Tensor network simulations of quantum circuits with finite fidelity

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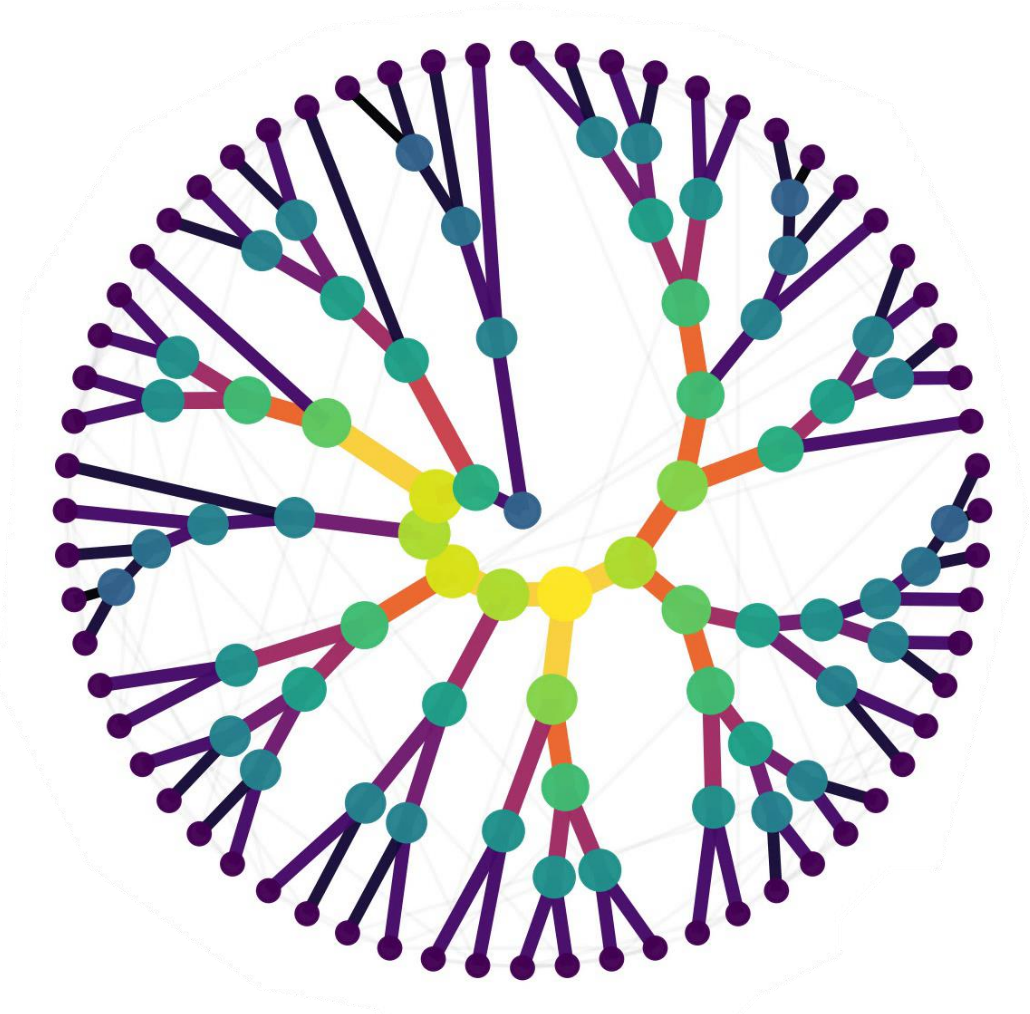
Technical University of Munich

Bari - September 26th, 2023



In collaboration with:

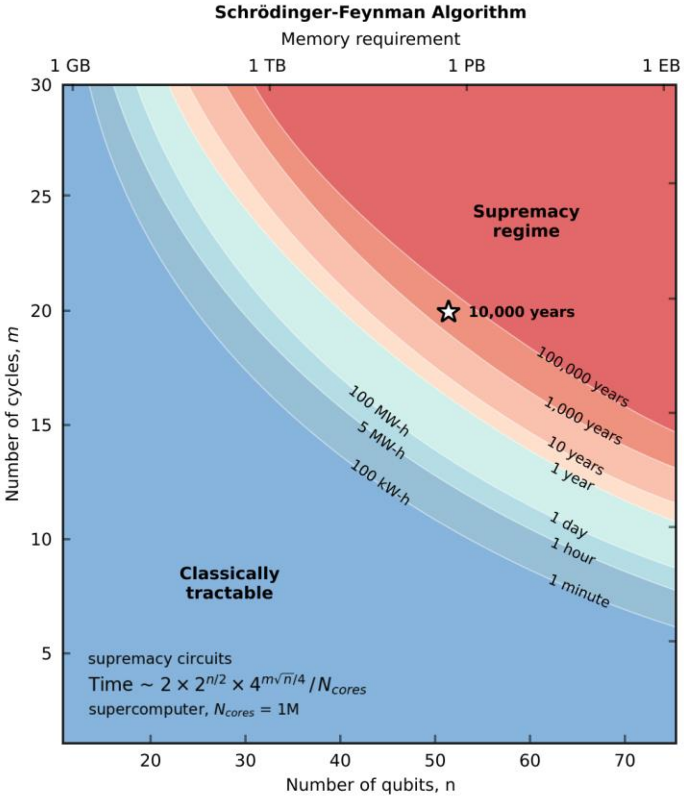
Peter Rabl (TUM, WMI)

Giuseppe Magnifico (UniBa)

Saverio Pascazio (UniBa)

Quantum advantage

"…classical systems cannot simulate highly entangled quantum systems efficiently, and we hope to hasten the day when well controlled quantum systems can perform tasks surpassing what can be done in the classical world." John Preskill



Google's original division of classically tractable vs. supremacy regimes

Quantum advantage and tensor networks

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Quantum
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PAPERS PERSPECTIV

Hyper-optimized tensor network contraction

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

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[2]Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, California 91125, USA
[3]Department of Physics, Boston University, Boston, MA, 02215, USA
[4]Institut quantique & Département de physique, Université de Sherbrooke, Québec J1K 2R1, Canada

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arXiv > quant-ph > arXiv:2005.06787

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Quantum Physics

[Submitted on 14 May 2020]

