XEB.jl: Challenging Quantum Supremacy in Julia

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Quantum Speedups

Exponential speedups

- Shor's algorithm for integer factoring
- HHL algorithm for linear equations

Polynomial speedups

- Grover's algorithm for searching

Requires fault-tolerant quantum computing (long terms)

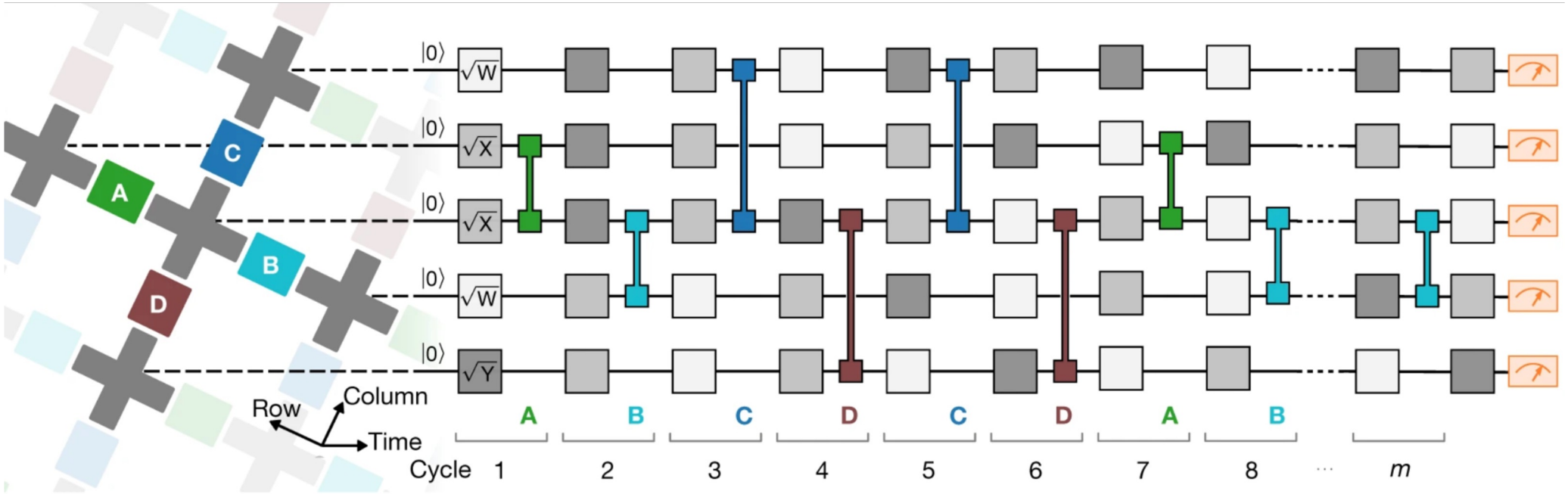
Can we verify quantum advantages on near-term devices?

- Random quantum circuit sampling (Google 2019[1], USTC 2021[2, 3])
- Gaussian Boson sampling (USTC 2021[4, 5])
- IQP circuits
- …

[1] Arute, F. *et al.* Quantum supremacy using a programmable superconducting processor. *Nature* **574**, 505–510 (2019).
[2] Wu, Y. *et al.* Strong Quantum Computational Advantage Using a Superconducting Quantum Processor. *Phys. Rev. Lett.* **127**, 180501 (2021).
[3] Zhu, Q. *et al.* Quantum Computational Advantage via 60-Qubit 24-Cycle Random Circuit Sampling. (2021) doi:10.48550/arXiv.2109.03494.
[4] Zhong, H.-S. *et al.* Quantum computational advantage using photons. *Science* **370**, 1460–1463 (2020).
[5] Zhong, H.-S. *et al.* Phase-Programmable Gaussian Boson Sampling Using Stimulated Squeezed Light. 9.

Random quantum circuit sampling

- Apply a random circuit to an initial state
- Measure the final state and get bitstrings
- Compute the linear cross-entropy benchmarking (XEB)



Linear XEB

$$\chi(p,q) = 2^n \left[\sum_{x \in \{0,1\}^n} p(x)q(x) \right] - 1$$

- Can approximate fidelity under certain assumption
- Experimentally feasible
- There is evidence of hardness[5-8]

[6] Aaronson, S. & Chen, L. Complexity-Theoretic Foundations of Quantum Supremacy Experiments. 66.
[7] Bouland, A., Fefferman, B., Nirkhe, C. & Vazirani, U. On the complexity and verification of quantum random circuit sampling. *Nature Phys* **15**, 159–163 (2019).
[8] Aaronson, S. & Gunn, S. On the Classical Hardness of Spoofing Linear Cross-Entropy Benchmarking. *Theory of Computing* **16**, 1–8 (2020).
[9] Krovi, H. Average-case hardness of estimating probabilities of random quantum circuits with a linear scaling in the error exponent. 26.

