From Easy to Hard:

Tackling Quantum Problems with Learned Gadgets For Real Hardware

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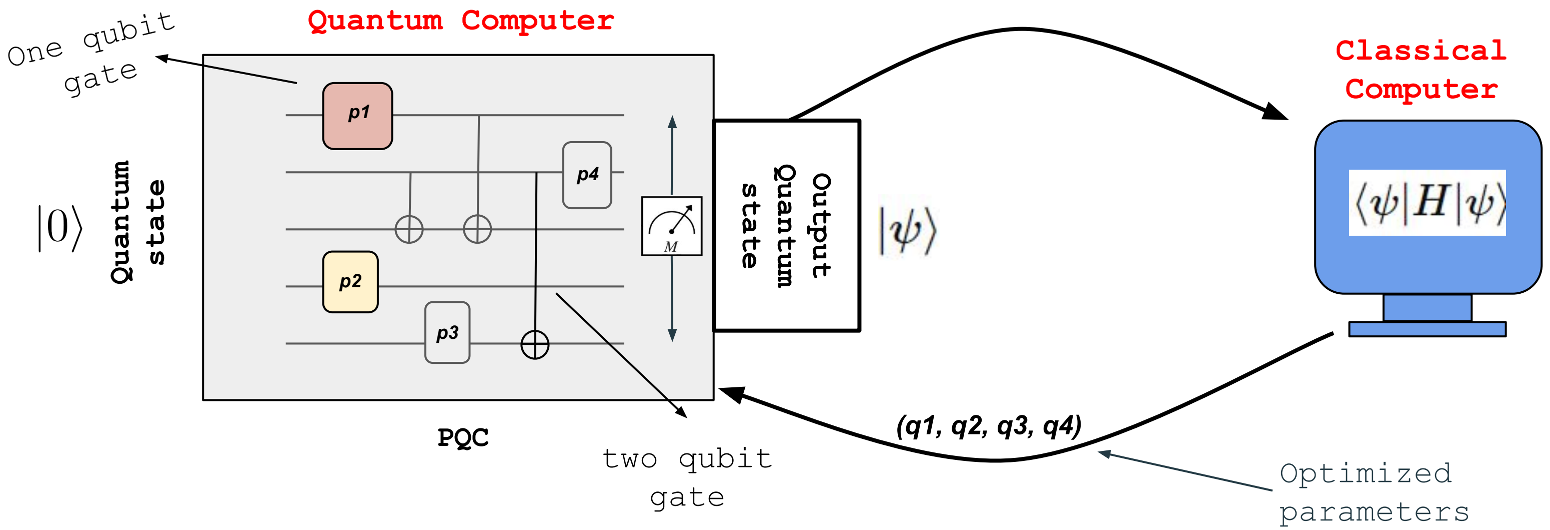
Work in collaboration

Leopoldo Sarra

Second Workshop of
Machine Learning for Quantum Technology

Erlangen, Thursday, November 7th 2024

Variational Quantum Algorithms (VQAs)



Quantum computer (QC): Prepares quantum state (QS)

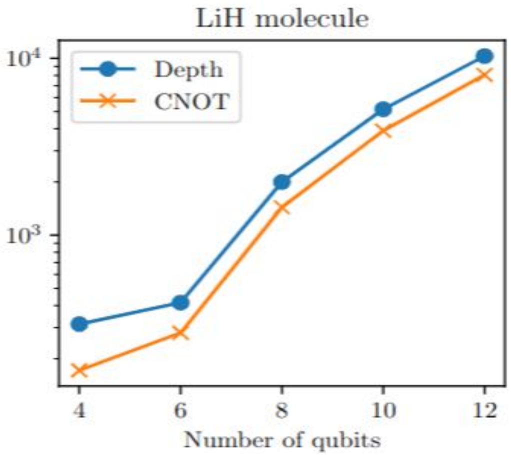
Classical computer (CC): Takes the QS and evaluate loss/cost function.

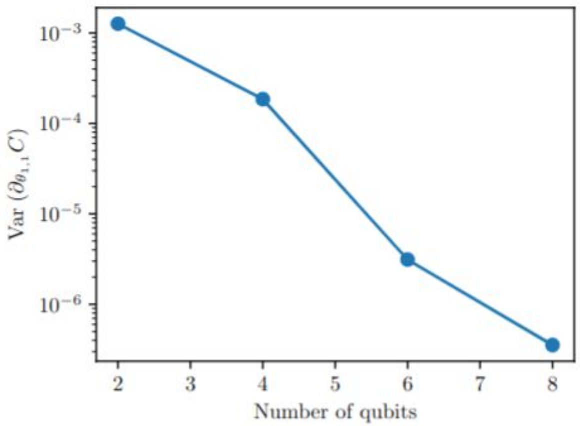
Optimization loop: Optimize cost function in CC and feed back optimized parameters to QC.