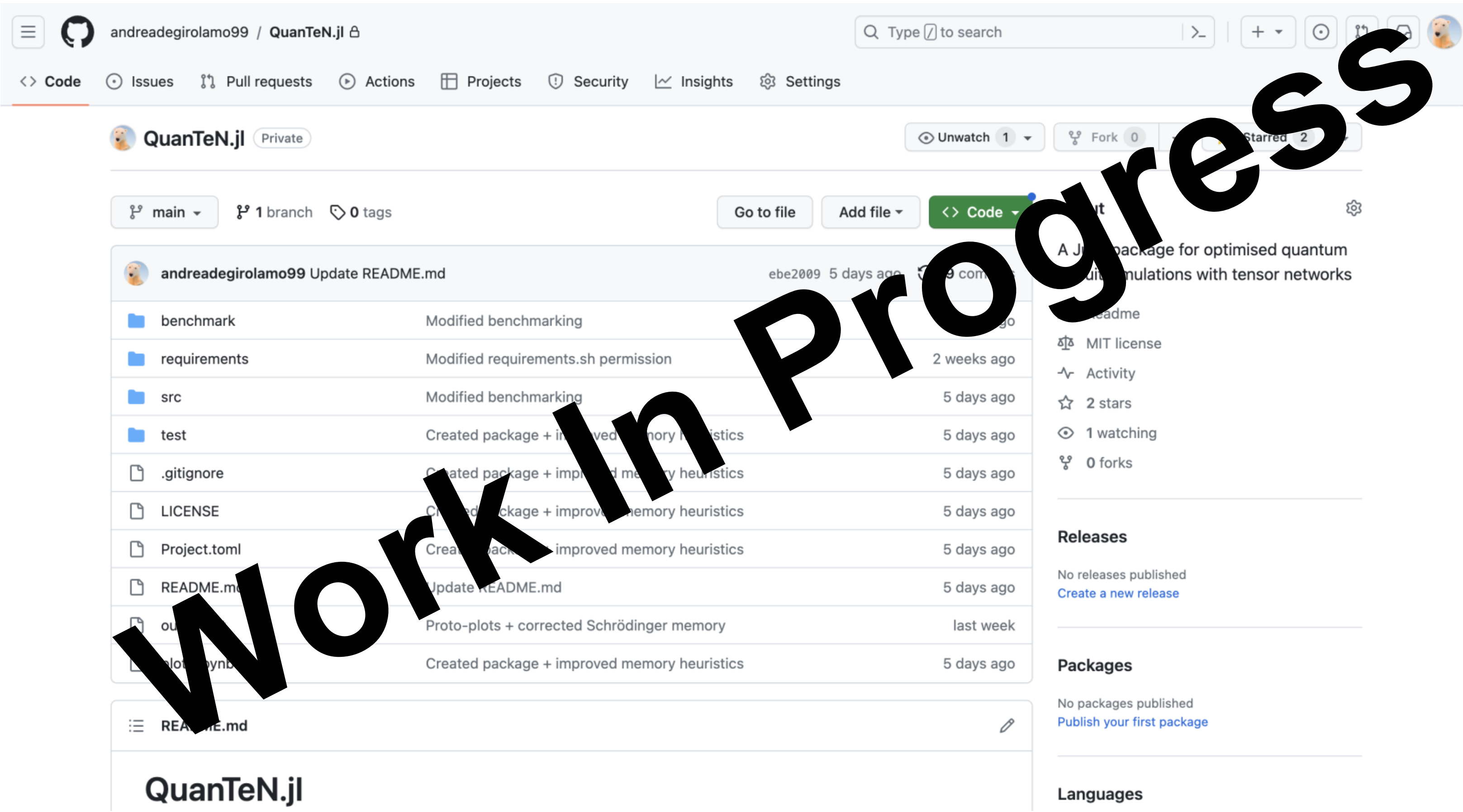
Classical Simulation of Quantum Supremacy Circuits

Cupjin Huang, Fang Zhang, Michael Newman, Junjie Cai, Xun Gao, Zhengxiong Tian, Junyin Wu, Haihong Xu, Huanjun Yu, Bo Yuan, Mario Szegedy, Yaoyun Shi, Jianxin Chen

A performance of 1.2 Eflops (single-preicision), or 4.4 Eflops (mixed-precision) for simulating a 10×10×(1+40+1) circuit (a new milestone for classical simulation of RQC), using about 42 million Sunway cores. The time to sample Goolge Sycamore in a simulation way is reduced from years to 304 seconds.

QuanTeN.jl

Hyper-optimized contractions + simulations with finite fidelity



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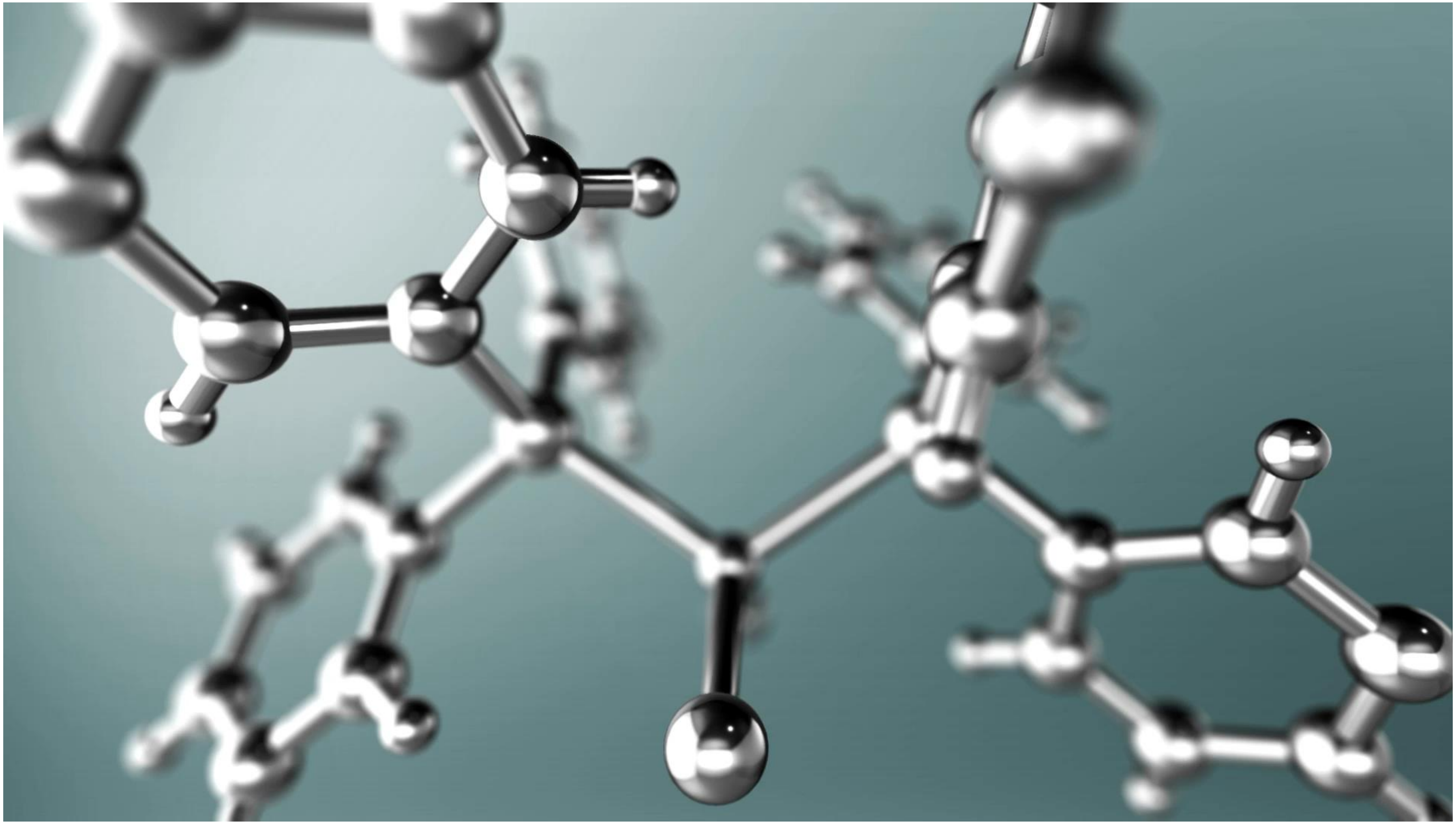
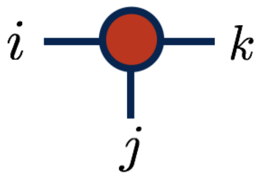
2. Exact contractions

