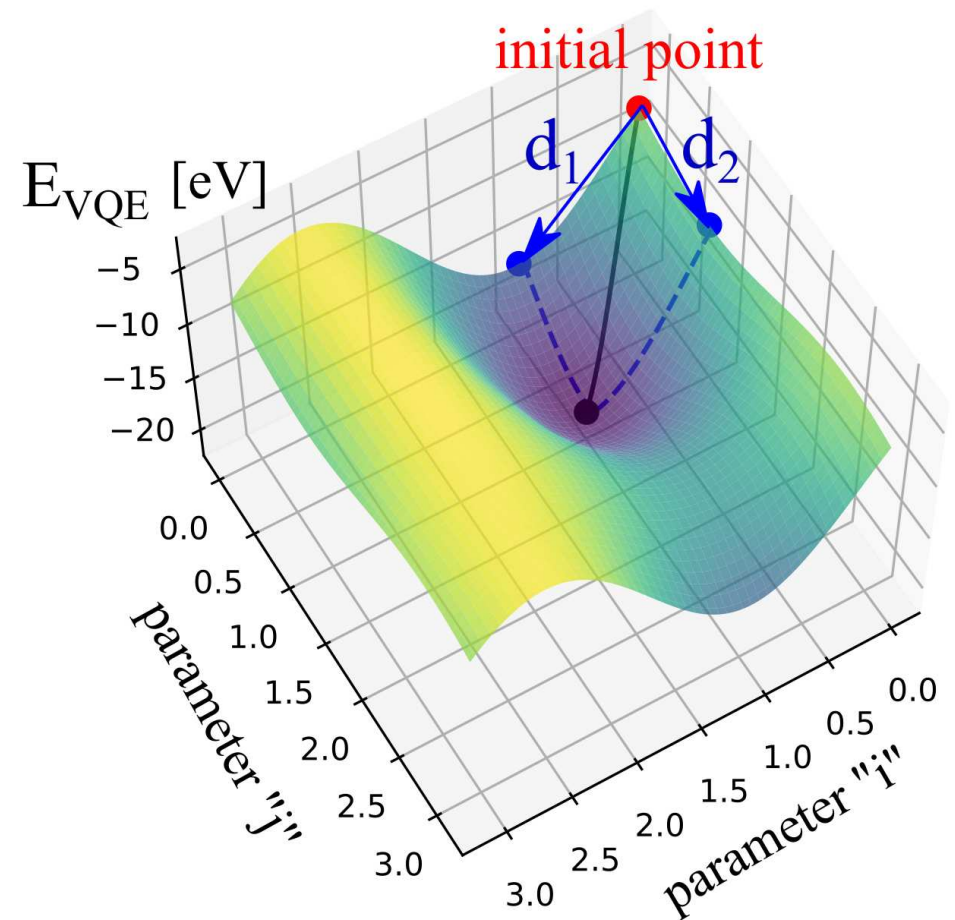


~~Decrease the learning rate~~
Increase

- Perform line search along a well defined direction



- How to determine search direction?
- What is the range of the line search?
- layer-by-layer optimization



Batched Line Search Strategy for Navigating through Barren Plateaus
in Quantum Circuit Training

gate containing parameter p_i : U_p

$$|\Psi\rangle = U_1 \cdot U_2 \cdot U_3 \dots \overbrace{(A \cdot \cos(p_i) + B \cdot \sin(p_i) + C)}^{U_p} \dots U_{K-2} \cdot U_{K-1} \cdot U_K |0\rangle$$

matrices

$$|\Psi\rangle = \cos(p_i)|a\rangle + \sin(p_i)|b\rangle + |c\rangle$$

scalars

$$E = \langle \Psi | H | \Psi \rangle = \kappa \cdot \sin(2p_i + \xi) + \gamma \cdot \sin(p_i + \phi) + C$$

