Benchmarking quantum algorithms with Tensor Network simulators

Carlos Ramos-Marimón, Tensor Networks expert

Seminar on Quantum Computer Benchmarks (TQCI International Conference, Paris Jun 24th 2025)

Quobly was launched in November 2022

quobly

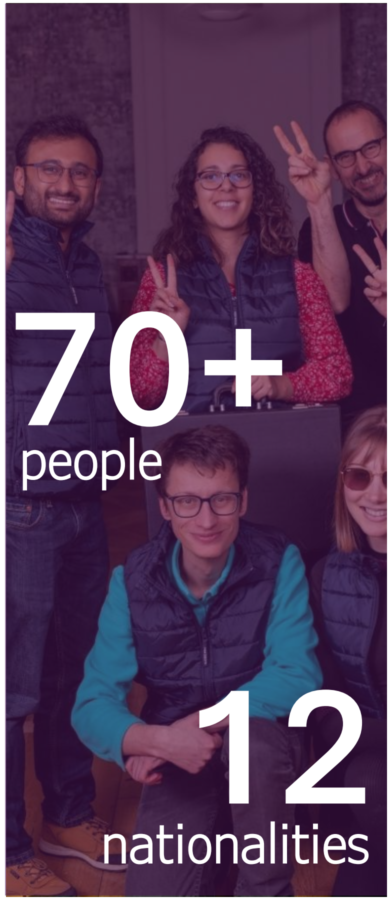
3 co-founders met in GRENOBLE

€37M funding to date

€19M seed funding in 2023

€2.5M 2023 EIC Transition Awardee

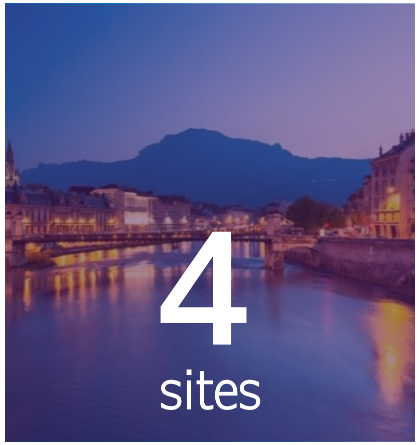
€10M revenue through Proqcima Awardee



70+ people

12 nationalities

2 lab partnerships: CEA & CNRS



4 sites

ST strategic partnership

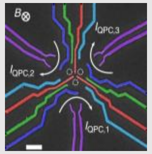
Our networks: IEC, ISO, MINALOGIC, EIC Scaling Club Selected Club Member, le lab quantique, uIC, QuantAlps, #QEI, QUANTUM FLAGSHIP, FRANCE 2030, LES MAISONS DU QUANTIQUE, FRANCE DEEPTECH, CREATIVE DESTRUCTION LAB, Le HUB Quantique, Teratec

Quobly was born from the combined expertise of CEA and CNRS at Grenoble

ACADEMIC

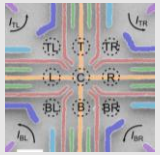
READY

2017 — nature COMMUNICATIONS



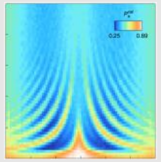
Coherent long-distance displacement of individual electron spins

2020 — nature nanotechnology



Coherent control of individual electron spins in a 2D array (9 quantum dots)

2021 — nature nanotechnology



Distant spin entanglement via fast and coherent electron shuttling

DEVELOPING THE KNOW-HOW FOR CONTROLLING MULTIPLE SPIN QUBITS

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quobly

ACADEMIC READY

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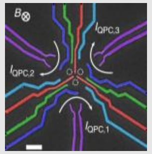

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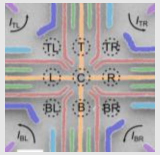

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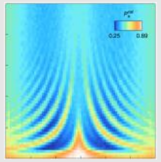
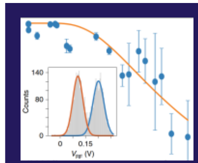


Distant spin entanglement via fast and coherent electron shuttling

DEVELOPING THE KNOW-HOW FOR CONTROLLING MULTIPLE SPIN QUBITS

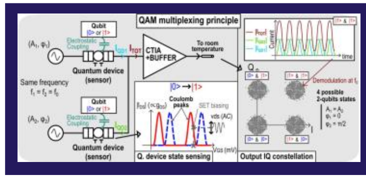
INDUSTRY READY

MANUFACTURING SPIN QUBITS IN INDUSTRIAL ENVIRONMENTS



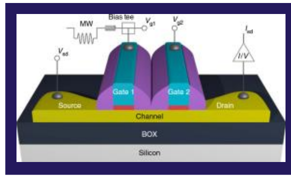
Gate-based high fidelity spin readout in a CMOS device

2019 — nature nanotechnology



Demonstrating QAM Multiplexing for Spin Qubits

2025 — IEEE



A CMOS silicon spin qubit

2016 — nature COMMUNICATIONS

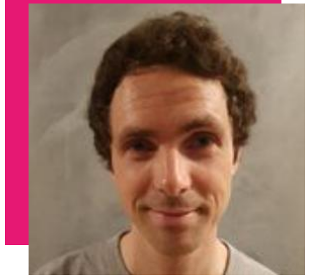
A single hole spin with enhanced coherence in natural silicon

2022 — nature nanotechnology

We leverage the semicon. industry's 60+ years of experience, fabless approach using commercial FD SOI technologies

The Quantum Information Team at Quobly

Benoît Vermersch



Thibaud Louvet

quantum algorithms
for quantum chemistry,
tensor networks

Carlos Ramos-Marimón

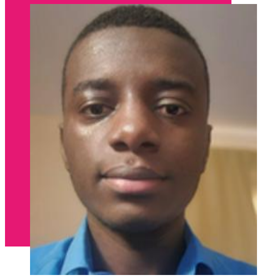
tensor networks

Nathan Miscopein

quantum error correction

Dimitri Lanier

channel learning



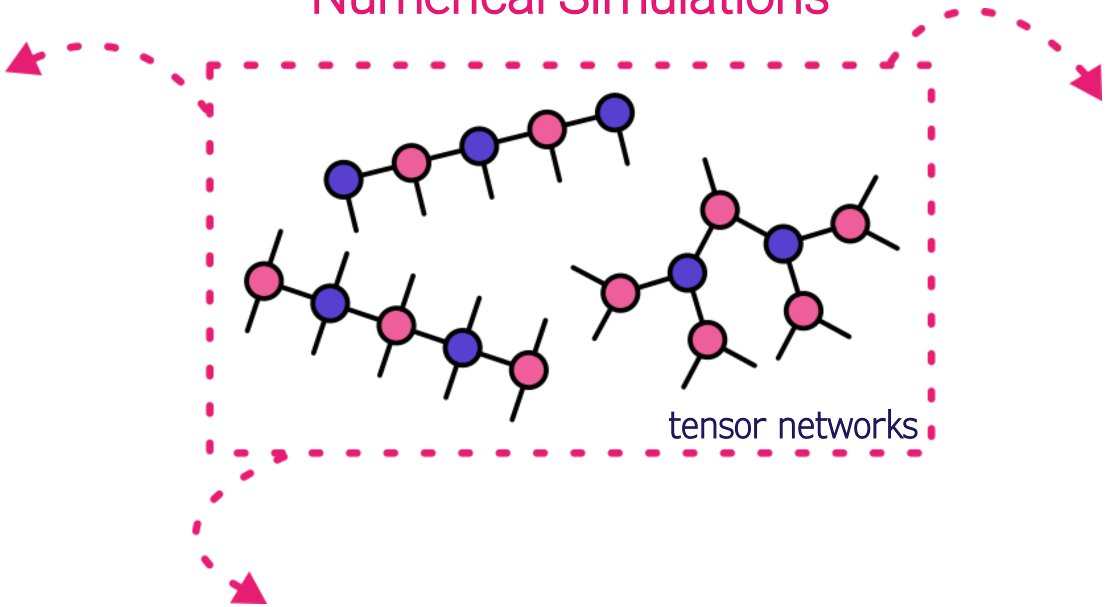
Amara Keita

quantum chemistry

The Quantum Information Team at Quobly

We support/guide hardware's development using quantum information tools adapted for the **large-scale** scenario

Numerical Simulations



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quobly

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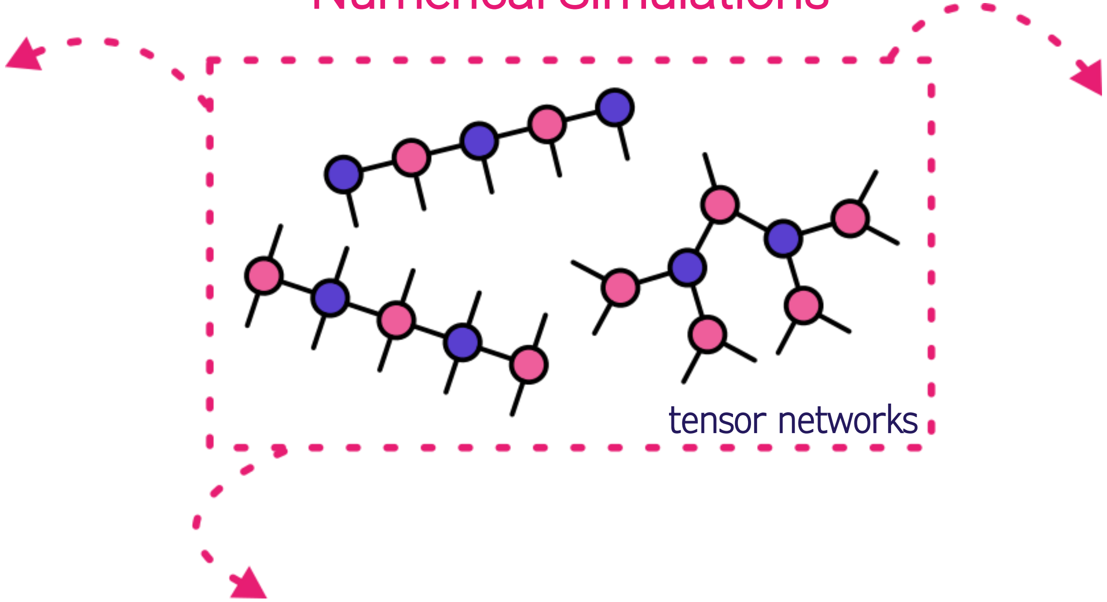
UGA Université Grenoble Alpes

Measurements & Benchmarking

- Cross-validate QPU outputs
- Understanding noise impact
- Ideal outcomes as baseline for fidelity estimations

Numerical Simulations



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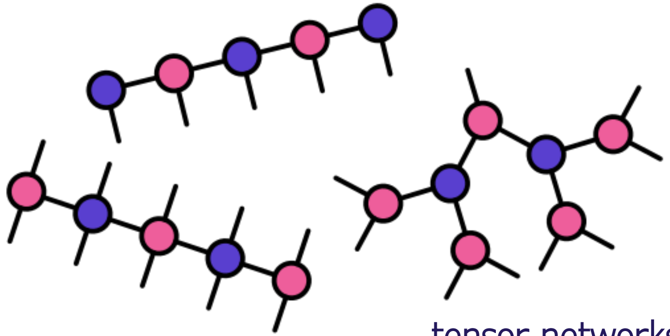
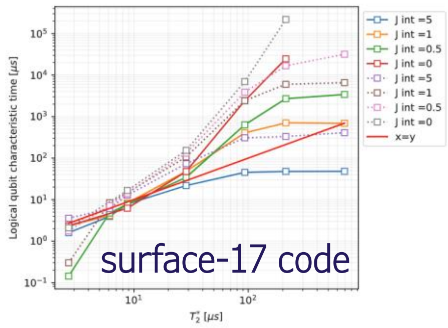


Architectures and QEC

- Realistic setting performance assessments
- Explore new schemes
- Error mitigation research