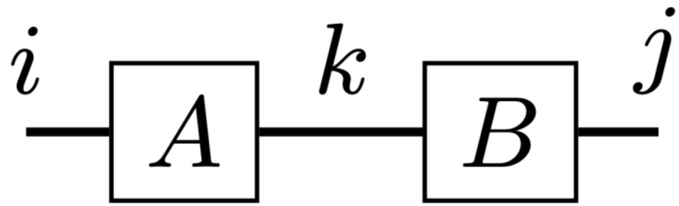


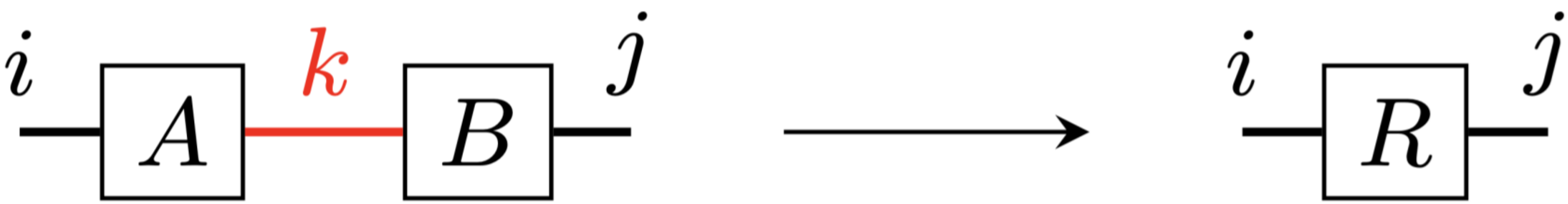
Tensor notation

vector	v_j	
matrix	M_{ij}	
3-index tensor	T_{ijk}	

Source: https://tensornetwork.org/

Contractions



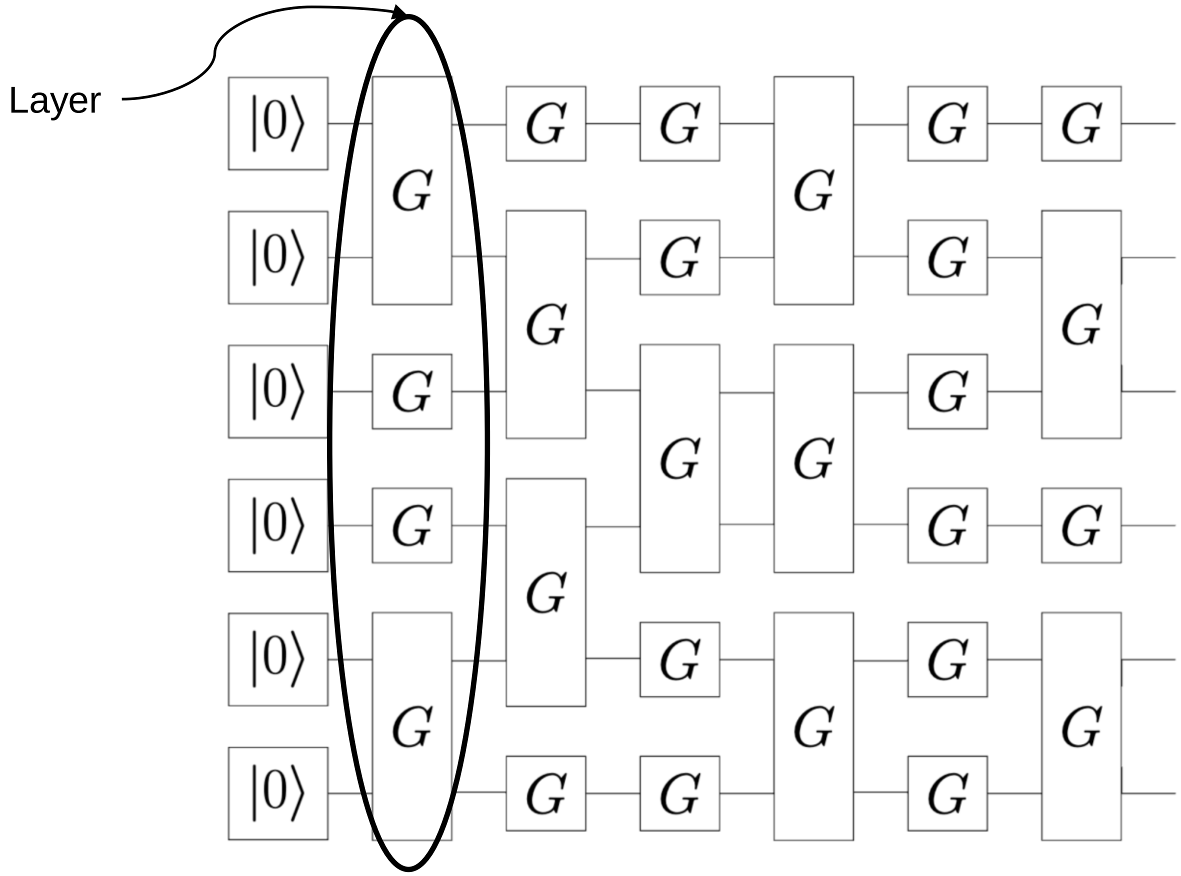


$$R_{ij} = \sum_k A_{ik} B_{kj}$$

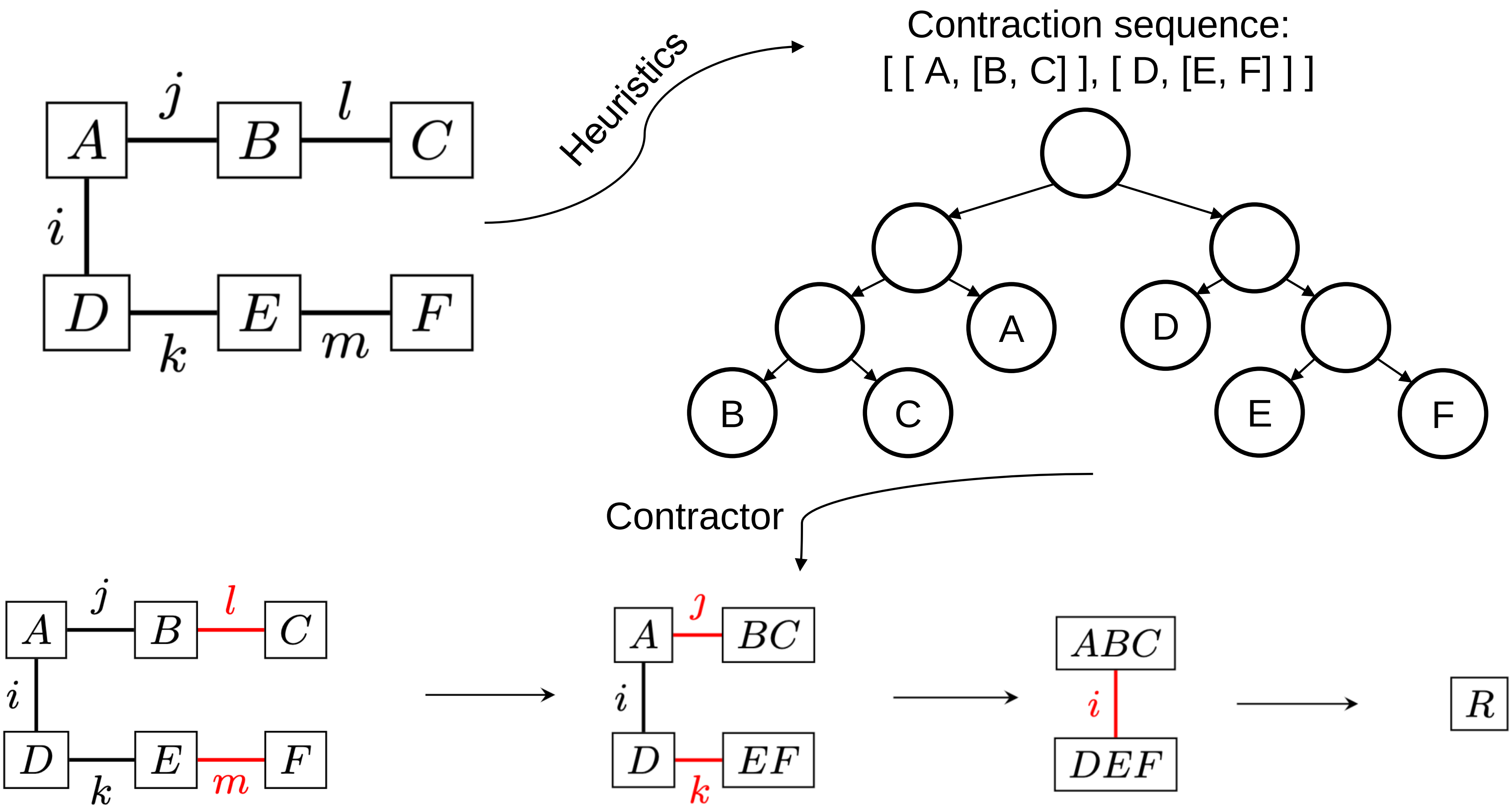
Tensor network approach for quantum circuits