PQC = parameterized quantum circuit

Circuit construction strategies

Problem inspired ansatz: contain a lot of one and two qubit gate and enormous depth. Scales rapidly with qubits.



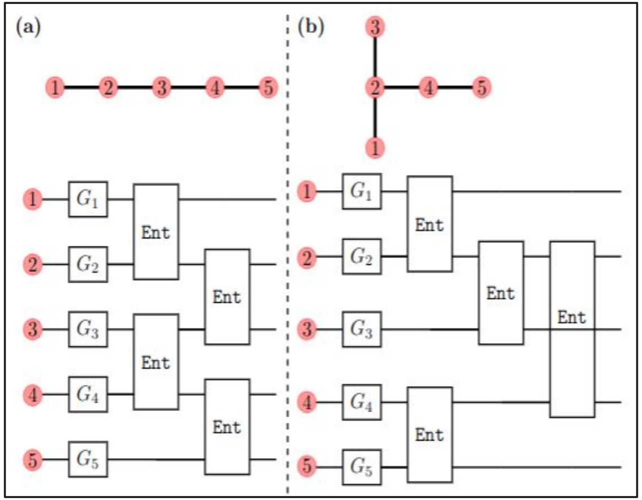


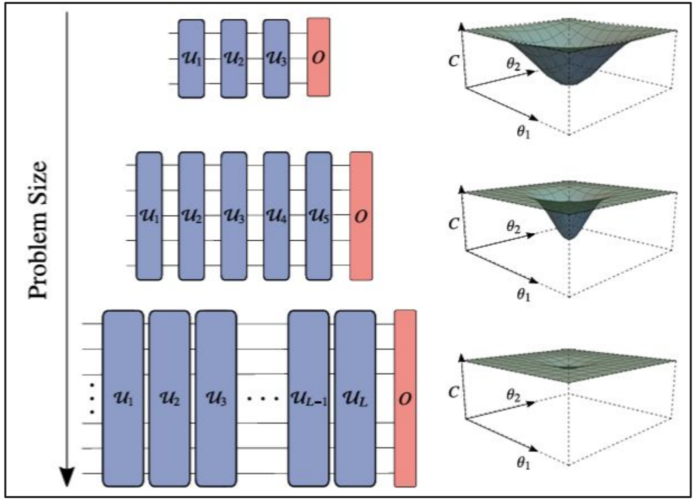
Example
UCCSD ansatz for Variational Quantum Eigensolver(VQE)

Barren Plateaus!

Circuit construction strategies

Problem-agnostic ansatz: Contain small number gates and depth.



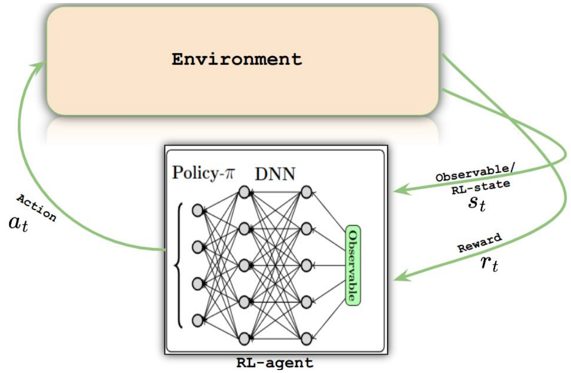


Example
Hardware efficient ansatz

Noise-Induced Barren Plateau

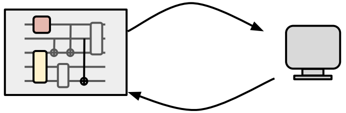
[2] Cerezo, Marco, et al. Nature communications 12.1 (2021): 1791.

Reinforcement learning (RL) for circuit design

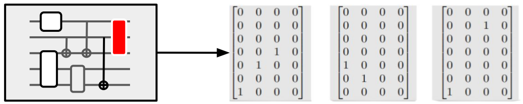


Kundu, Akash. "Reinforcement learning-assisted quantum architecture search for variational quantum algorithms." arXiv preprint arXiv:2402.13754 (2024).