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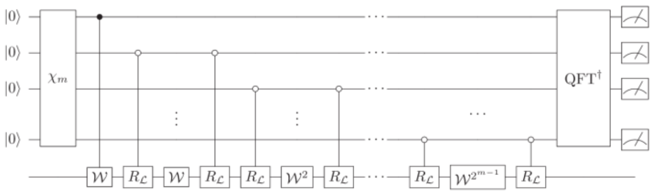
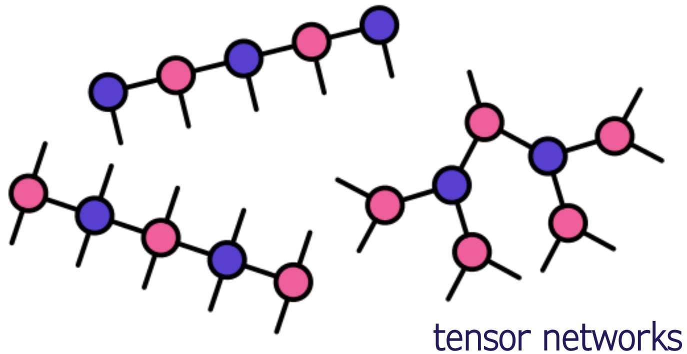


Numerical Simulations



tensor networks

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- Realistic setting performance assessments
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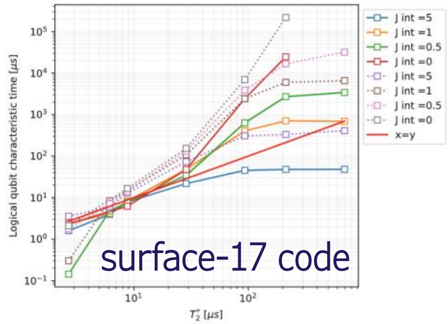


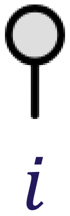
FTQC algorithm R&D

- Simulate logical-level FT circuits
- Assess algorithm resilience to noise
- Estimate resource overheads
- Benchmark decoders and optimizers

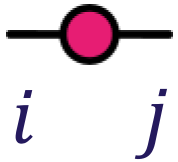
Tensor Networks in the context of Quantum

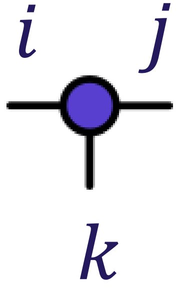
What are Tensor Networks? First: **graphic notation**

vectors

$v_i =$ 

matrices

$A_{ij} =$ 

$T_{ijk} =$ 

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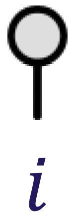
$v_i =$ 

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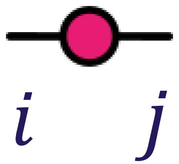
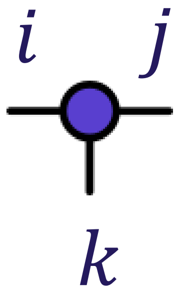
$A_{ij} =$ 

$T_{ijk} =$ 

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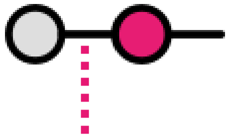
$$\sum_i v_i A_{ij} =$$ 

contraction

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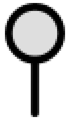
$v_i =$ 

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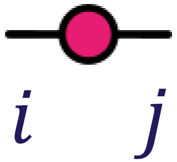
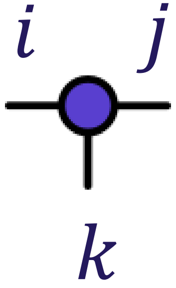
$A_{ij} =$ 

$T_{ijk} =$ 

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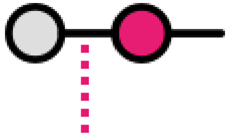
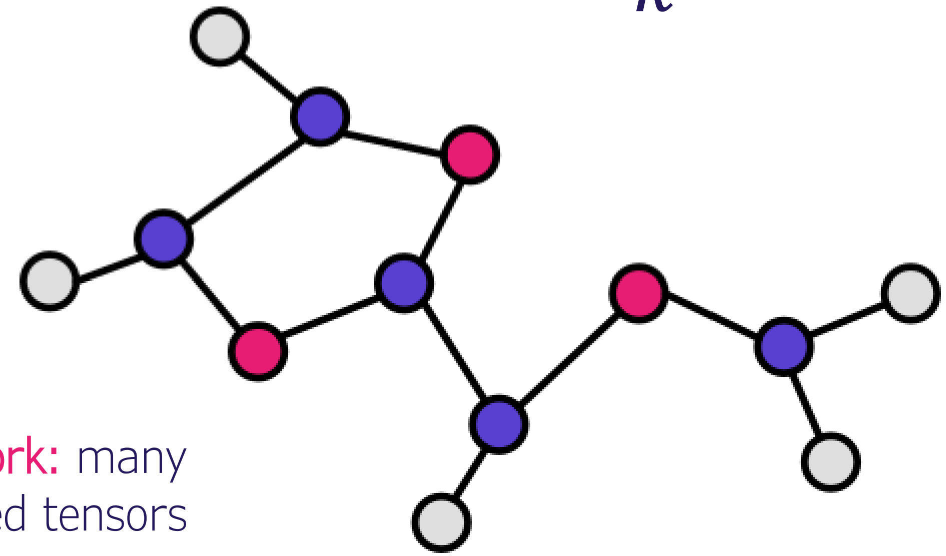
$\sum_i v_i A_{ij} =$ 

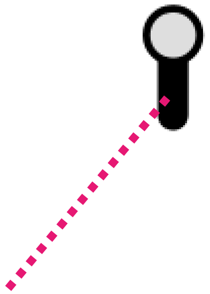
contraction



Tensor Network: many (**small**) contracted tensors

Tensor Networks in the context of Quantum

We can decompose big vectors and matrices into networks of small tensors



$$D = 2^5 = 32$$

Tensor Networks in the context of Quantum

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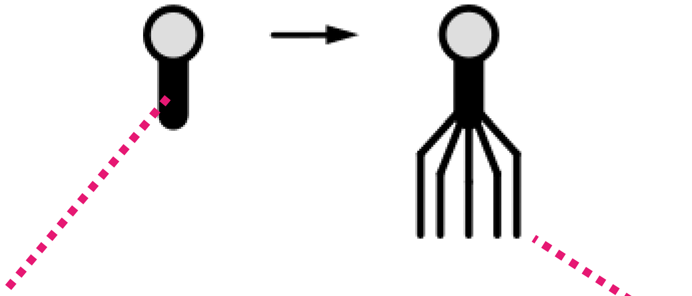

$D = 2^5 = 32$ $\quad$ $d = 2$

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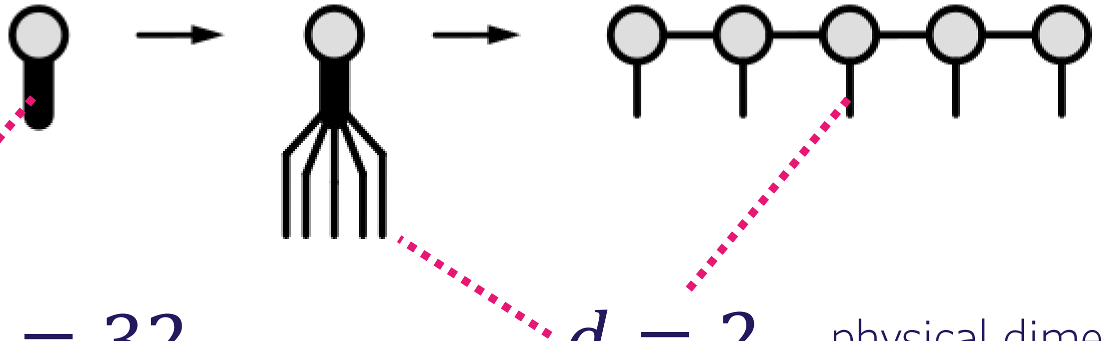

$D = 2^5 = 32$ $d = 2$ physical dimension

Tensor Networks in the context of Quantum

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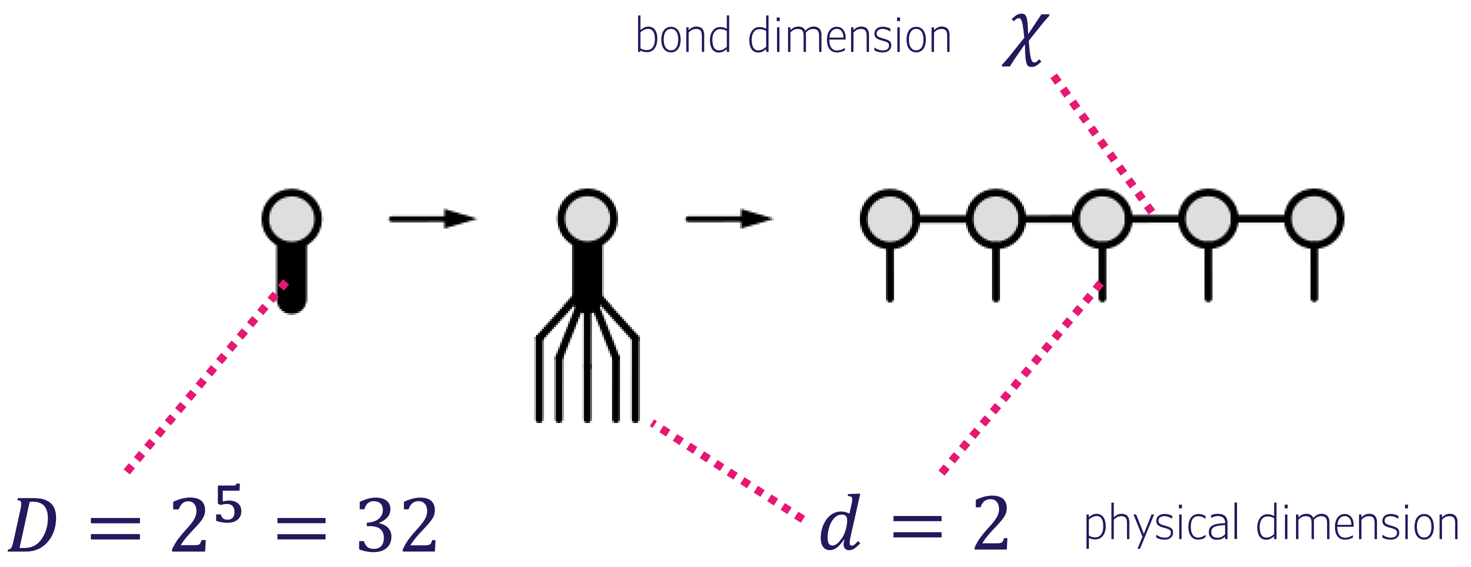

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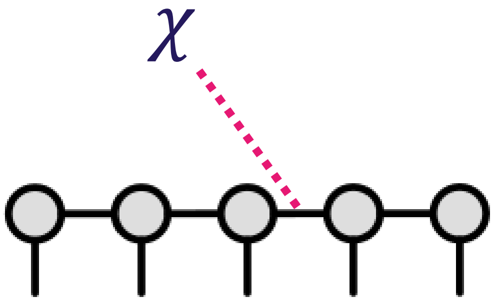
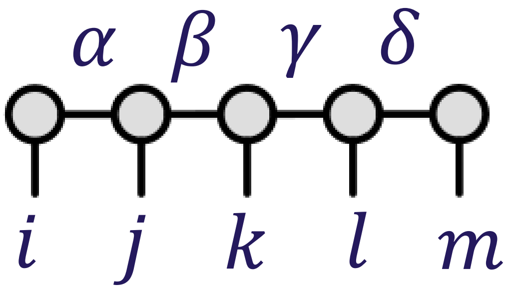


Matrix Product State

Tensor Networks in the context of Quantum

We can decompose big vectors and matrices into networks of small tensors

$$\sum_{\alpha\beta\gamma\delta} T^{i}_{\alpha}\, T^{j}_{\alpha\beta}\, T^{k}_{\beta\gamma}\, T^{l}_{\gamma\delta}\, T^{m}_{\delta} =$$