Initial state: MPS

Evolution: n-qubit gate → rank-$2n$ tensor



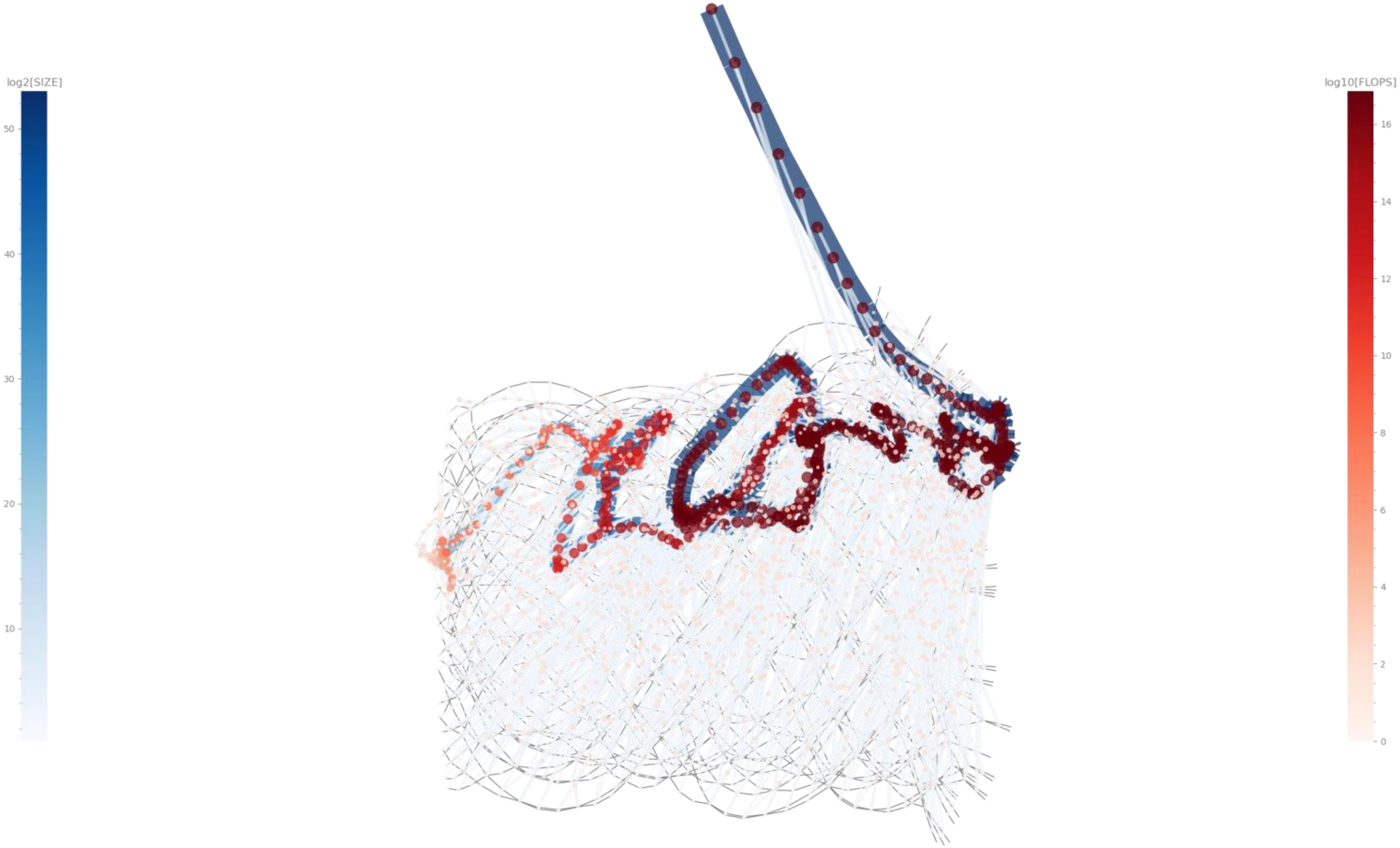
Schrödinger method



Heuristics – opt_einsum and cotengra

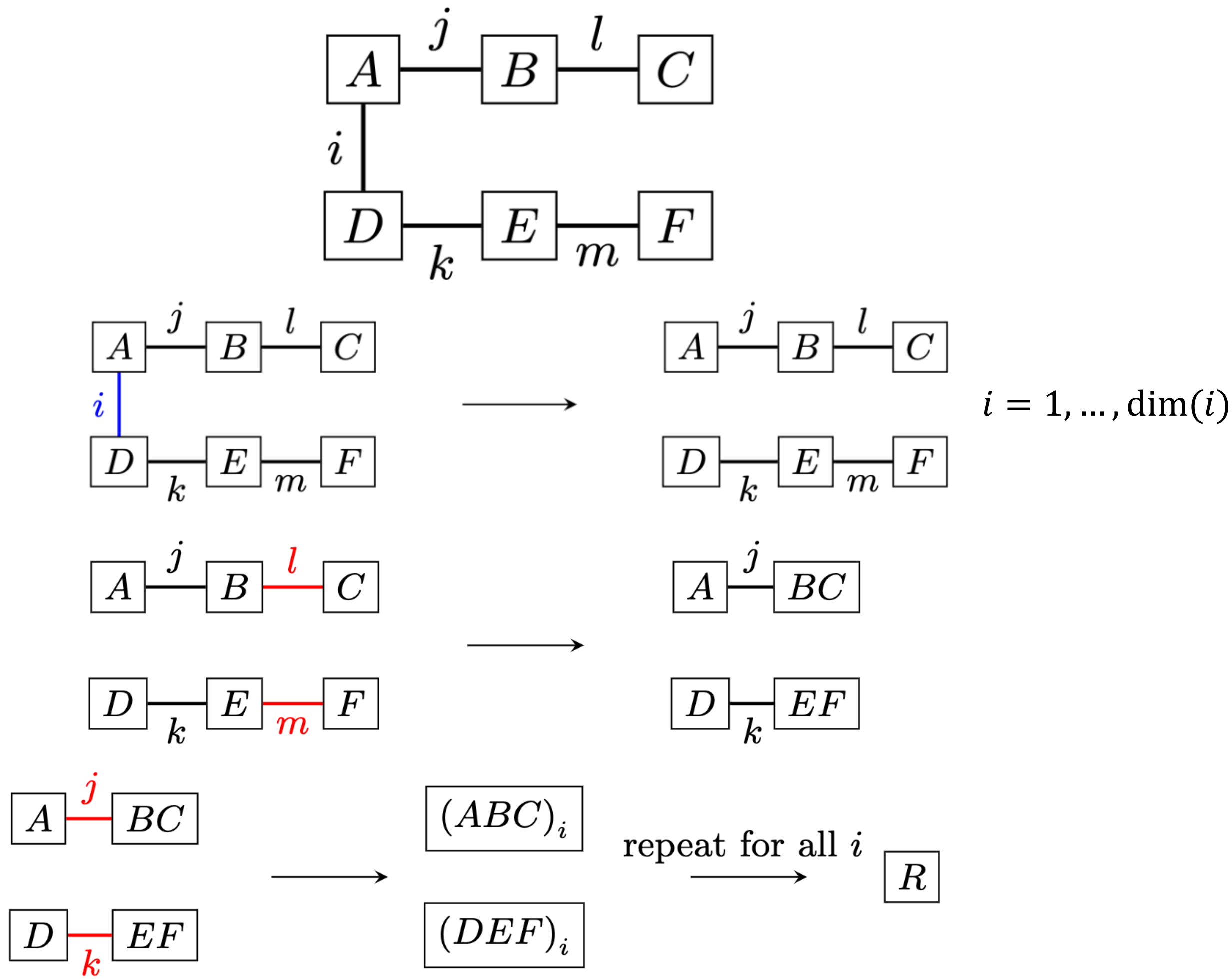
opt_einsum: random-greedy approach to minimize size of contractions

cotengra: collection of many heuristics to optimize the contraction tree



Schrödinger-Feynman method

Slicing:

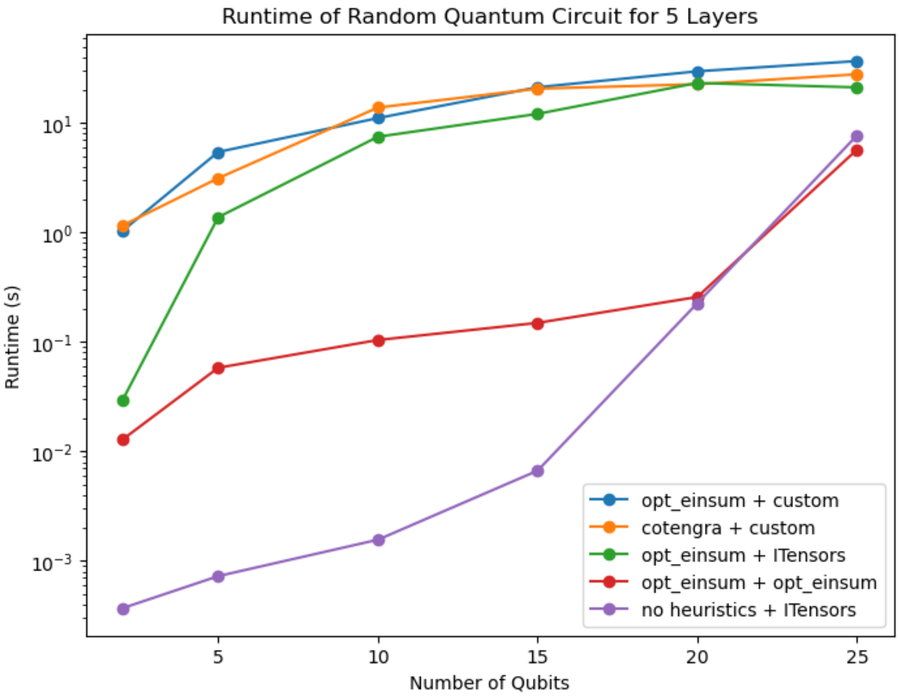


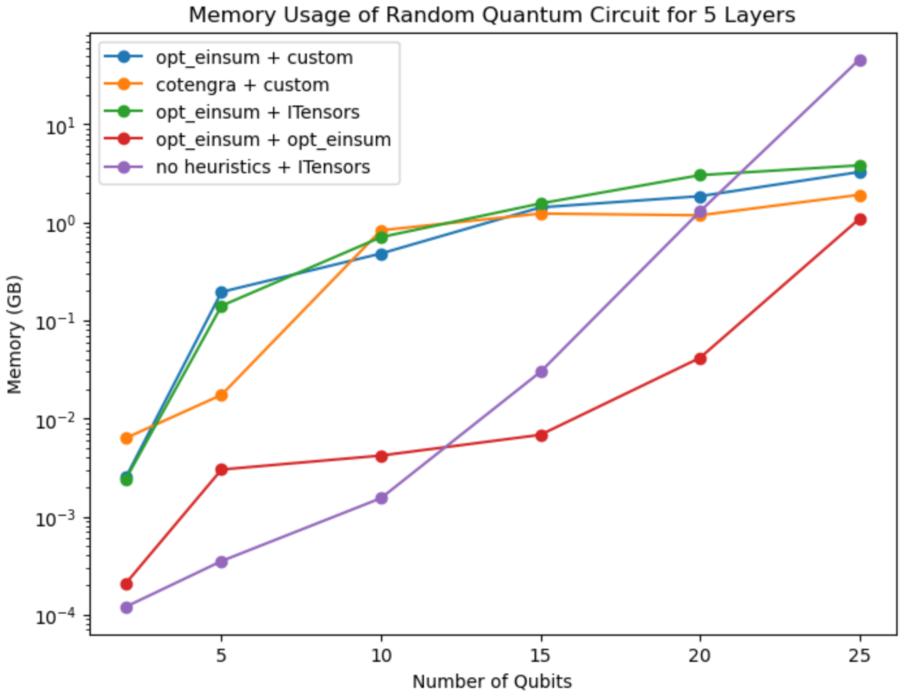
Results – Benchmarking exact contractions

Heuristics	Contractors
opt_einsum	custom
cotengra	custom
opt_einsum	ITensors.jl
opt_einsum	opt_einsum
Left to right	ITensors.jl

Results – Benchmarking exact contractions

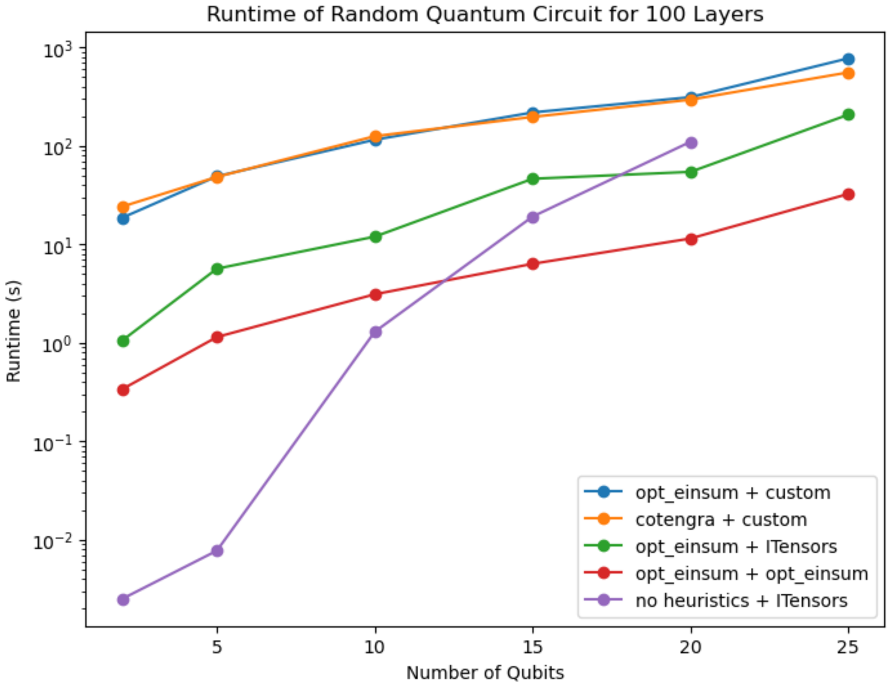
Low number of layers:

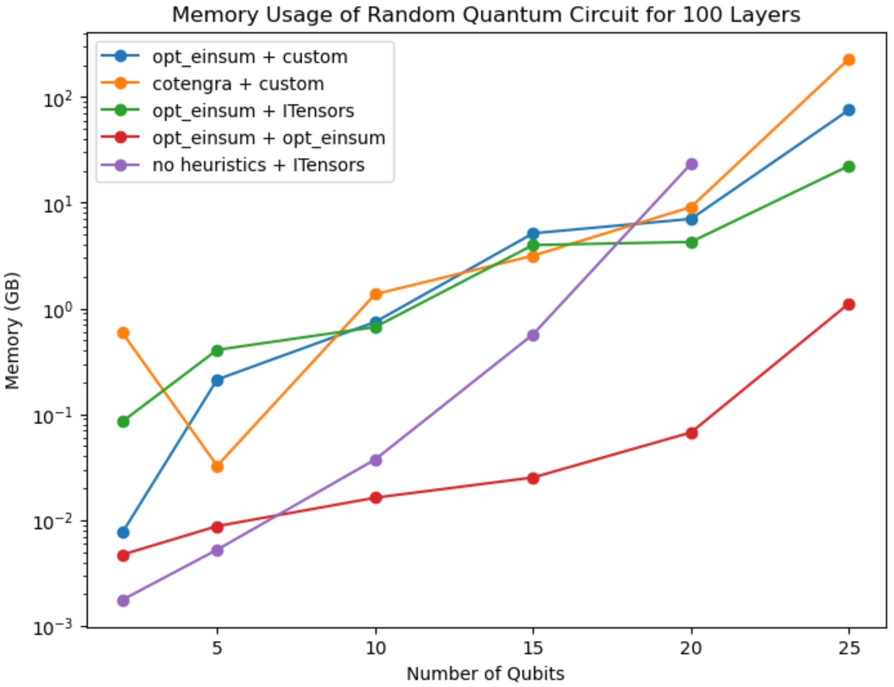




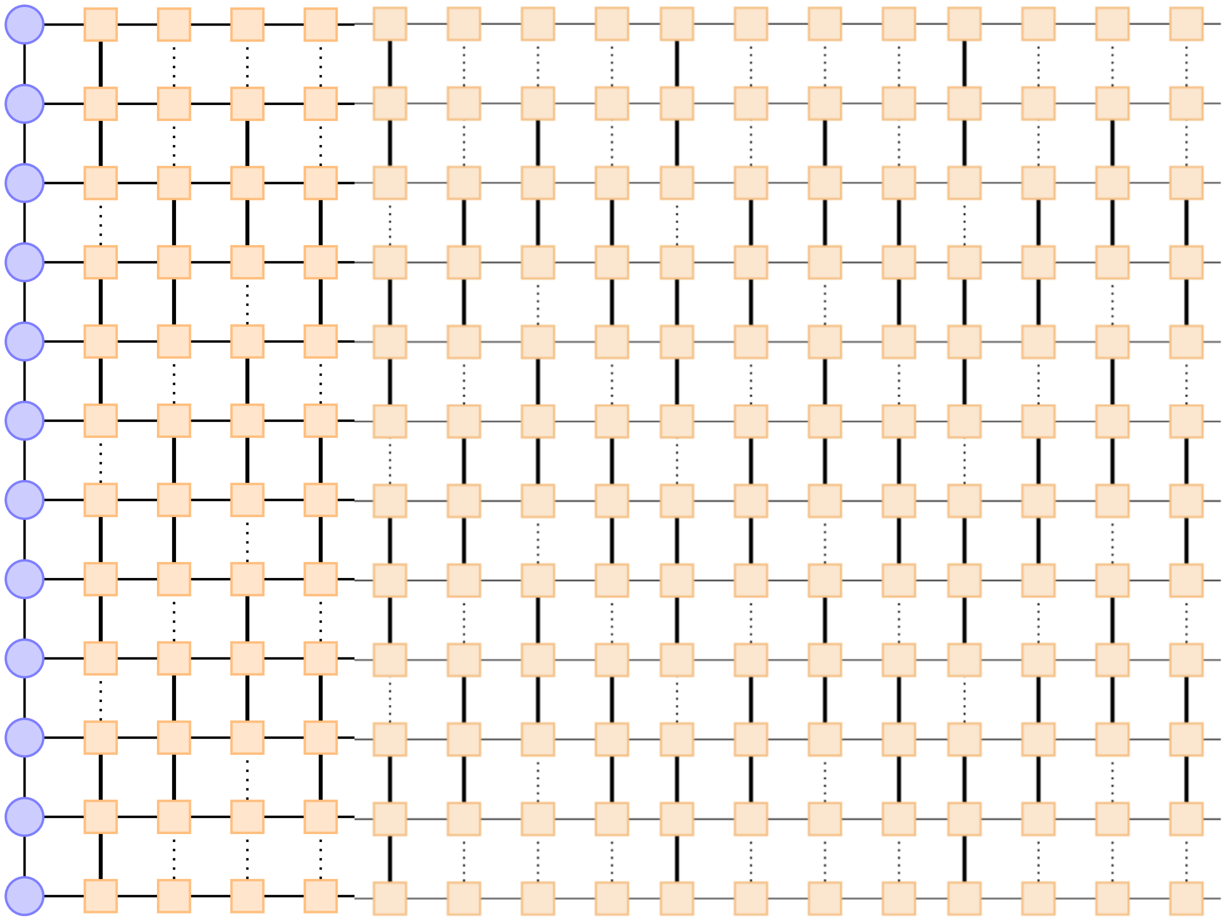
Results – Benchmarking exact contractions

High number of layers:



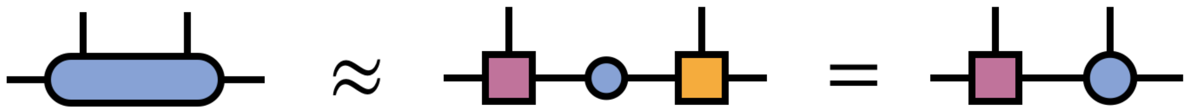


3. Simulations with finite fidelity



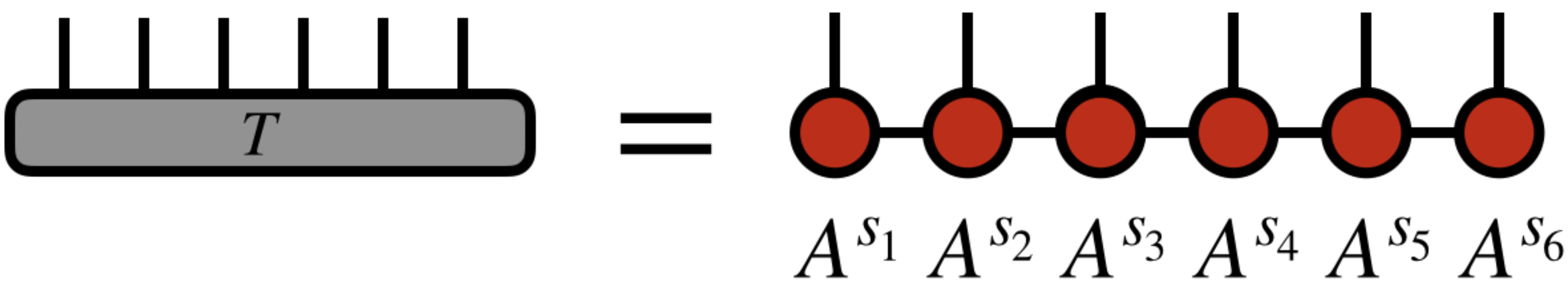
SVD and MPS

Singular Value Decomposition (SVD):