Environment → Variational Quantum Algorithms (VQAs)



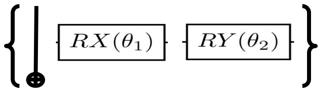
RL-state → Quantum circuit encoded in ML-friendly format



Reward → Cost function $C(\vec{\theta}) = \langle 0|U^\dagger(\vec{\theta})HU(\vec{\theta})|0\rangle$ →

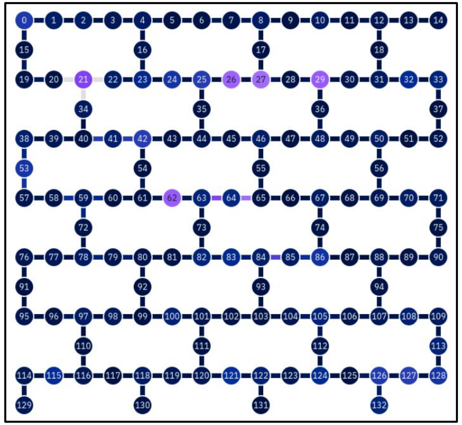
$$R = \begin{cases} r & \text{if } C_t < \zeta, \\ -r & \text{if } t \geq T_{\max} \text{ and } C_t \geq \zeta, \end{cases}$$

Action space → Quantum gates



; { Any operator pool }

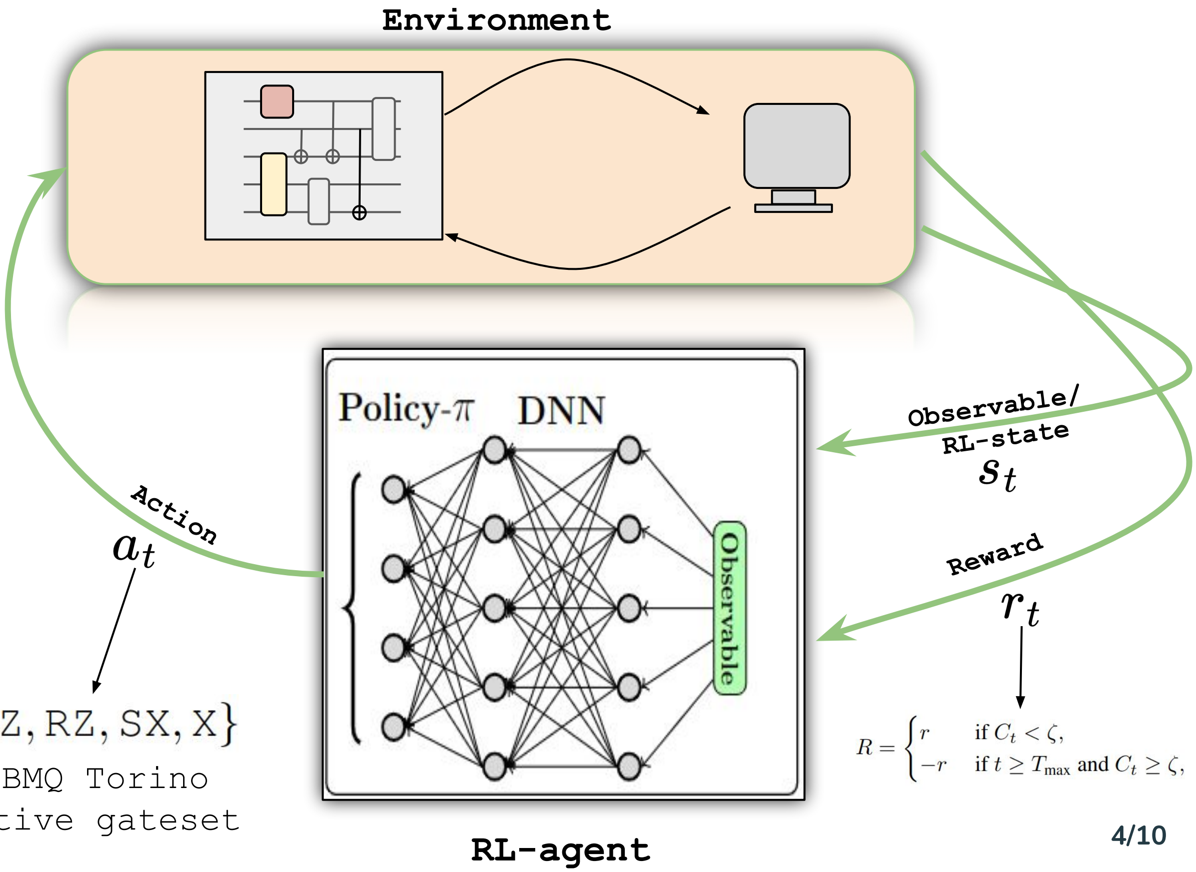
RL for circuit design for quantum hardware



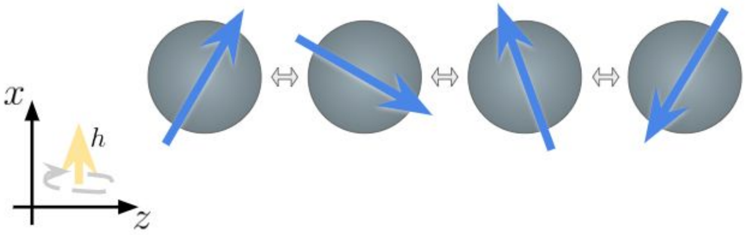
IBMQ Torino hardware on IBM Heron processor