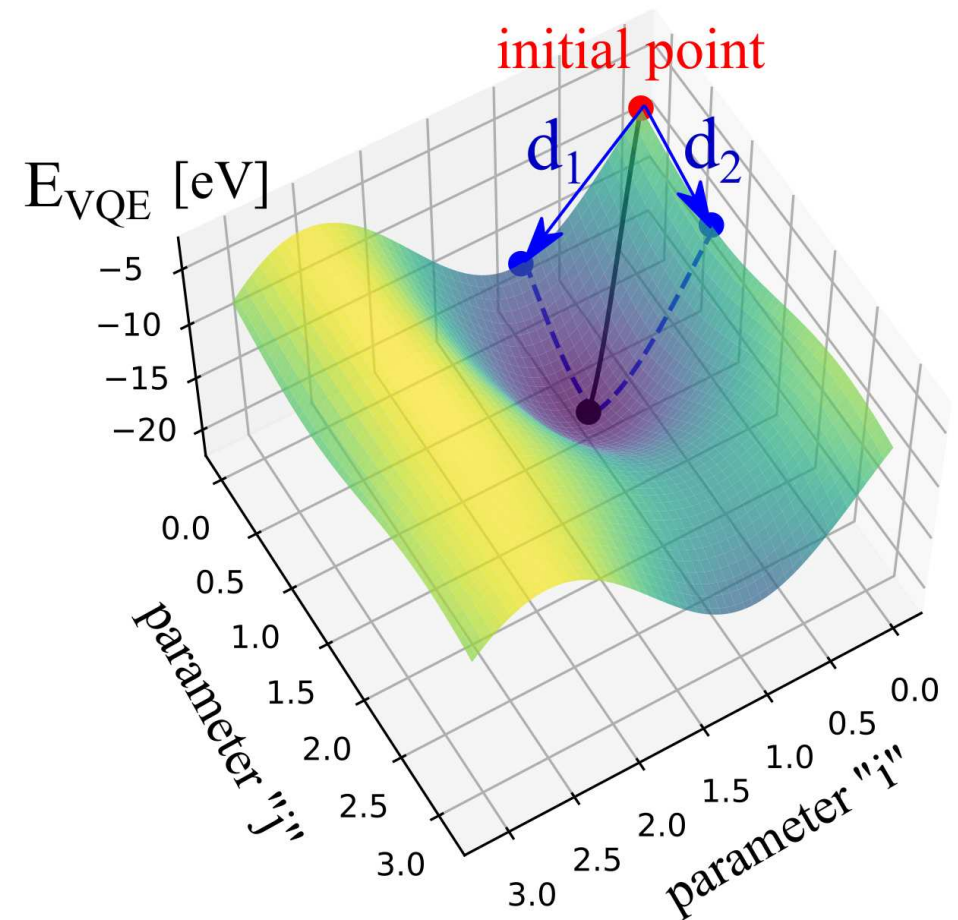
knowing the constants, the line search becomes efficient

$$E_{VQE} = \kappa \cdot \sin(2\theta_i + \xi) + C$$

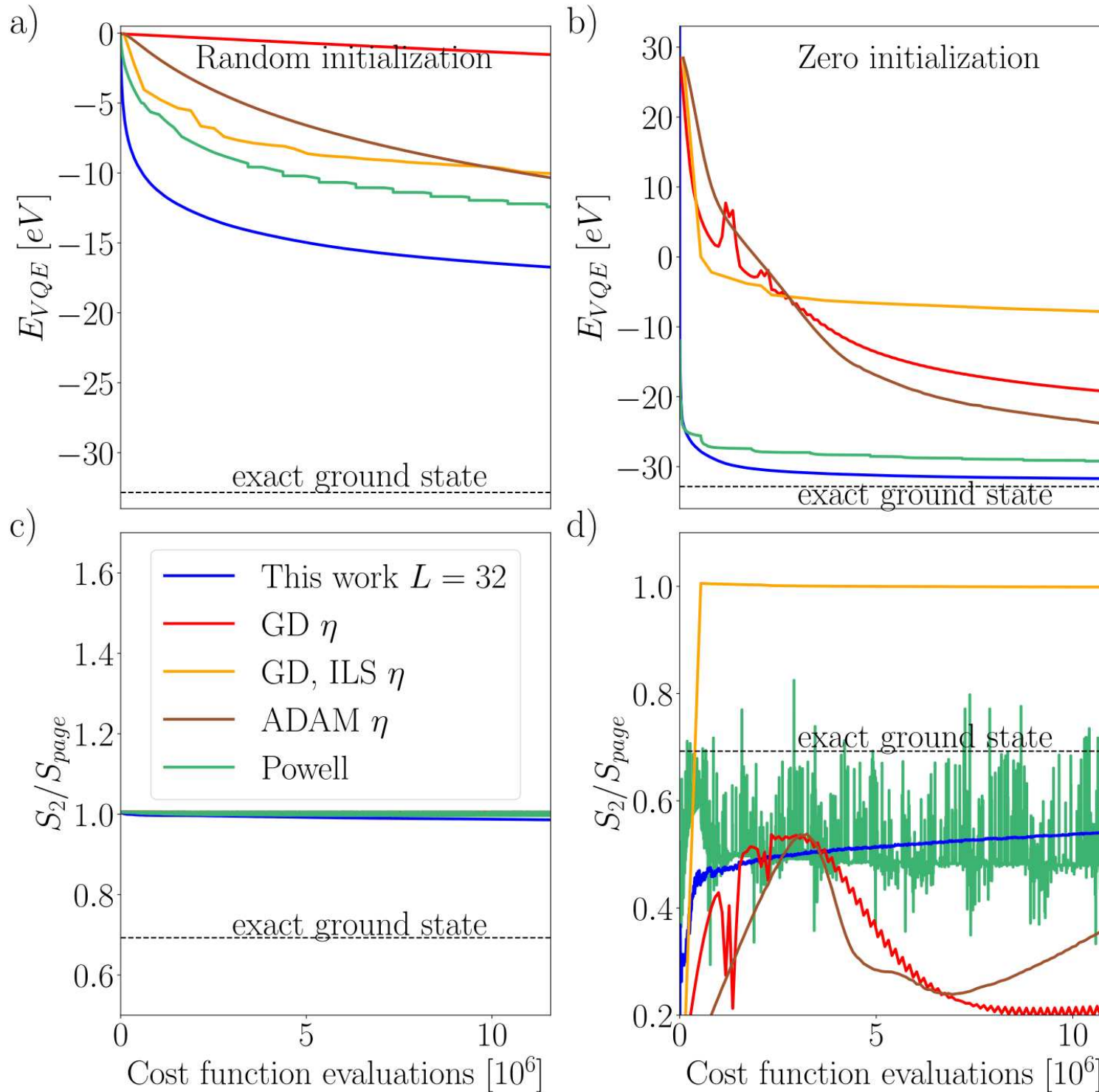
- randomly select a subset Λ of the parameters
- determine the parameter-wise minimum θ_i^*
- we define the search direction