Successive SVDs and truncation of singular values produce a matrix-product state (MPS) approximation of a tensor:

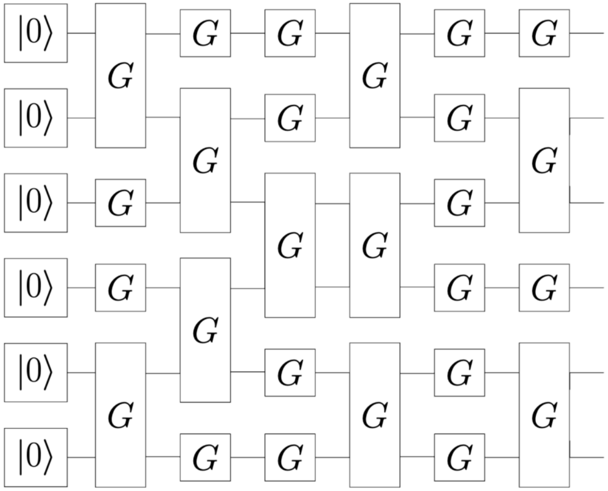
$$T^{s_1 s_2 s_3 s_4 s_5 s_6} = \sum_{\{\alpha\}} A^{s_1}_{\alpha_1} A^{s_2}_{\alpha_1 \alpha_2} A^{s_3}_{\alpha_2 \alpha_3} A^{s_4}_{\alpha_3 \alpha_4} A^{s_5}_{\alpha_4 \alpha_5} A^{s_6}_{\alpha_5}$$