$\{\mathrm{CZ}, \mathrm{RZ}, \mathrm{SX}, \mathrm{X}\}$

IBMQ Torino native gateset

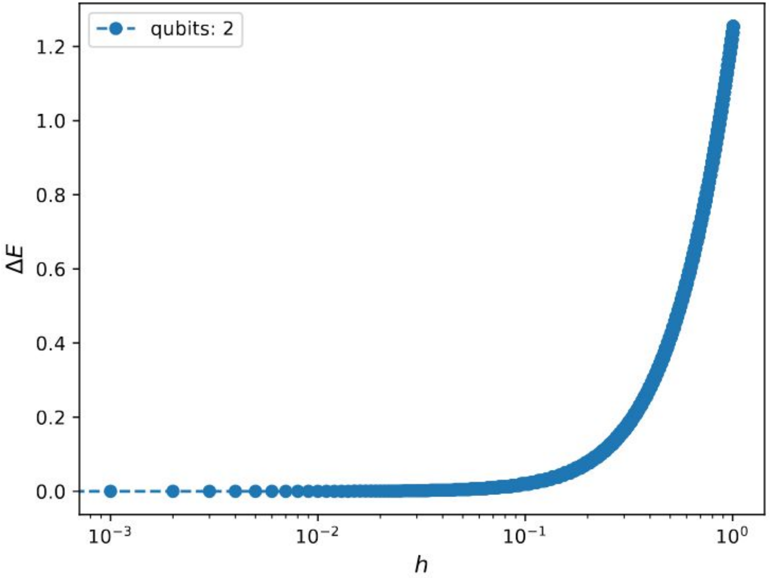


Let's solve transverse field Ising model!



$$H = -J \sum_{\langle i,j \rangle}^{N} \sigma_i^z \sigma_j^z - h \sum_i \sigma_i^x$$

energy gap



$J = 1$ and h varying

Shortcomings: circuit design for quantum hardware

Curriculum reinforcement learning for quantum architecture search under hardware errors

Yash J. Patel, Akash Kundu, Mateusz Ostaszewski, Xavier Bonet-Monroig, Vedran Dunjko, Onur Danaci

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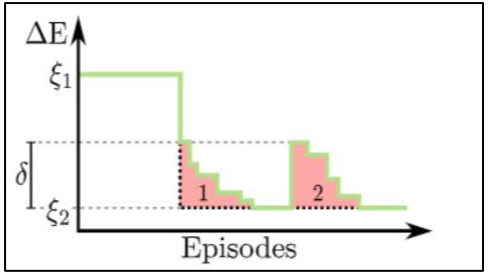
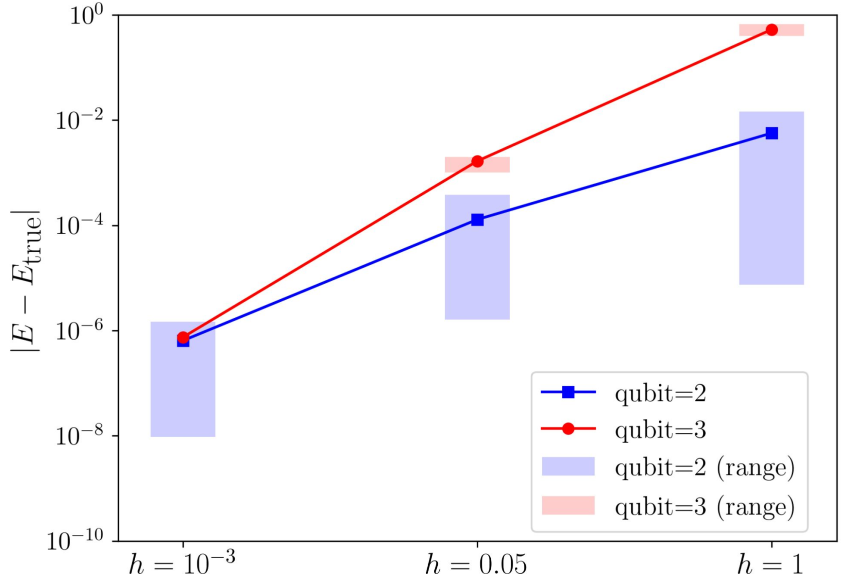
Uses curriculum RL



No prior knowledge needed!