$$d_i = \begin{cases} \theta_i^* - \theta_i & \text{if } i \in \Lambda \\ 0 & \text{otherwise.} \end{cases}$$

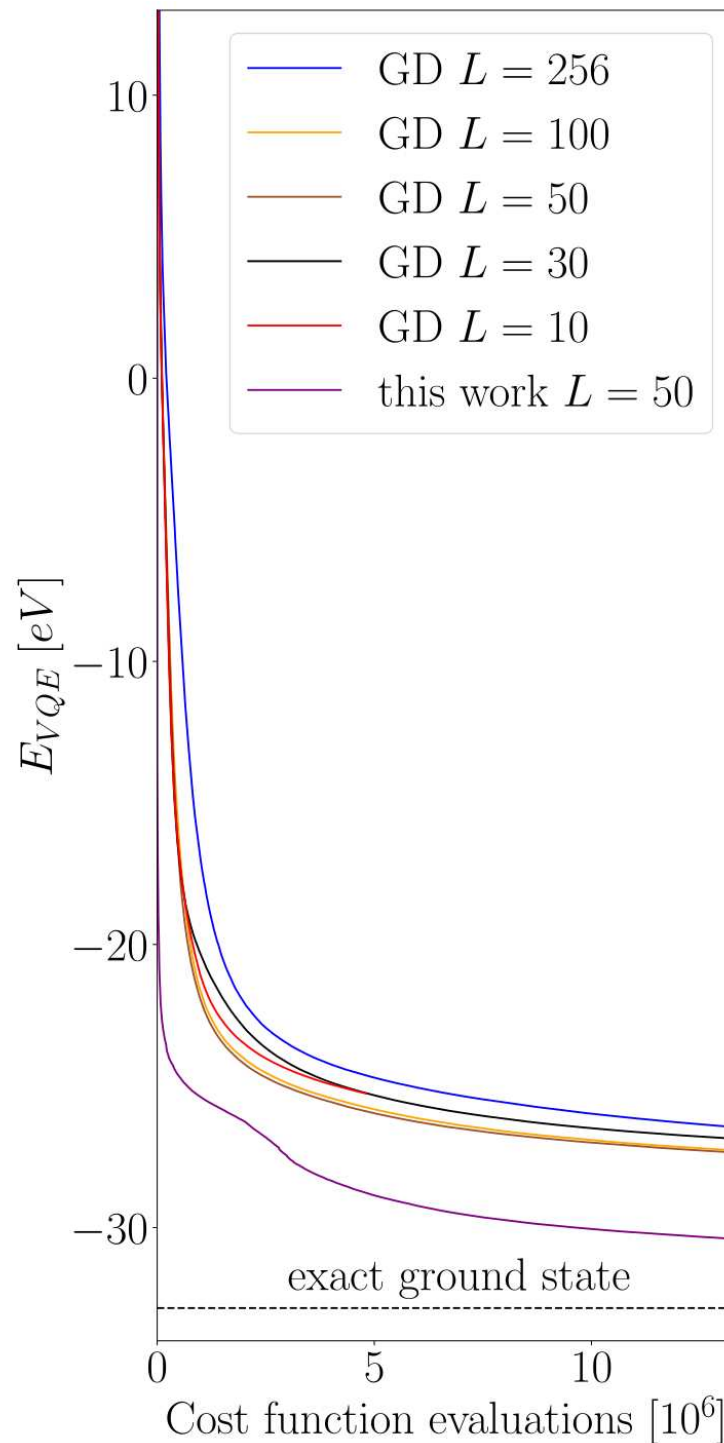
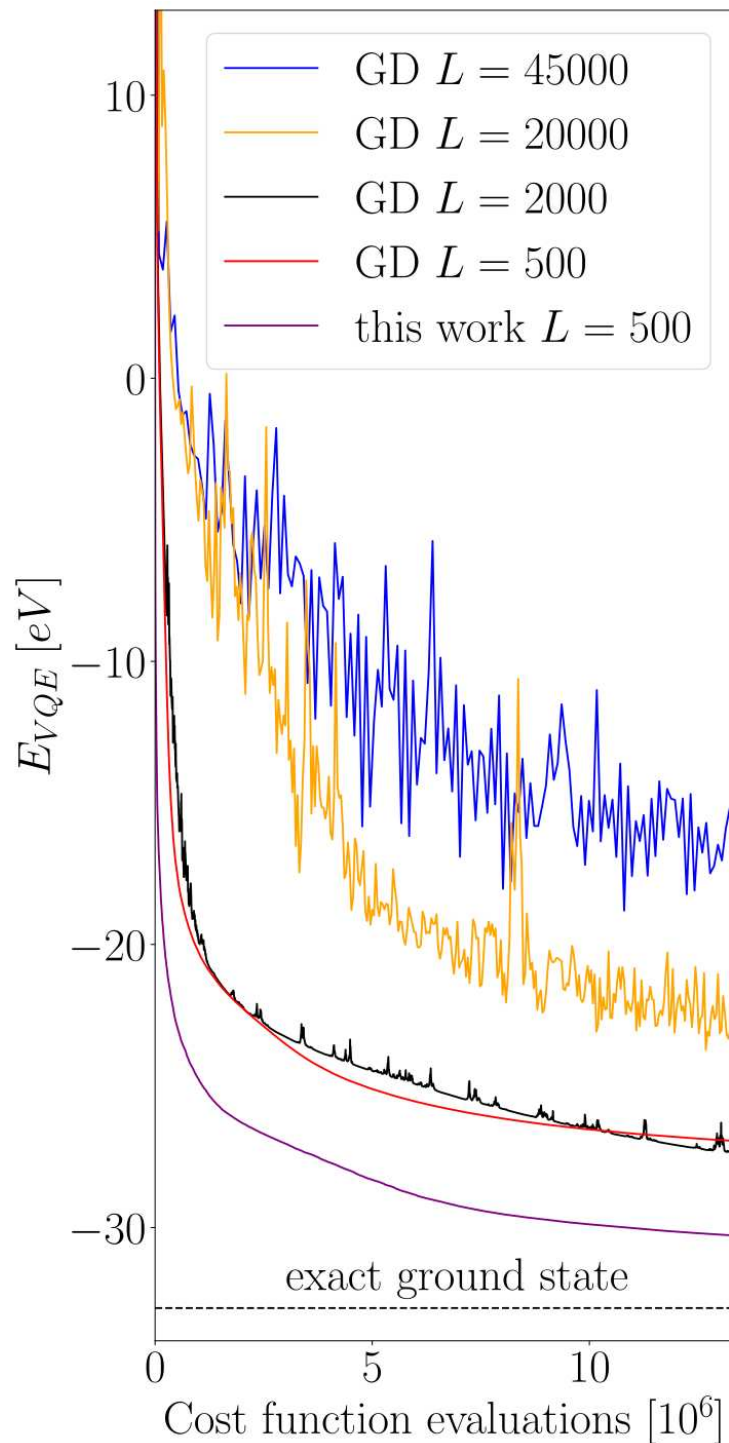
- decreasing values in E_{VQE} are **automatically** associated with moderate entanglement entropy.
- There are **no additional hyper-parameters** in the algorithm



Compare optimization strategies



Why is our method so efficient?