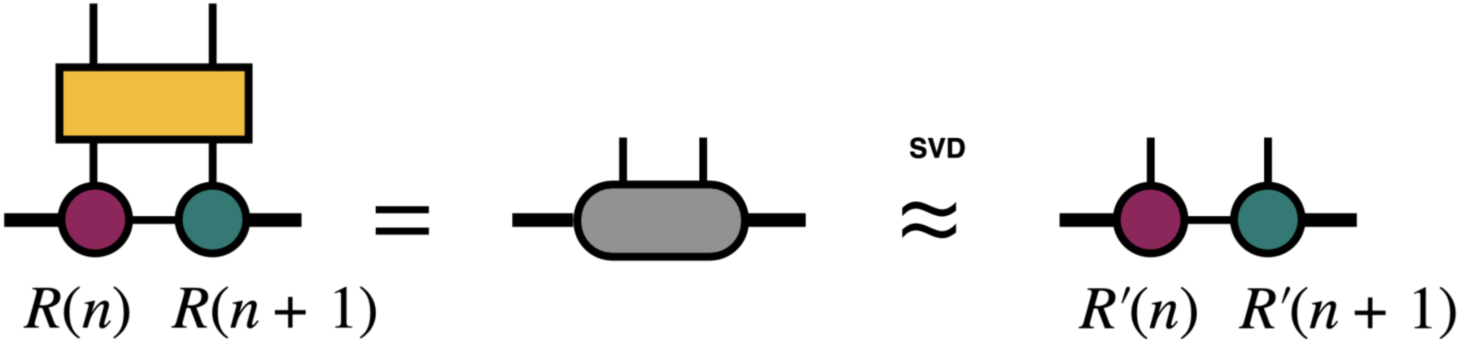
Bond dimension grows exponentially with the number of entangling gates applied

Time-Evolving Block Decimation (TEBD)

Remember random quantum circuit:

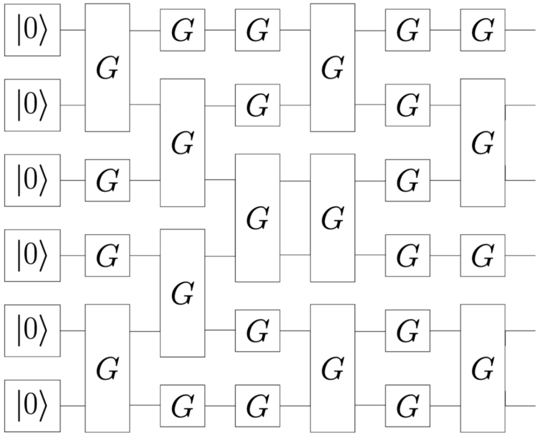


For each layer, apply gates and, for entangling gates, perform truncated SVD [6]

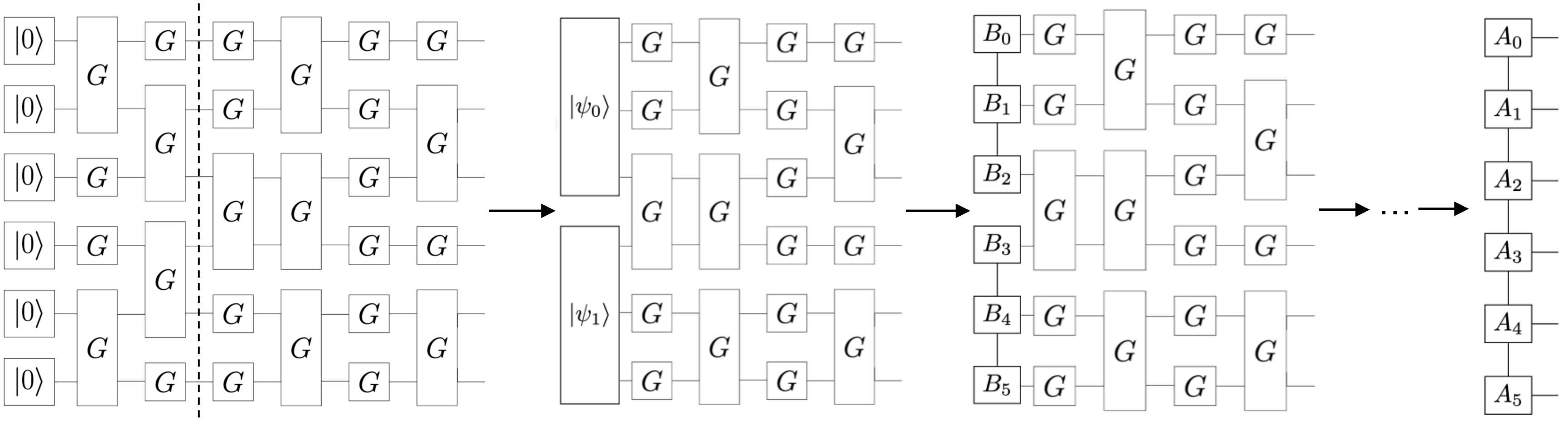


Cluster-TEBD

Remember random quantum circuit:

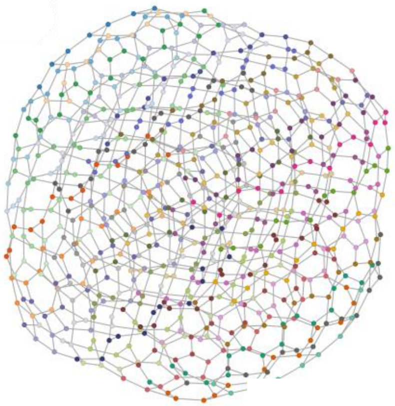


Instead, contract multiple layers until exact state fits in memory



Summary

Heuristics for optimized exact contractions of deep quantum circuits



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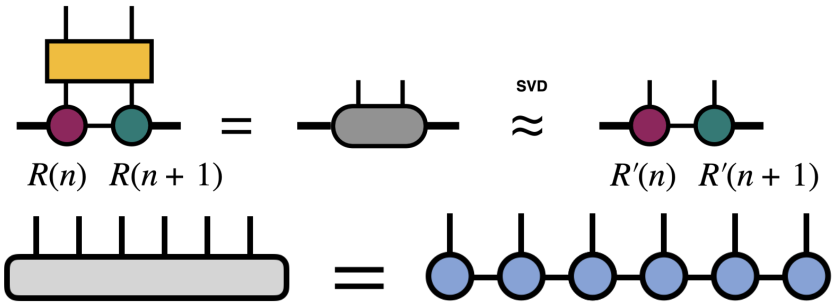
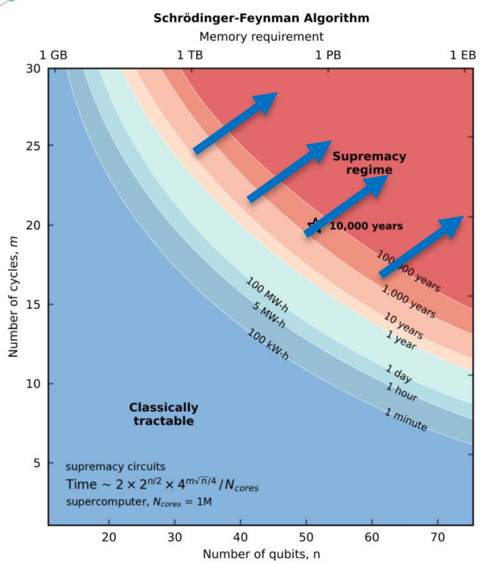
SVD and MPS to store many-qubit quantum circuits





Push boundaries to find actual quantum advantage threshold

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[4] Johnnie Gray and Stefanos Kourtis, "Hyper-optimized tensor network contraction". Quantum 5, 410 (2021)

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