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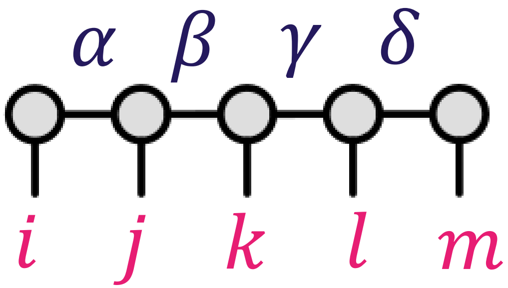
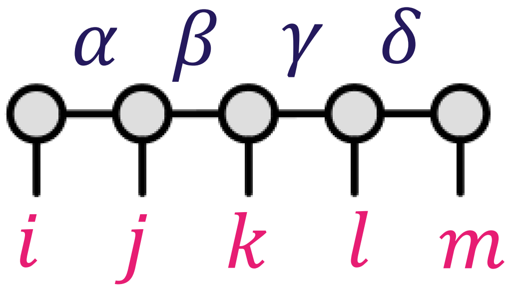


Matrix Product State

Tensor Networks in the context of Quantum

Who is our big vector?

$$\sum_{\alpha\beta\gamma\delta} T_{\alpha}^{i}\, T_{\alpha\beta}^{j}\, T_{\beta\gamma}^{k}\, T_{\gamma\delta}^{l}\, T_{\delta}^{m} =$$



Matrix Product State

$$\parallel$$

$$C^{ijklm}$$

Tensor Networks in the context of Quantum

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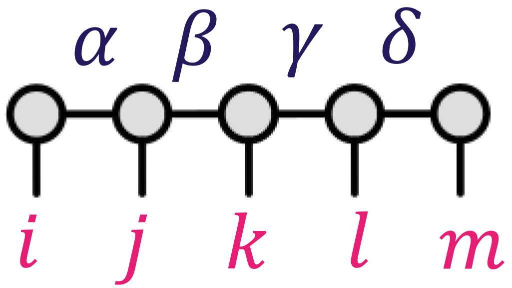


Matrix Product State

$$\parallel$$

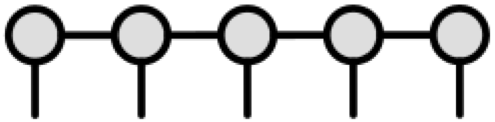
$$C^{ijklm}$$

$$|\psi\rangle = \sum_{ijklm} C^{ijklm} |ijklm\rangle$$

components of the quantum state

Tensor Networks in the context of Quantum

Compare:

$C^{ijklm\ldots}$ vs 

Tensor Networks in the context of Quantum

Compare:

$C^{ijklm\ldots}$ vs 

Entries $\mathbf{2^N}$ $\mathbf{(N-2)d\chi^2 + 2d\chi}$

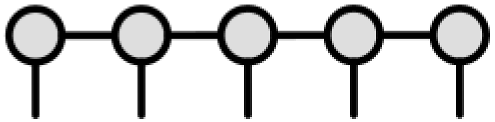
Tensor Networks in the context of Quantum

Compare:

	$C^{ijklm\ldots}$	vs	
Entries	2^N		$(N-2)d\chi^2 + 2d\chi$
Memory	exponential in the number of qubits N		linear in the number of qubits N

Tensor Networks in the context of Quantum

good scaling



$$(N-2)d\chi^2 + 2d\chi$$

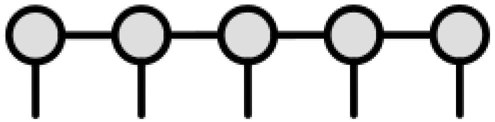
linear in the number of qubits N

provided

the bond dimensions χ grow **subexponentially** with N

Tensor Networks in the context of Quantum

good scaling



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for most of the realistic tasks we want to simulate classically, the bond dimension **grows exponentially** ☹

Tensor Networks in the context of Quantum

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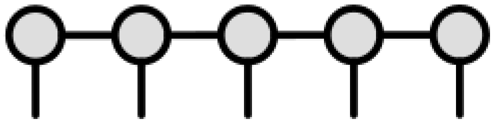

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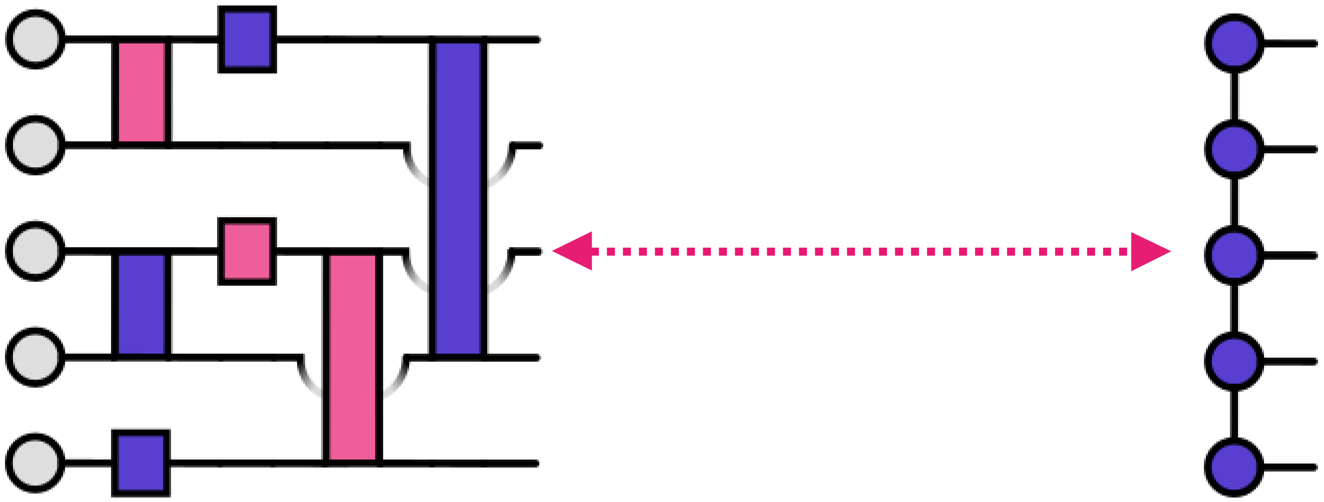
ENTANGLEMENT BARRIER

$$S_{entropy} \sim \log(\chi)$$

Tensor Networks in the context of Quantum

Matrix Product States can represent the quantum state of our register
provided the produced amount of entanglement is bounded



Current focus: high performance packages like QUIMB

"Using the **Cotengra/Quimb packages**, NVIDIA's new **cuQUANTUM SDK**, and the **Selene supercomputer**, we've generated a sample of the Sycamore quantum circuit at depth=20 in record time (**less than 10 minutes**).

This sets the benchmark for quantum circuit simulation performance and will help advance the field of quantum computing by improving our ability to verify the behavior of quantum circuits."

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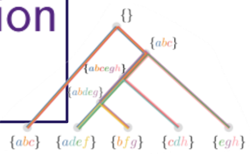
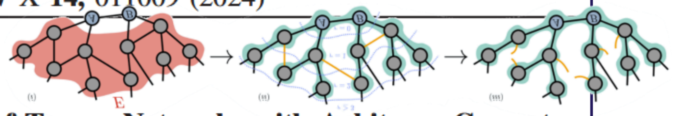
Hyper-optimized tensor network contraction

Johnnie Gray[1,2] and Stefanos Kourtis[1,3,4]



PHYSICAL REVIEW X **14,** 011009 (2024)



Hyperoptimized Approximate Contraction of Tensor Networks with Arbitrary Geometry

Johnnie Gray and Garnet Kin-Lic Chan

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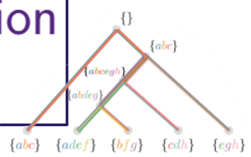
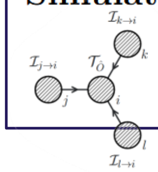


Simulating quantum dynamics in two-dimensional lattices with tensor network influence functional belief propagation

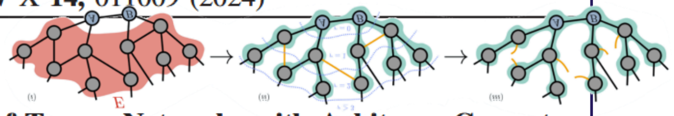
Gunhee Park (박건희),[1] Johnnie Gray,[2] and Garnet Kin-Lic Chan[2]



PHYSICAL REVIEW X **14,** 011009 (2024)

Hyperoptimized Approximate Contraction of Tensor Networks with Arbitrary Geometry

Johnnie Gray and Garnet Kin-Lic Chan

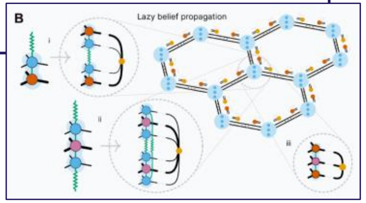


SCIENCE ADVANCES | RESEARCH ARTICLES

PHYSICS

Fast and converged classical simulations of evidence for the utility of quantum computing before fault tolerance

Tomislav Begušić†, Johnnie Gray†, Garnet Kin-Lic Chan*



Current focus: high performance packages like QUIMB

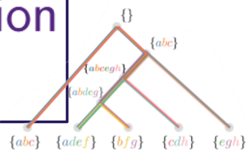
quobly

"Using the **Cotengra/Quimb packages**, NVIDIA's new **cuQUANTUM SDK**, and the **Selene supercomputer**, we've generated a sample of the Sycamore quantum circuit at depth=20 in record time (**less than 10 minutes**).

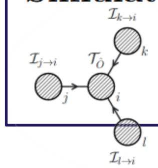
This sets the benchmark for quantum circuit simulation performance and will help advance the field of quantum computing by improving our ability to verify the behavior of quantum circuits."

Hyper-optimized tensor network contraction

Johnnie Gray[1,2] and Stefanos Kourtis[1,3,4]

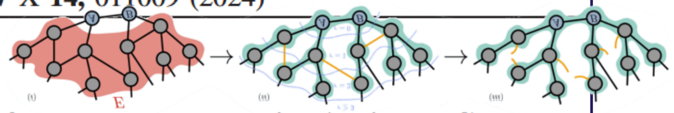


Simulating quantum dynamics in two-dimensional lattices with tensor network influence functional belief propagation



Gunhee Park (박건희),[1] Johnnie Gray,[2] and Garnet Kin-Lic Chan[2]

PHYSICAL REVIEW X **14,** 011009 (2024)



Hyperoptimized Approximate Contraction of Tensor Networks with Arbitrary Geometry

Johnnie Gray and Garnet Kin-Lic Chan

SCIENCE ADVANCES | RESEARCH ARTICLES

PHYSICS

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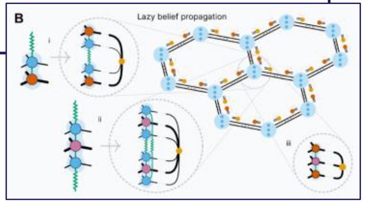
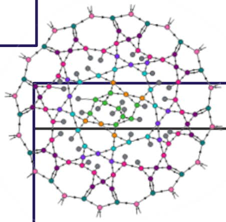




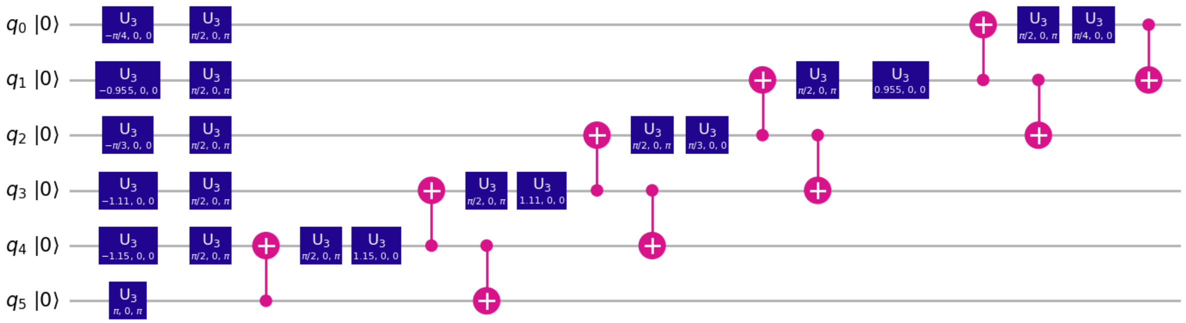
PHYSICAL REVIEW X **12,** 011047 (2022)