With action space: $\{\mathrm{CZ}, \mathrm{RZ}, \mathrm{SX}, \mathrm{X}\}$ (available on quantum hardware)

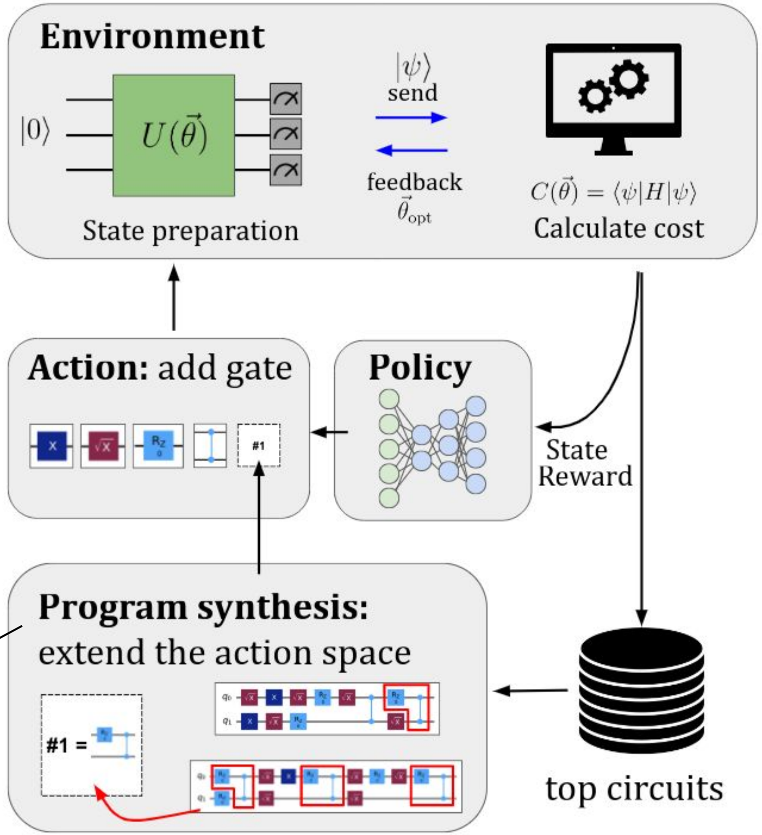


Our solution: Gadget Reinforcement Learning (GRL)

We extend the action space with recurring patterns ("gadgets")

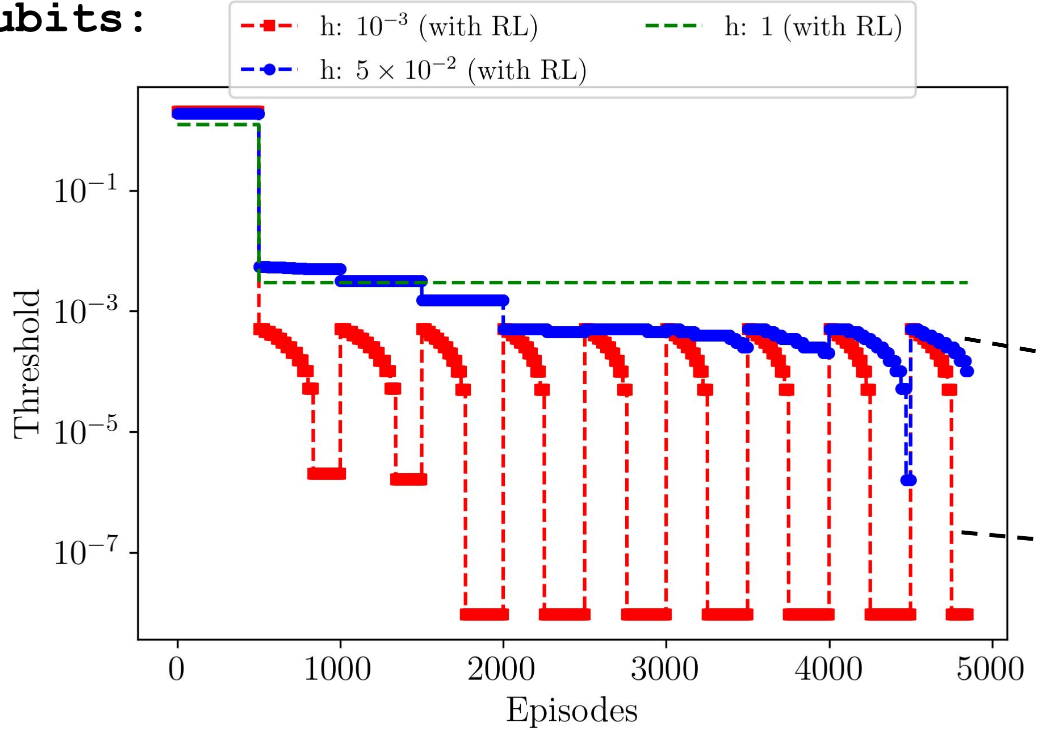
Trenkwalder, L. M., López-Incera, A., Nautrup, H. P., Flamini, F., & Briegel, H. J. (2023). Automated gadget discovery in the quantum domain. Machine Learning: Science and Technology, 4(3), 035043.

Sarra, Leopoldo, Kevin Ellis, and Florian Marquardt. "Discovering quantum circuit components with program synthesis." Machine Learning: Science and Technology 5.2 (2024): 025029.