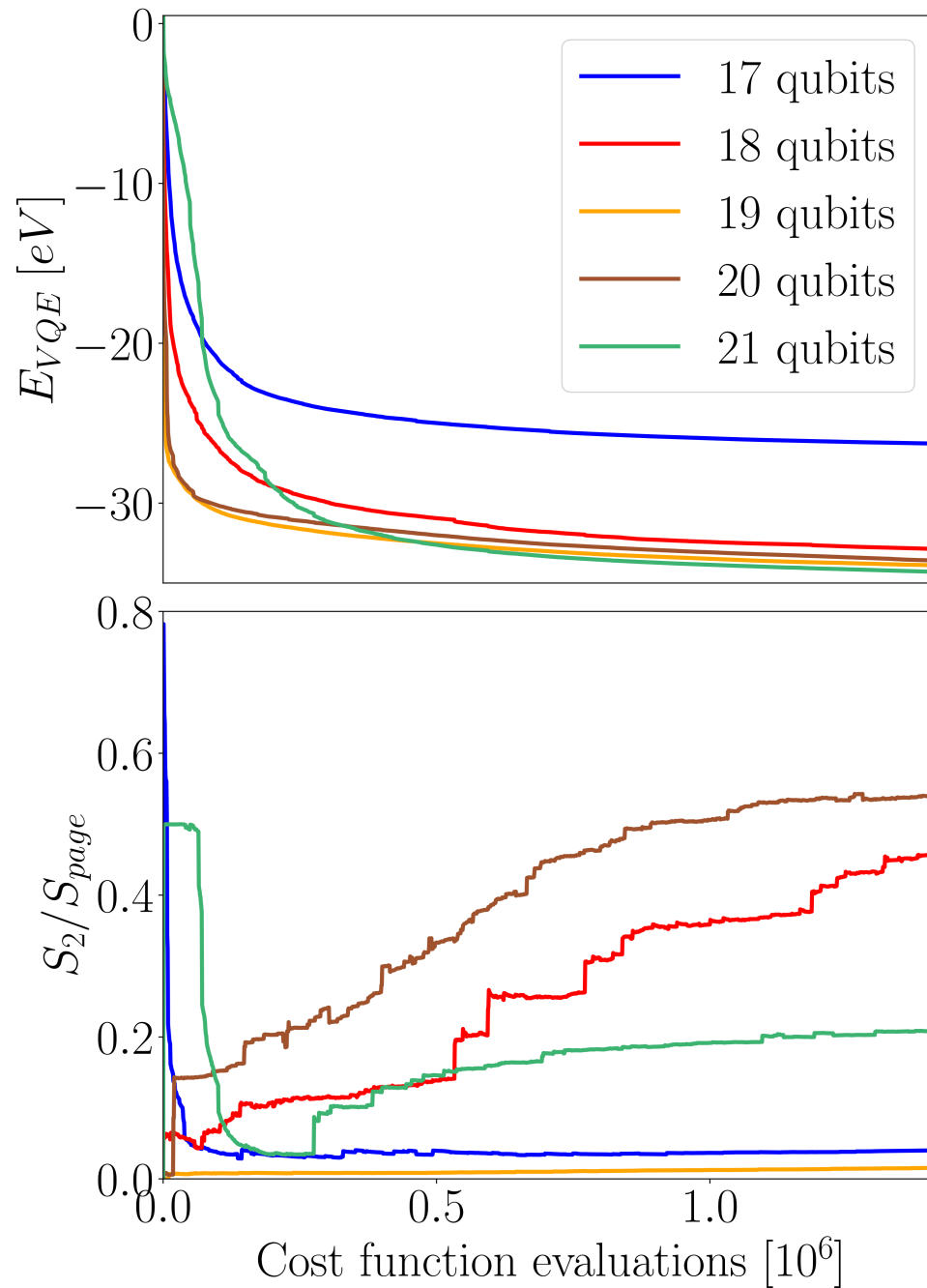


**L... the number of
parameters updated
in one iteration**

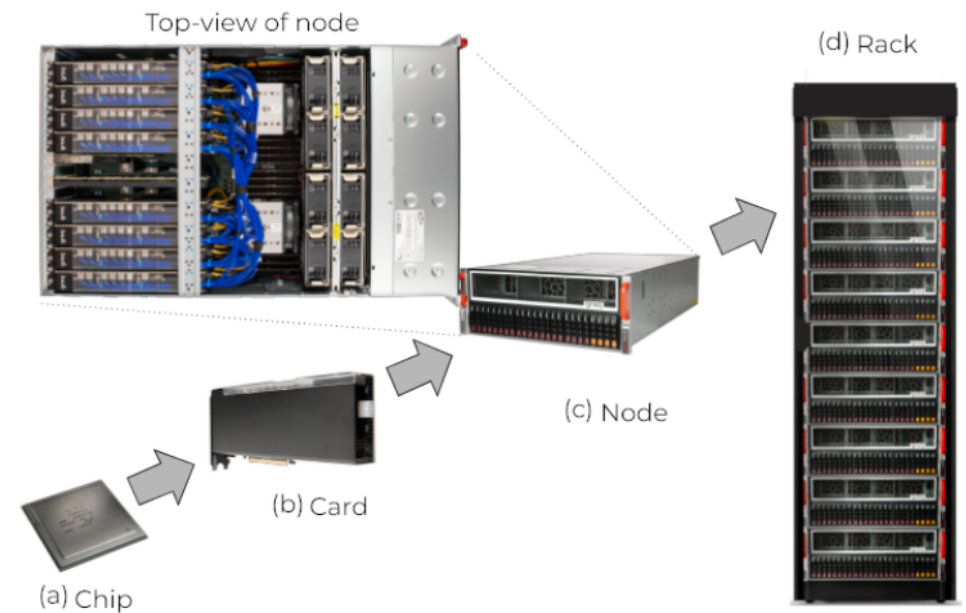
GD... Gradient descend



Qubit benchmark

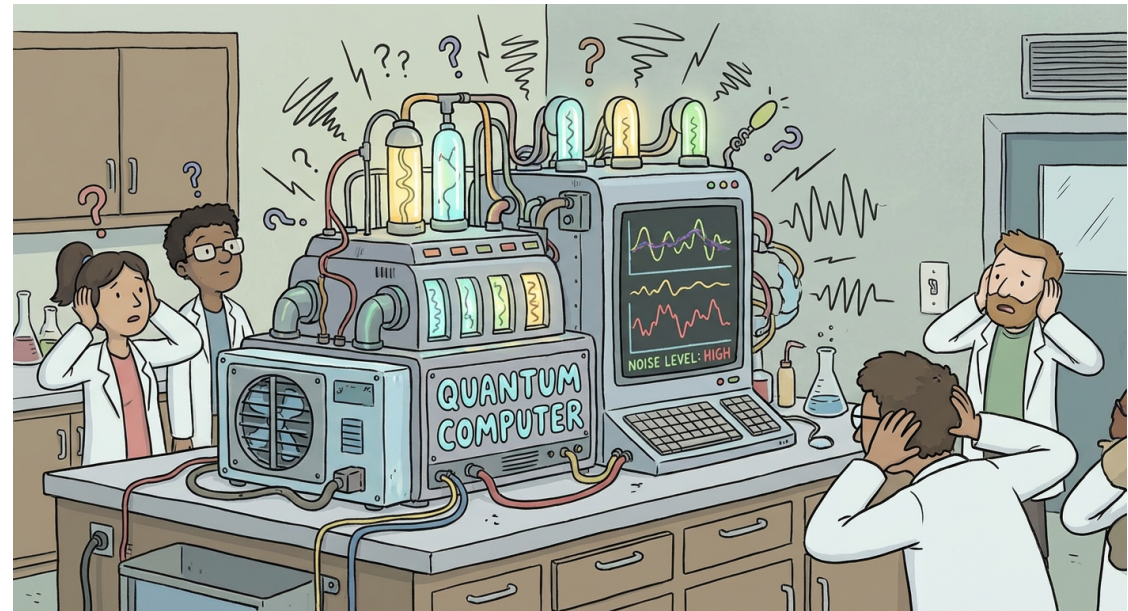


Experiments done on Groq accelerators



Looking Ahead

- **Shot noise:** how many time we need to run the quantum circuit and measure the output to advance the circuit training
- **Noise implementations** in Squander to include noise in QML algorithms
 - **Unital** noise
 - **Non-Unital** noise
- Retrain circuits with noise included



Acknowledgement



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contact: Peter Rakyta, peter.rakyta@ttk.elte.hu