Variational Power of Quantum Circuit Tensor Networks

Reza Haghshenas,[1,*] Johnnie Gray,[1,†] Andrew C. Potter,[2,3] and Garnet Kin-Lic Chan[1,‡]

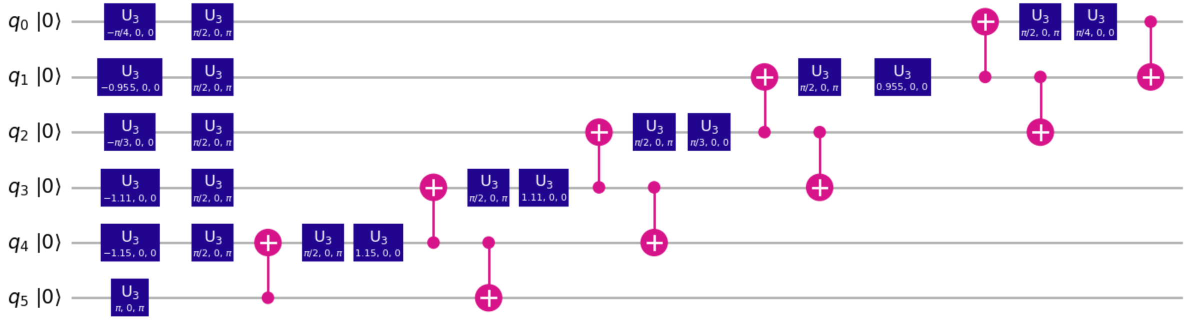
Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization

W-State



stair-like

W-State

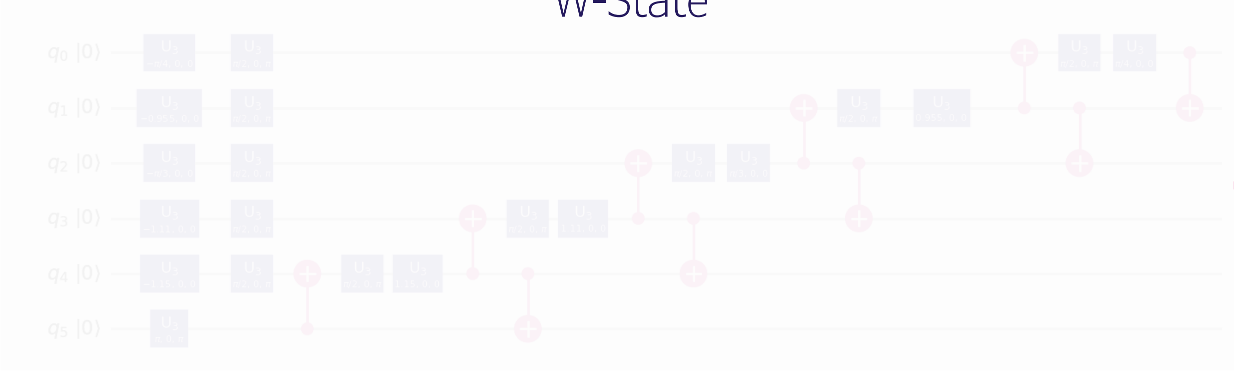


stair-like

exact MPS with $\chi = 2$,
no need for compression

Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization

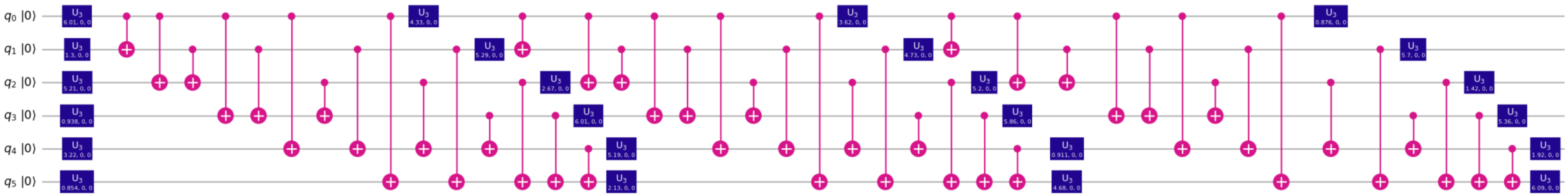
W-State



stair-like

layered

Random Real Amplitude All-to-All Ansatz



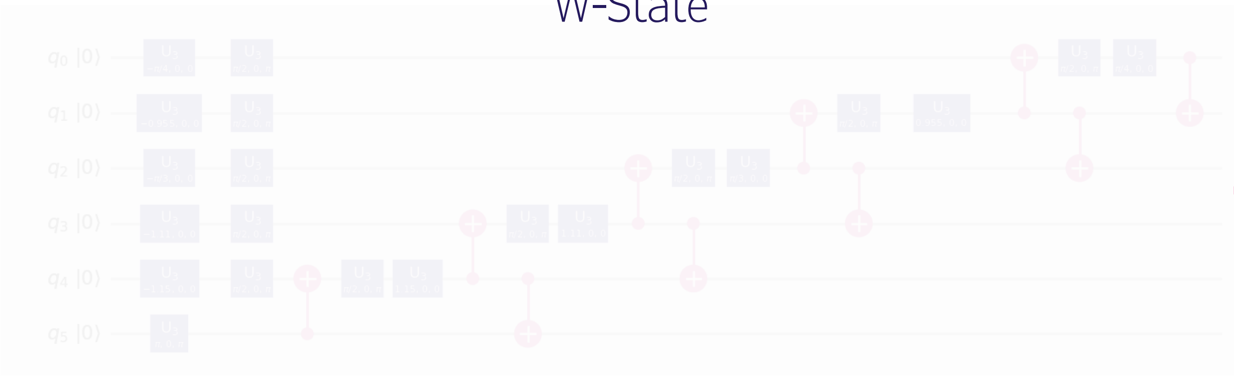
Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization

MUNICH QUANTUM TOOLKIT

Qiskit

quobly

W-State



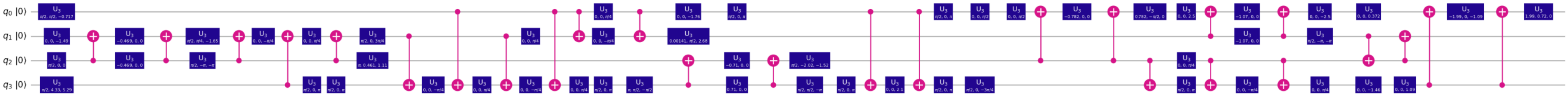
stair-like

layered

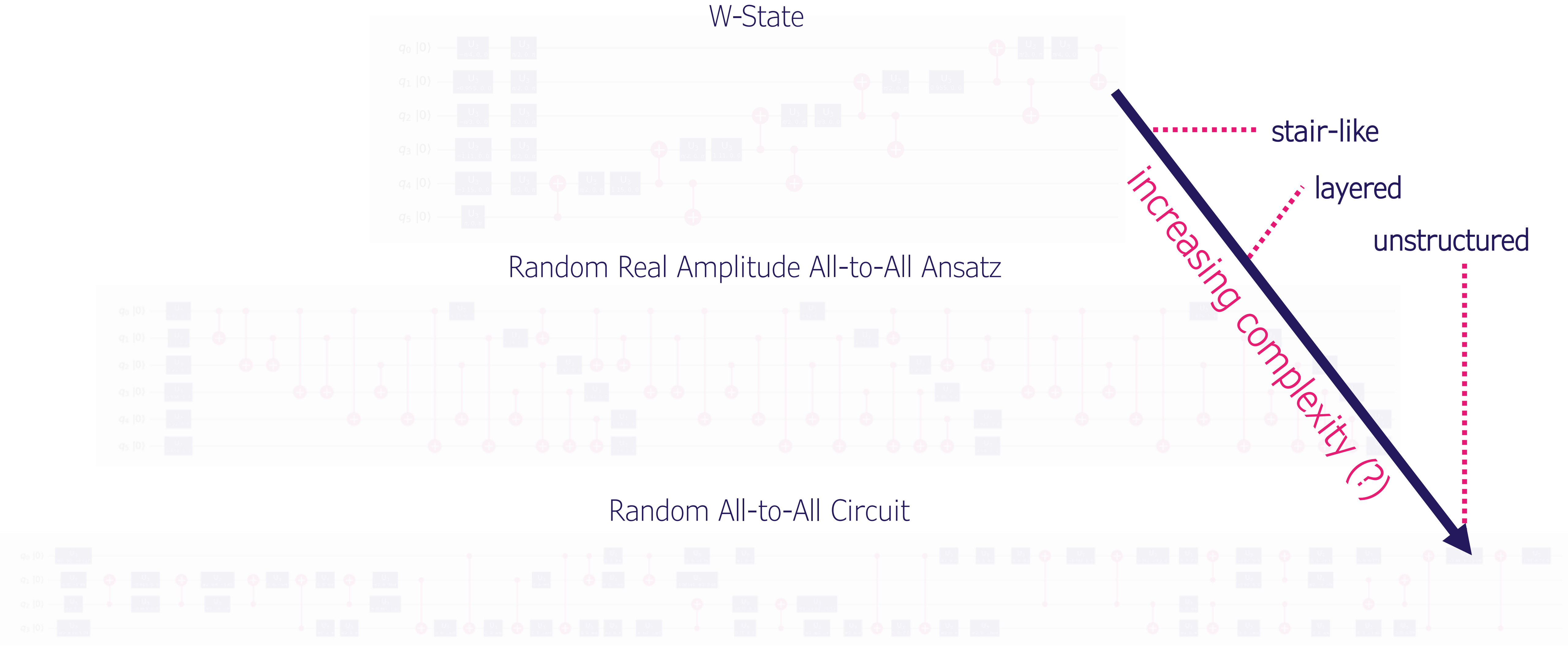
unstructured

Random Real Amplitude All-to-All Ansatz

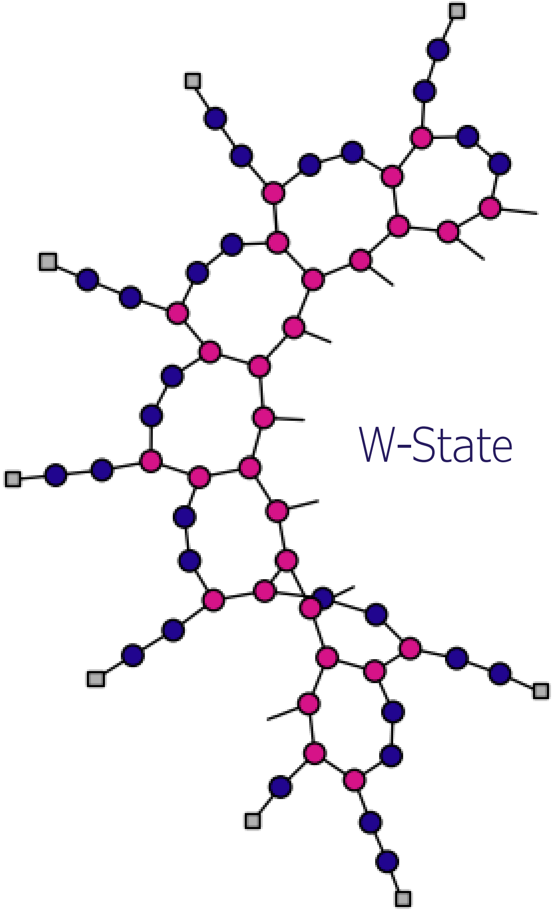
Random All-to-All Circuit



Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization



Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization



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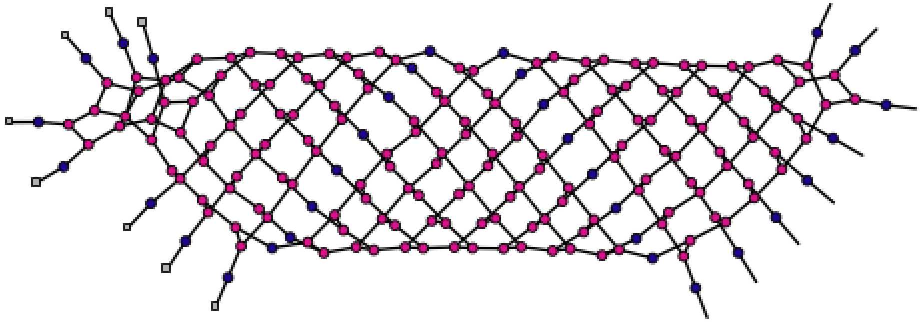
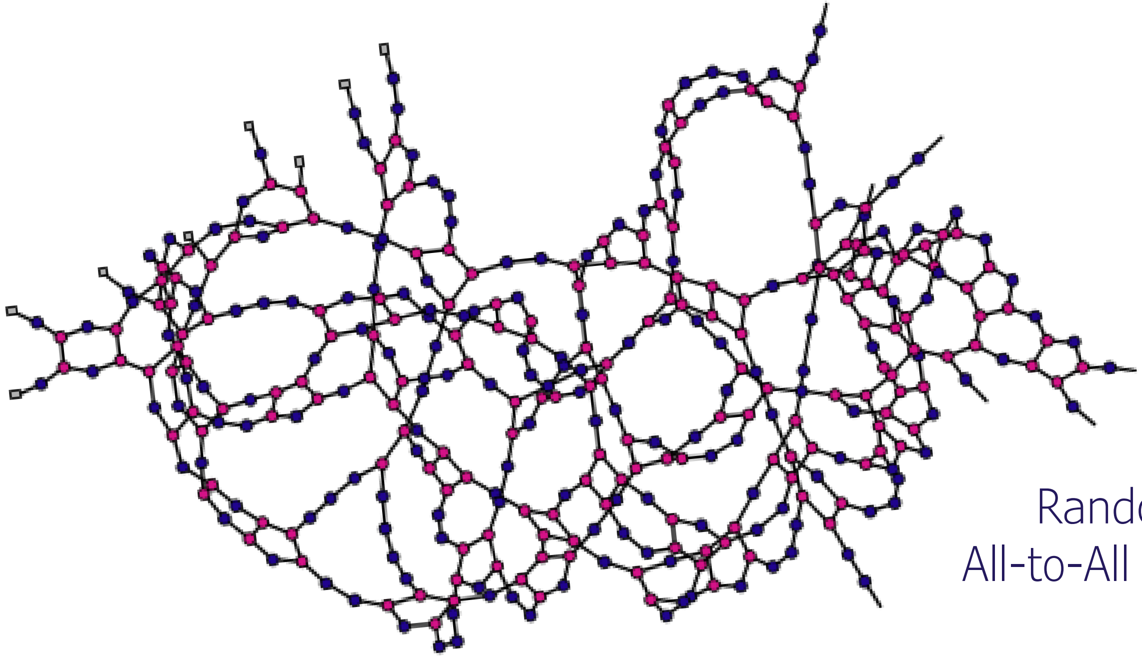


Random Real Amplitude
All-to-All Ansatz



Random
All-to-All Circuit

Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization

Can we classically **simulate and sample** interesting or/and complex quantum states **efficiently**?

Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization

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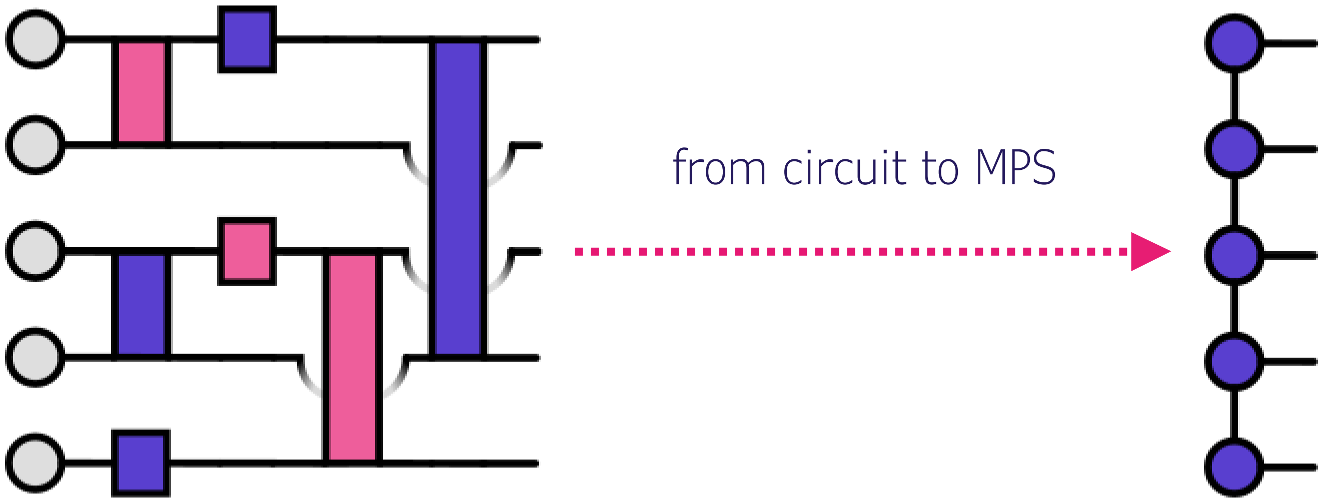
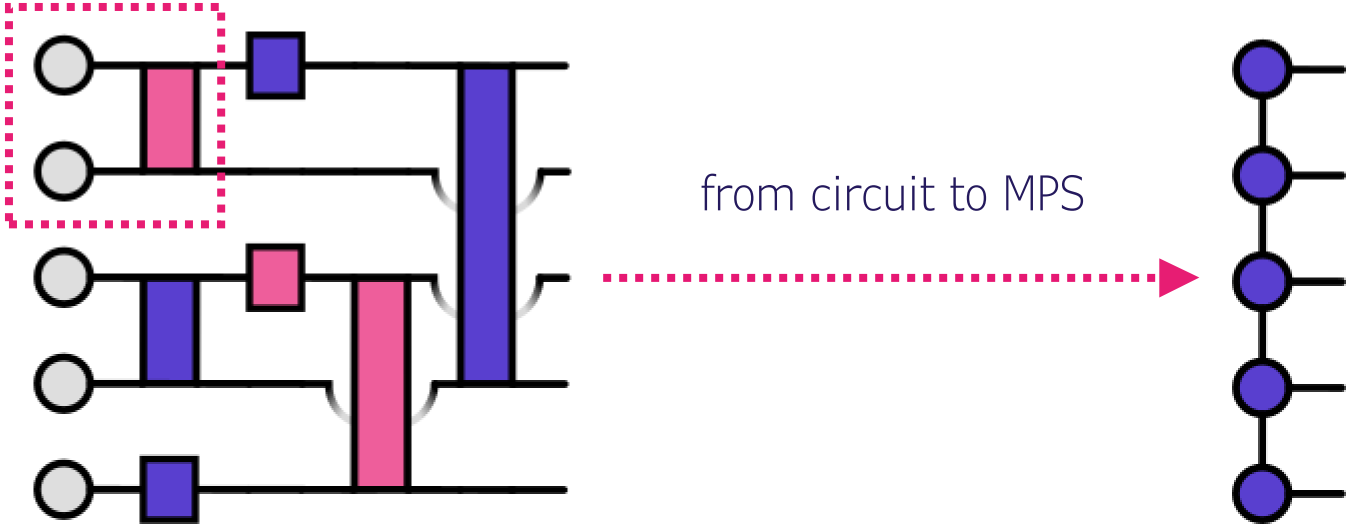


Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization

Can we classically simulate and sample interesting or/and complex quantum states **efficiently**?

absorb gates and refactorize



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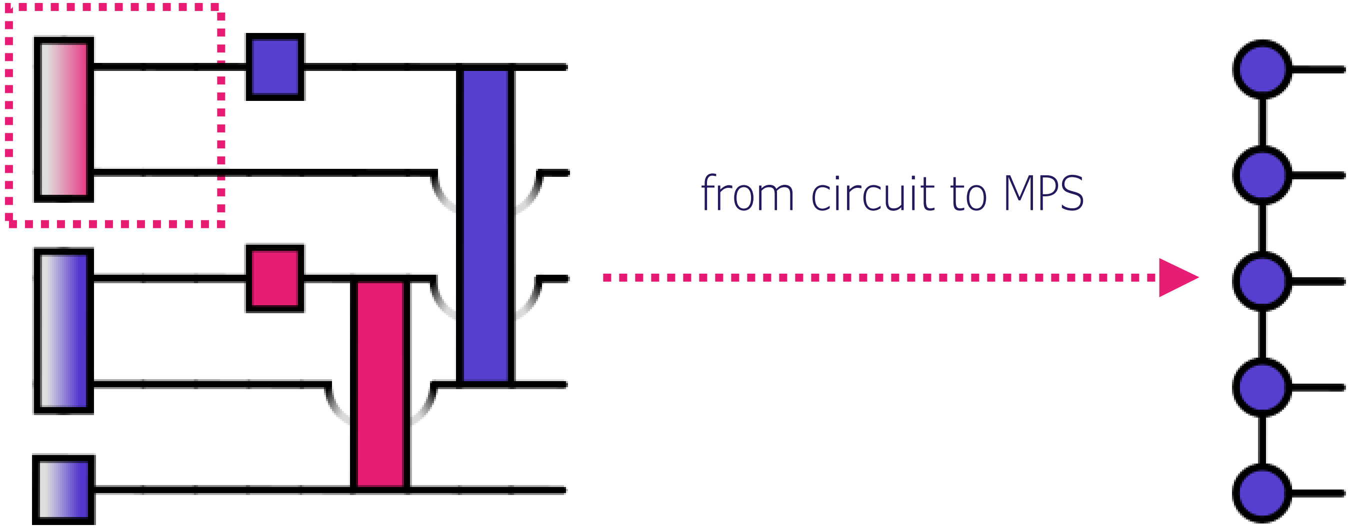

Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization

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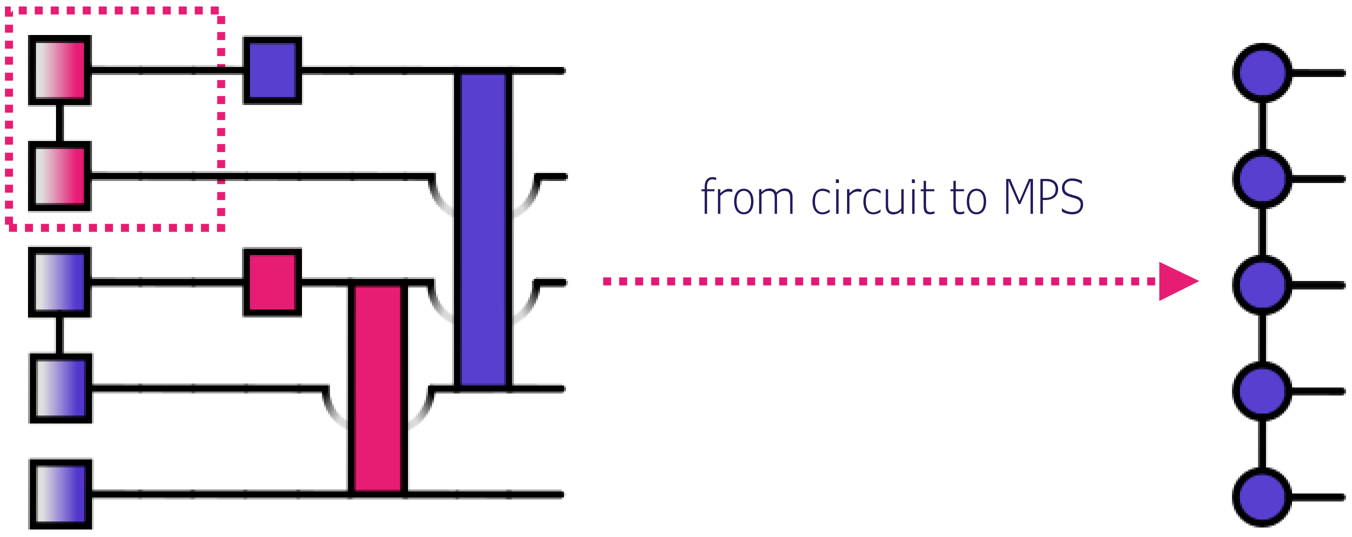
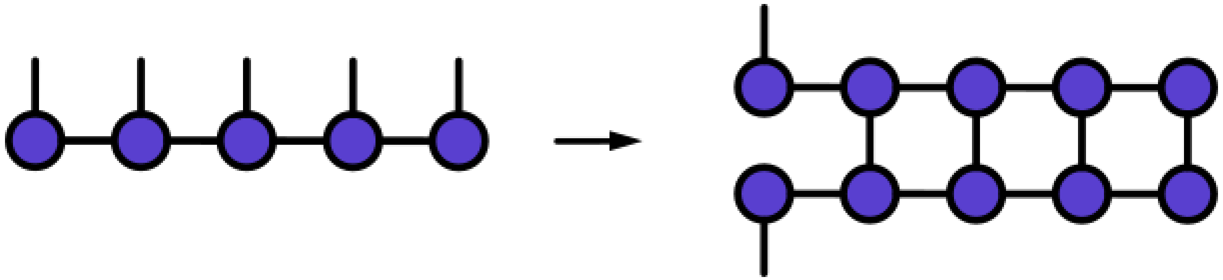


Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization

Can we classically simulate and **sample** interesting or/and complex quantum states **efficiently**?



$$\rho_1 = Tr_{2,3,4,5}\{|\psi\rangle\langle\psi|\}$$

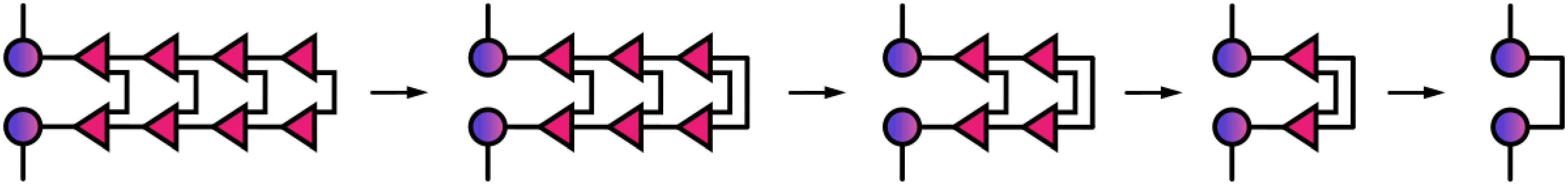
$$\rho_1 = \begin{pmatrix} P_0 & c \\ \bar{c} & P_1 \end{pmatrix}$$

sample from the probability distribution
in the diagonal of the reduced density matrix

draw a random number and
fix the state of that spin

Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization

The simplest way is qubit-by-qubit sampling because we can canonicalize the network



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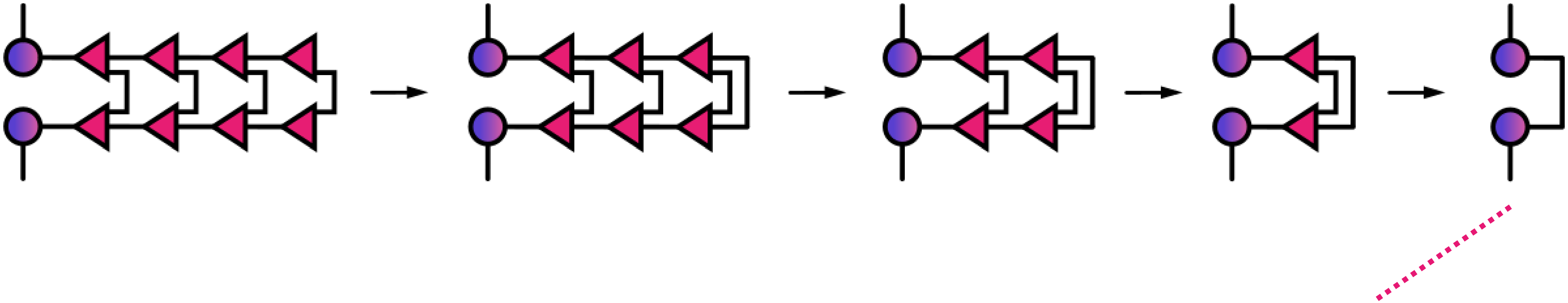

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$$|0\rangle, |1\rangle$$

Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization

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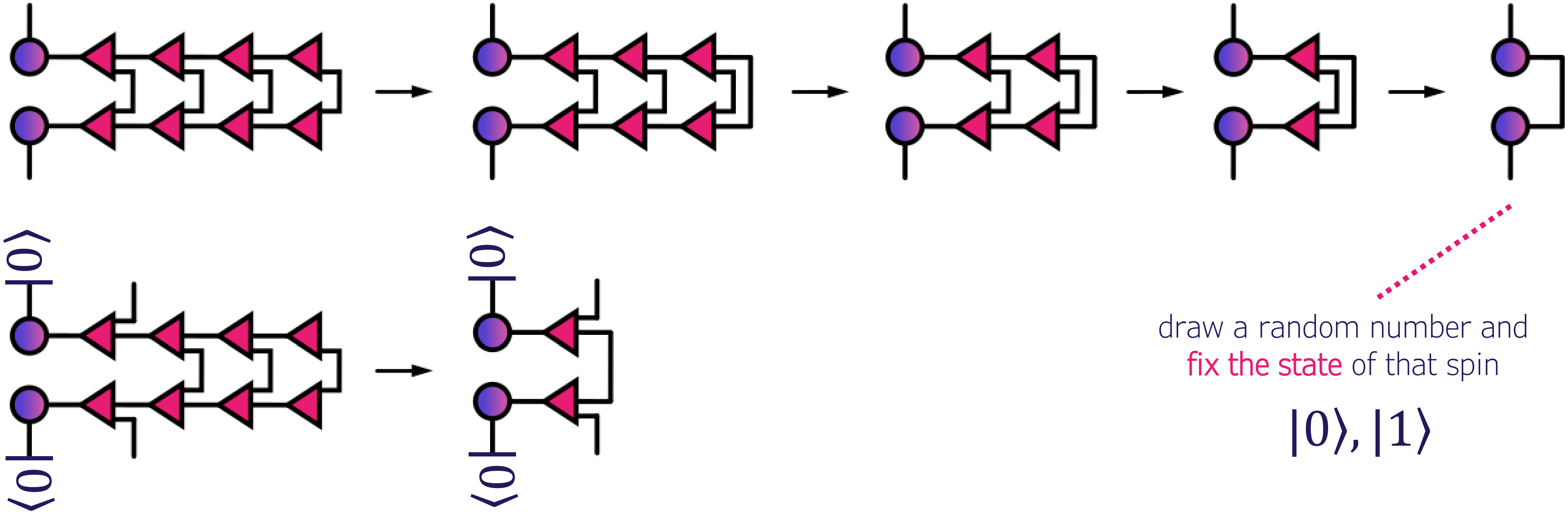

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Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization

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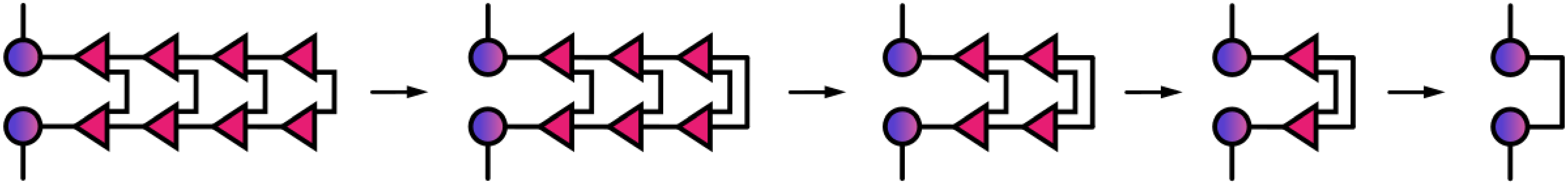
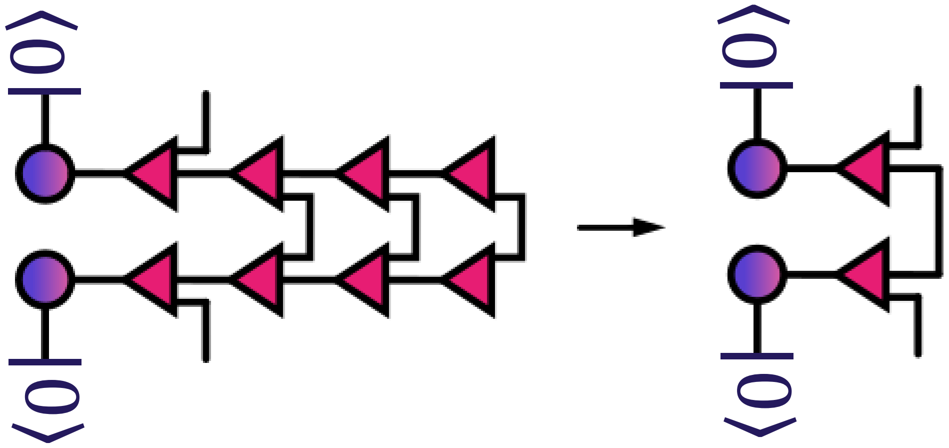