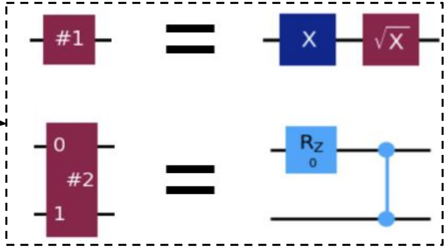


Learning from different regimes

2 qubits:



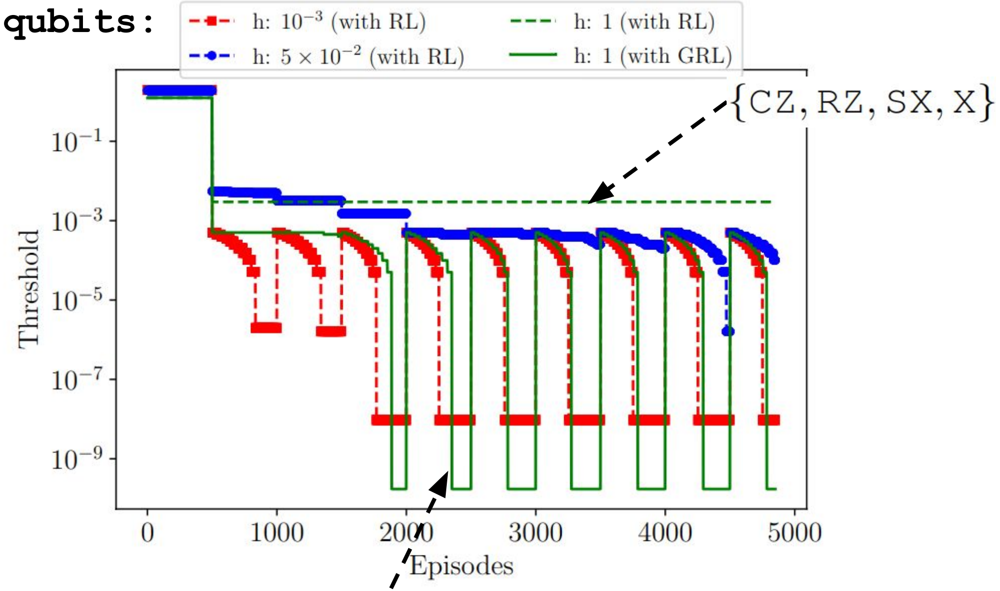
Action space: $\{\mathrm{CZ}, \mathrm{RZ}, \mathrm{SX}, \mathrm{X}\}$



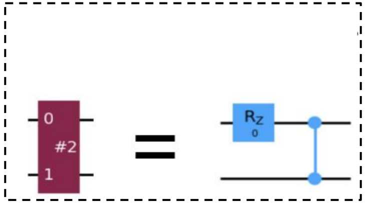
We learn

Learning from different regimes (and **applying it!**)

2 qubits:

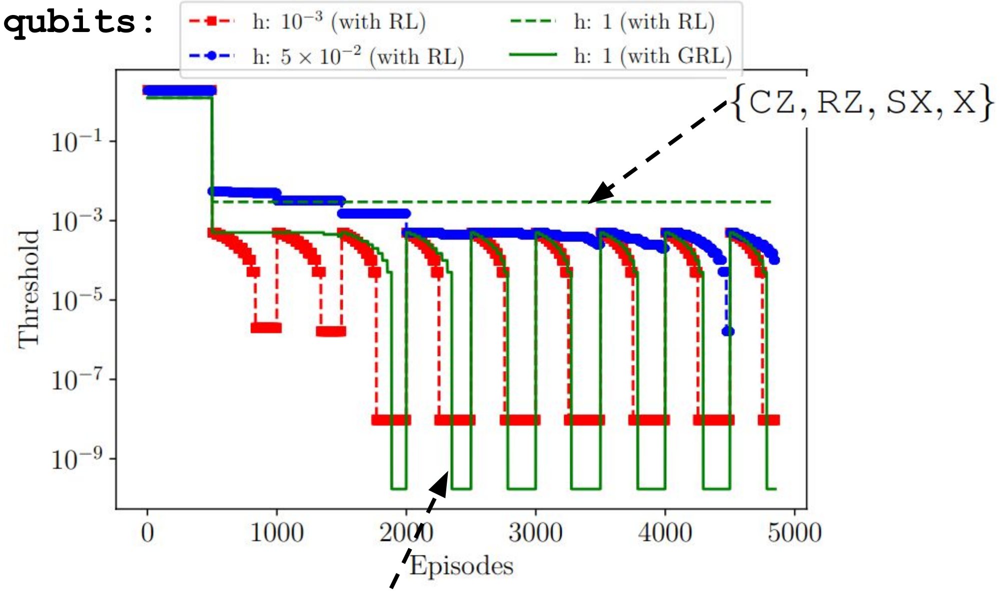


$\{\mathrm{CZ}, \mathrm{RZ}, \mathrm{SX}, \mathrm{X}\}$ +

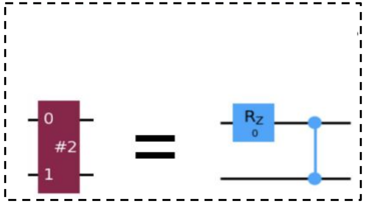


Learning from different regimes
(and **applying it!**)