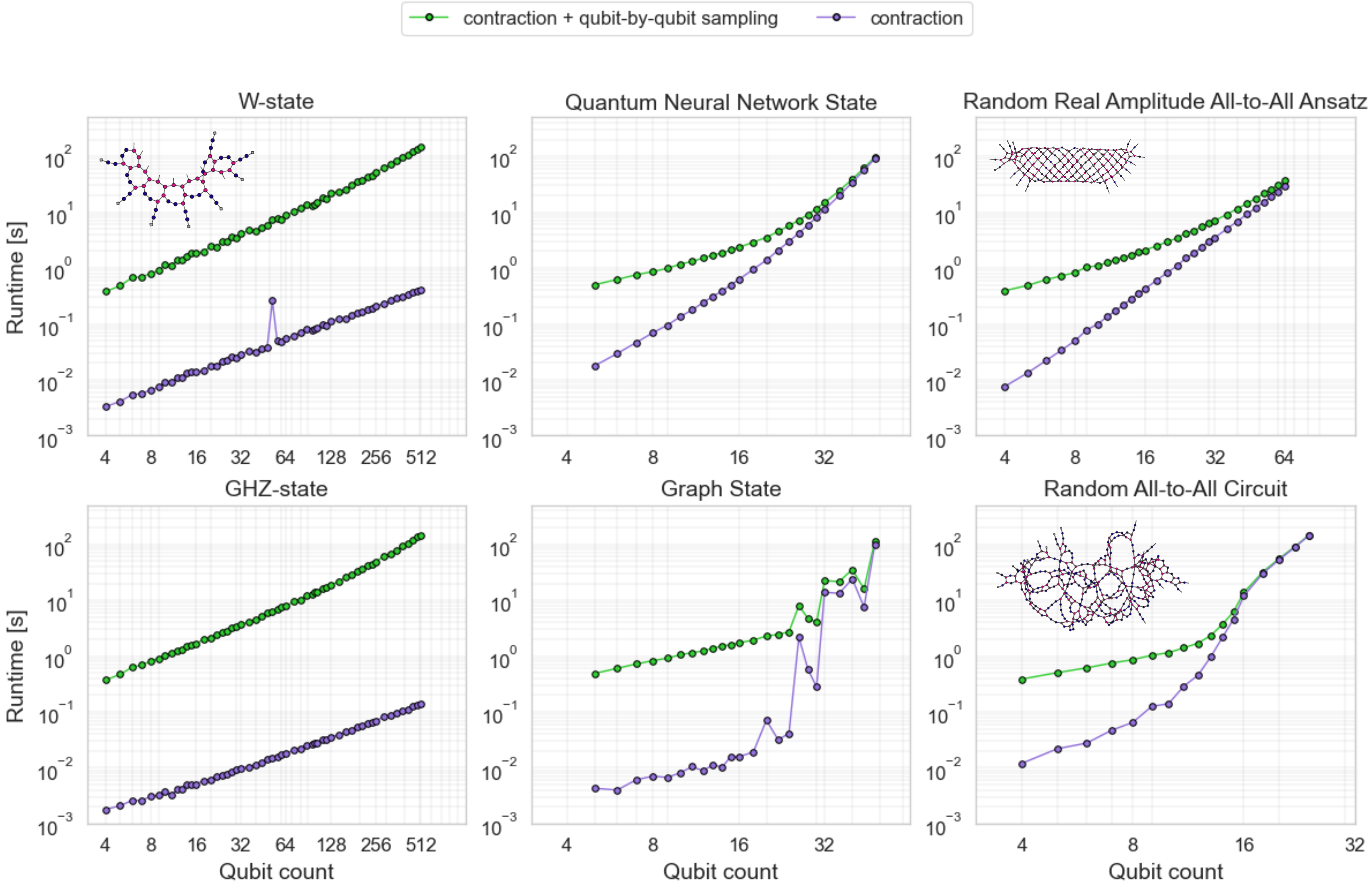


iterate N times

draw a random number and **fix the state** of that spin

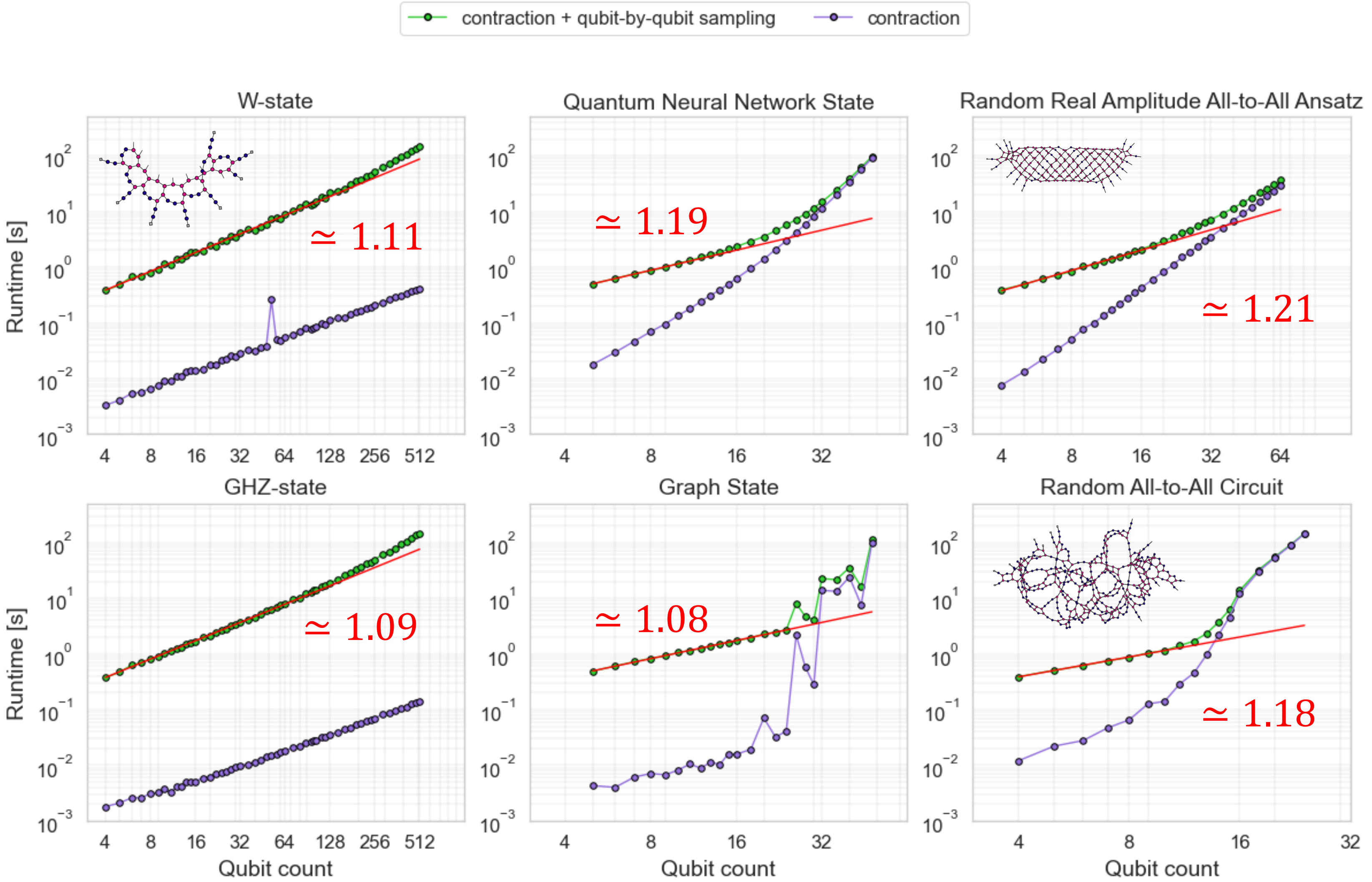
$$|0\rangle, |1\rangle$$

Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization



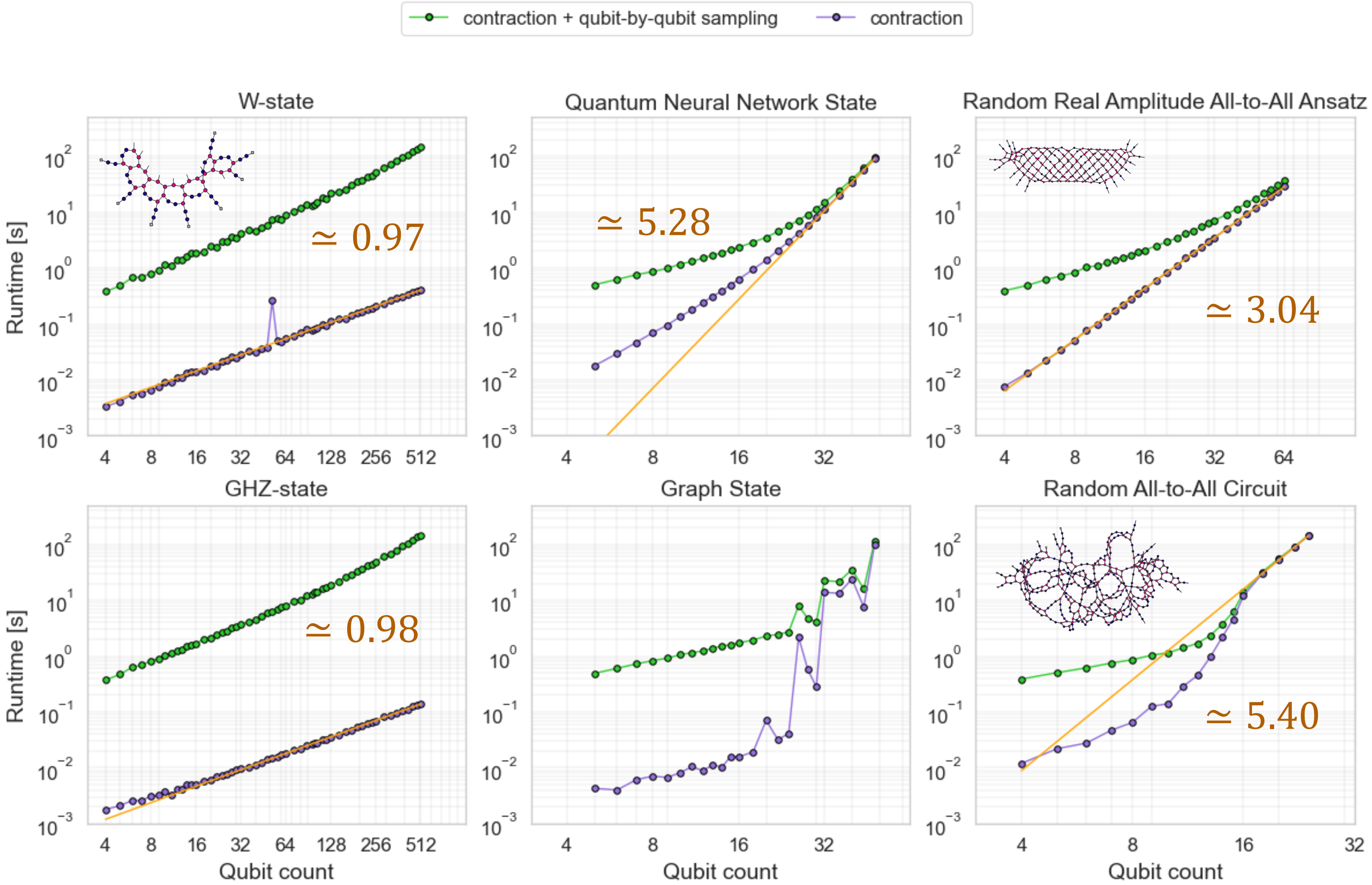
- For small (shallow) circuits the protocol is dominated by sampling.
- For wide (deep) circuits, the cost of contracting the MPS dominates the task.

Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization



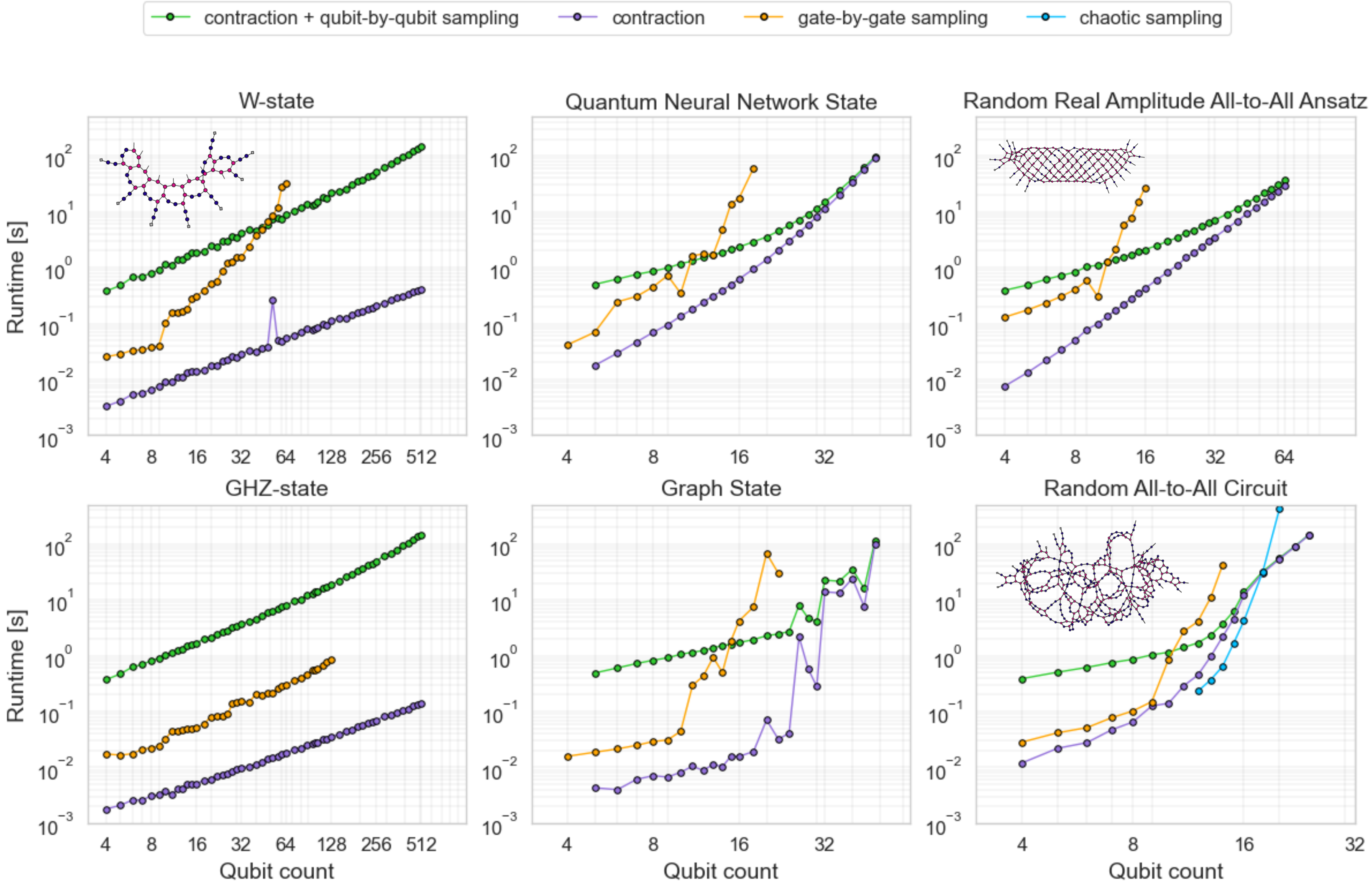
- For small (shallow) circuits the protocol is dominated by sampling.
- Qubit-by-qubit sampling scales linearly with circuit size.

Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization



- For wide (deep) circuits, the cost of contracting the MPS dominates the task.
- The biggest analyzed circuits illustrate the super linear scaling.

Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization

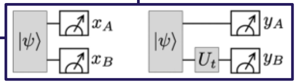


- Clever ways of sampling can improve the runtimes for shallow circuits! See gate-by-gate sampling.

PHYSICAL REVIEW LETTERS **128,** 220503 (2022)

How to Simulate Quantum Measurement without Computing Marginals

Sergey Bravyi,[1] David Gosset,[2,3,4] and Yinchen Liu[2,3]

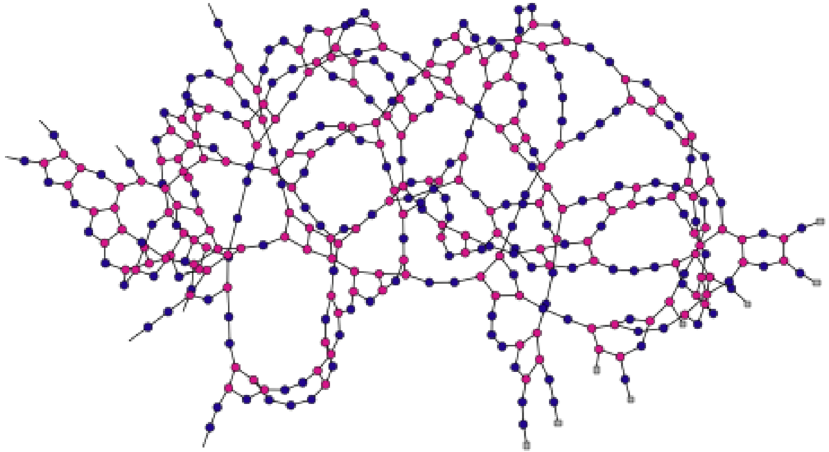


- Also chaotic sampling.

Hyper-optimized tensor network contraction

Johnnie Gray[1,2] and Stefanos Kourtis[1,3,4]

Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization



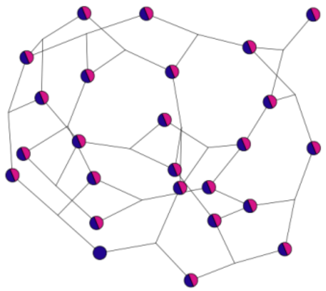
simplification

(anti-)diagonal projections, column reductions, gate-splitting...

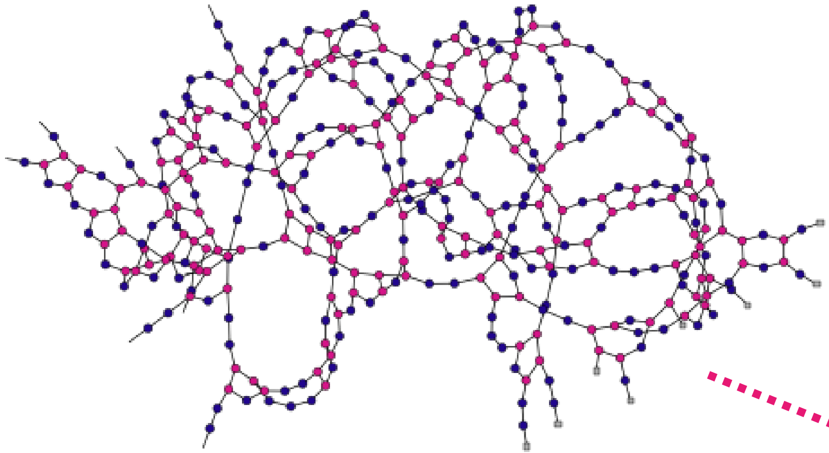
reverse light-cones

contract smaller circuits when targeting local properties

computing amplitudes



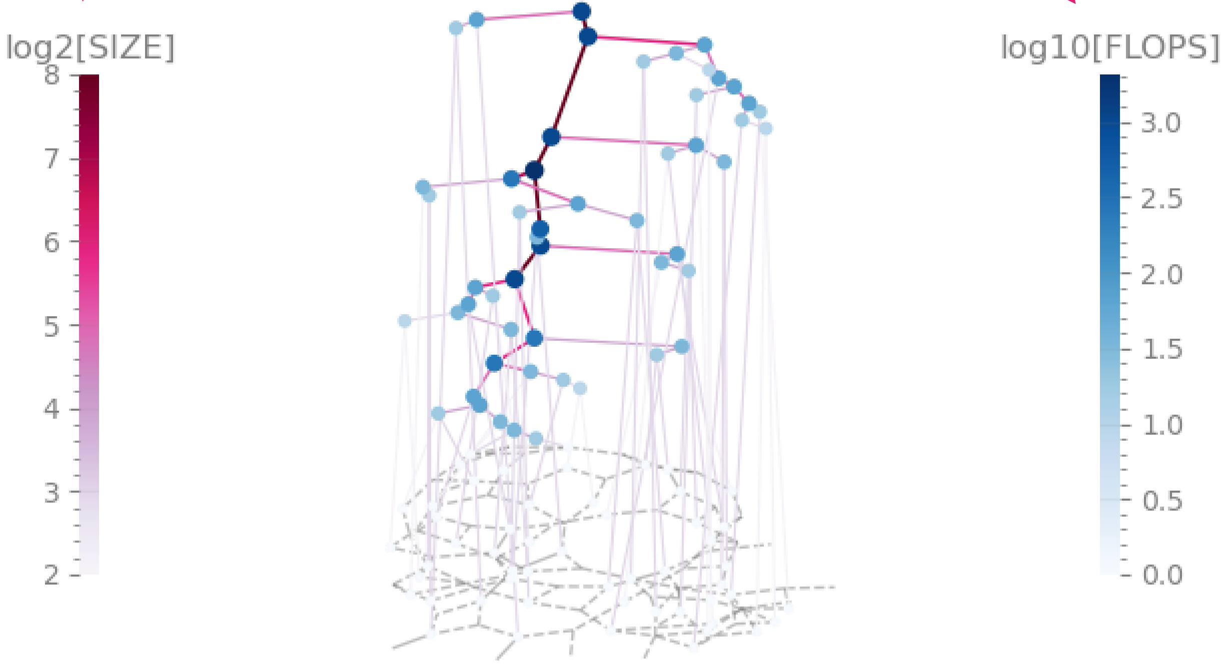
Classical Simulation of Quantum Algorithms: Samplings and Hyperoptimization



hyperoptimization of the contraction tree
find the best order
(maybe compressing in between)
using runtime and memory as cost functions

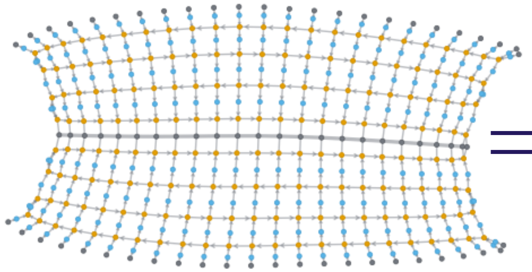
memory
size of intermediate tensors

runtime
float point operations per second



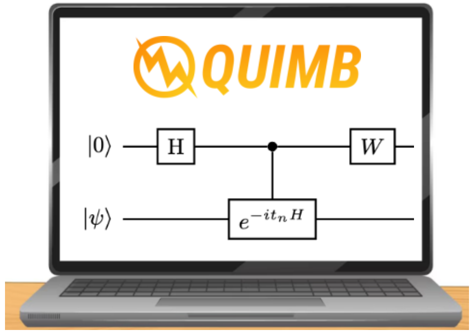
Classical Simulation of Quantum Algorithms: QPE for Chemistry

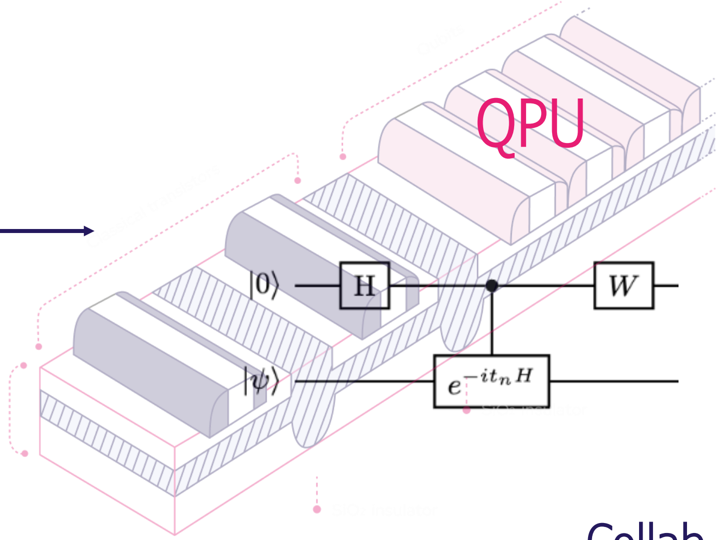
Classical preprocessing



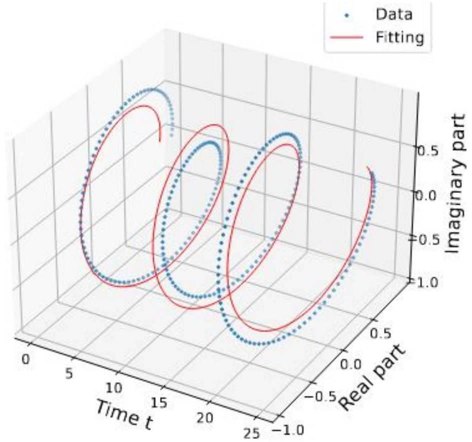
Large scale compilation,
Tensor quantum programming,
Qubitization

Internal Simulator





Semi-Classical QFT
Time-series analysis
...
Benchmark with
Tensor-Networks



Collab.: Quobly + Foxconn (Minh Hsui Hsieh group)

What is in the menu? Next steps…

- Can we further **improve efficiency** of classical simulations? Include realistic noise.

  HP-inspired directions: backend (GPU support), jitting, faster languages under the hood…

  Physics-inspired directions: swapped circuits; Belief Propagation; Magic and Pauli Weight as resources.

- Tensor Network powered **Quantum Phase Estimation Toolbox**.

- Tensor Network –based **benchmark of Quantum Error Correction** strategies.

- **We are building the Quantum Information Team:**

  Quantum Algorithms / Tensor Network / Quantum benchmark experts

  contact: benoit.vermersch@quobly.io