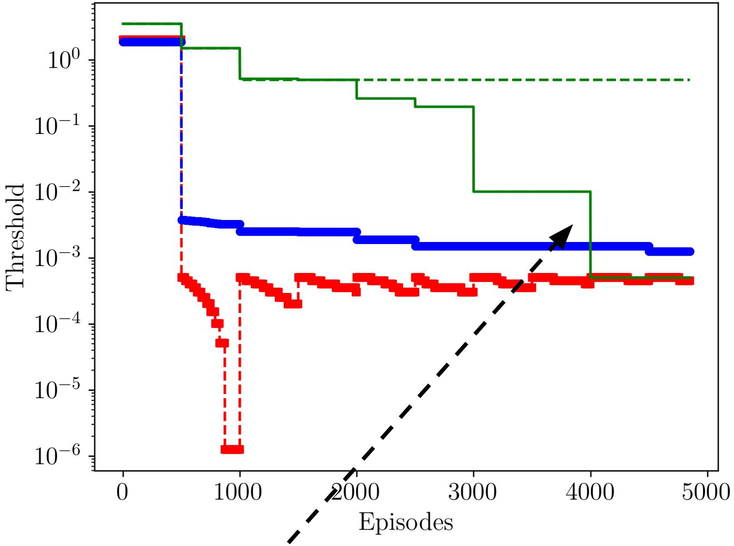
2 qubits:



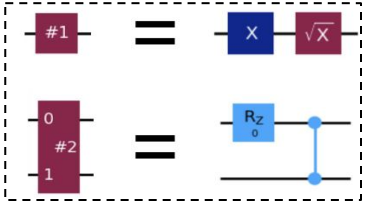
$\{CZ, RZ, SX, X\}$ +



3 qubits:



$\{CZ, RZ, SX, X\}$ +



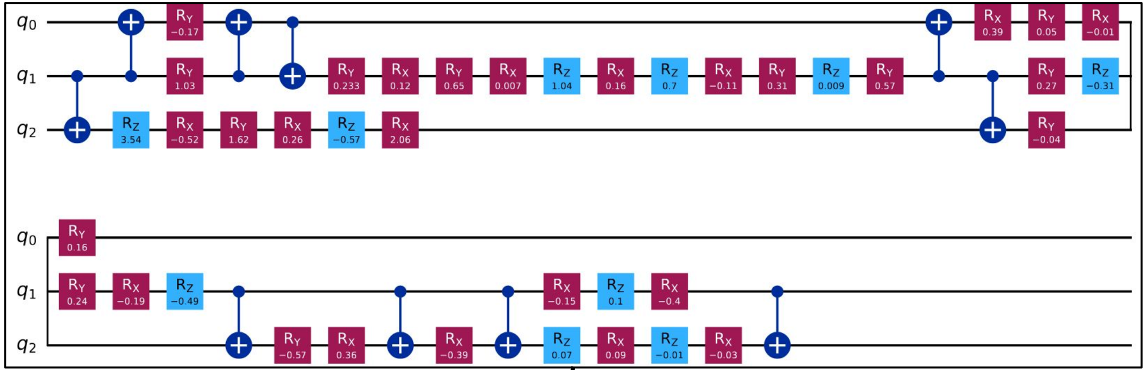
Transpilation on quantum hardware (3-qubit TFIM)

in

RL

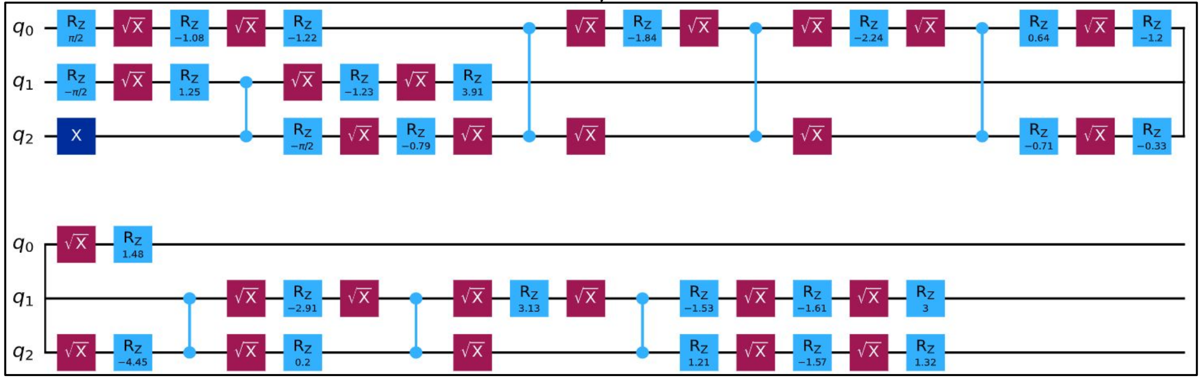
universal gate set

$$\{RX, RY, RZ, CX\}$$



54 1-qubit gates

Transpiled to real hardware

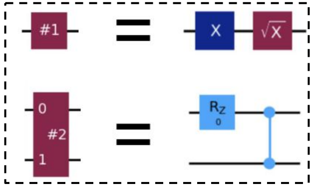


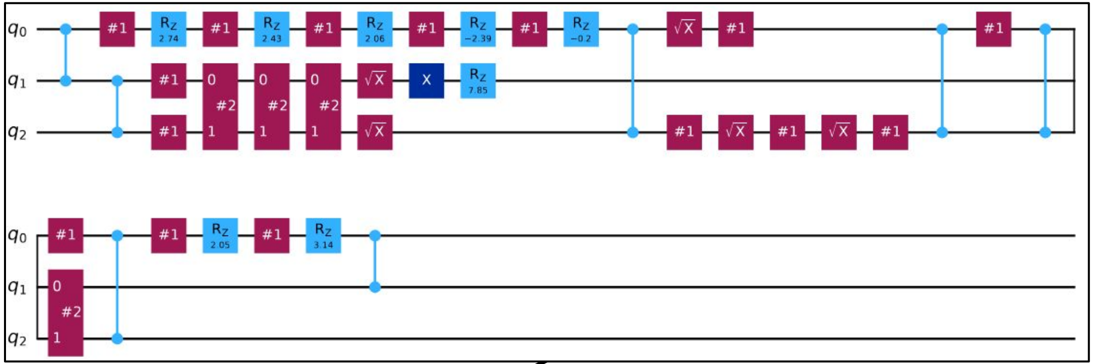
Transpilation on quantum hardware (3-qubit TFIM)

in

GRL

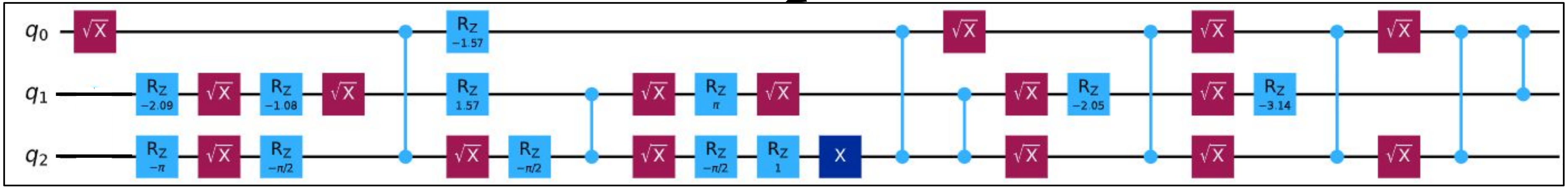
$\{CZ, RZ, SX, X\}$ +





Transpiled to real hardware

29 1-qubit gates



Some of other works

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KANQAS: Kolmogorov-Arnold Network for Quantum Architecture Search

Akash Kundu, Aritra Sarkar & Abhishek Sadhu

EPJ Quantum Technology **11**, Article number: 76 (2024) | Cite this article

Curriculum reinforcement learning for quantum architecture search under hardware errors

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Enhancing variational quantum state diagonalization using reinforcement learning techniques

Akash Kundu[7,1,2], Przemysław Bedełek[3], Mateusz Ostaszewski[3], Onur Danaci[4,5], Yash J Patel[6], Vedran Dunjko[4,6] and Jarosław A Miszczak[1]

Home > Quantum Machine Intelligence > Article

A quantum information theoretic analysis of reinforcement learning-assisted quantum architecture search

Research | Open access | Published: 06 August 2024

Volume 6, article number 49, (2024) Cite this article

Abhishek Sadhu, Aritra Sarkar & Akash Kundu

Thank you for listening!

From Easy to Hard: Tackling Quantum Problems with Learned Gadgets For Real Hardware

Akash Kundu, Leopoldo Sarra

arXiv:2411.00230

- Using extracted gadgets as extra actions improves RL efficiency
- Generalization between different regimes (simple/hard) and system size
- Allows solving problems directly with the native hardware gateset with more efficiently.