Experimental results

	#qubits	#depth	χ
Google 2019[1]	53	20	2.24×10^{-3}
USTC-1[2]	60	20	6.62×10^{-4}
USTC-2[3]	60	24	3.66×10^{-4}

[1] Arute, F. *et al.* Quantum supremacy using a programmable superconducting processor. *Nature* **574**, 505–510 (2019).
[2] Wu, Y. *et al.* Strong Quantum Computational Advantage Using a Superconducting Quantum Processor. *Phys. Rev. Lett.* **127**, 180501 (2021).
[3] Zhu, Q. *et al.* Quantum Computational Advantage via 60-Qubit 24-Cycle Random Circuit Sampling. (2021) doi:10.48550/arXiv.2109.03494.

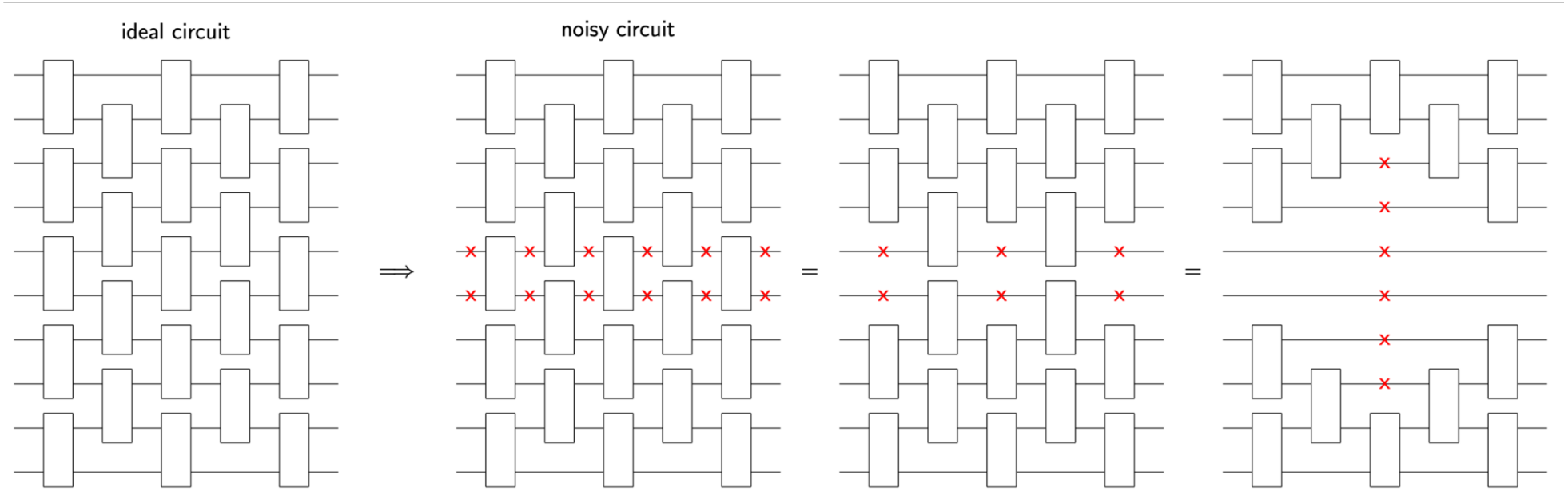
Spoofing algorithms

- Pan et al. 2021[10] (better XEB than Google with 512 GPU in 1 day)
- Gao et al. 2021[11] (~10% XEB of Google's with 1 GPU in a few seconds)

[10] Pan, F., Chen, K. & Zhang, P. Solving the sampling problem of the Sycamore quantum supremacy circuits. *arXiv:2111.03011 [physics, physics:quant-ph]* (2021).
[11] Gao, X. *et al.* Limitations of Linear Cross-Entropy as a Measure for Quantum Advantage. *arXiv:2112.01657 [cond-mat, physics:quant-ph]* (2021).

XEB.jl: an implementation of the spoofing algorithm in Gao et al.

- Add noises to divide and simplify the circuit
- Simulate each part with tensor networks
- Output bitstring with highest probability



Features of XEB.jl

- Random quantum circuit representation and simplification (Multigraphs.jl)
- Tensor network generation and contraction (OMEinsum.jl)
- Circuit simplification and simulation (Yao.jl)
- Contraction order optimization (OMEinsumContractionOrders.jl)
- Tensor network visualization (Makie.jl)
- GPU support (CUDA.jl)

https://github.com/ChenZhao44/XEB.jl

An Example

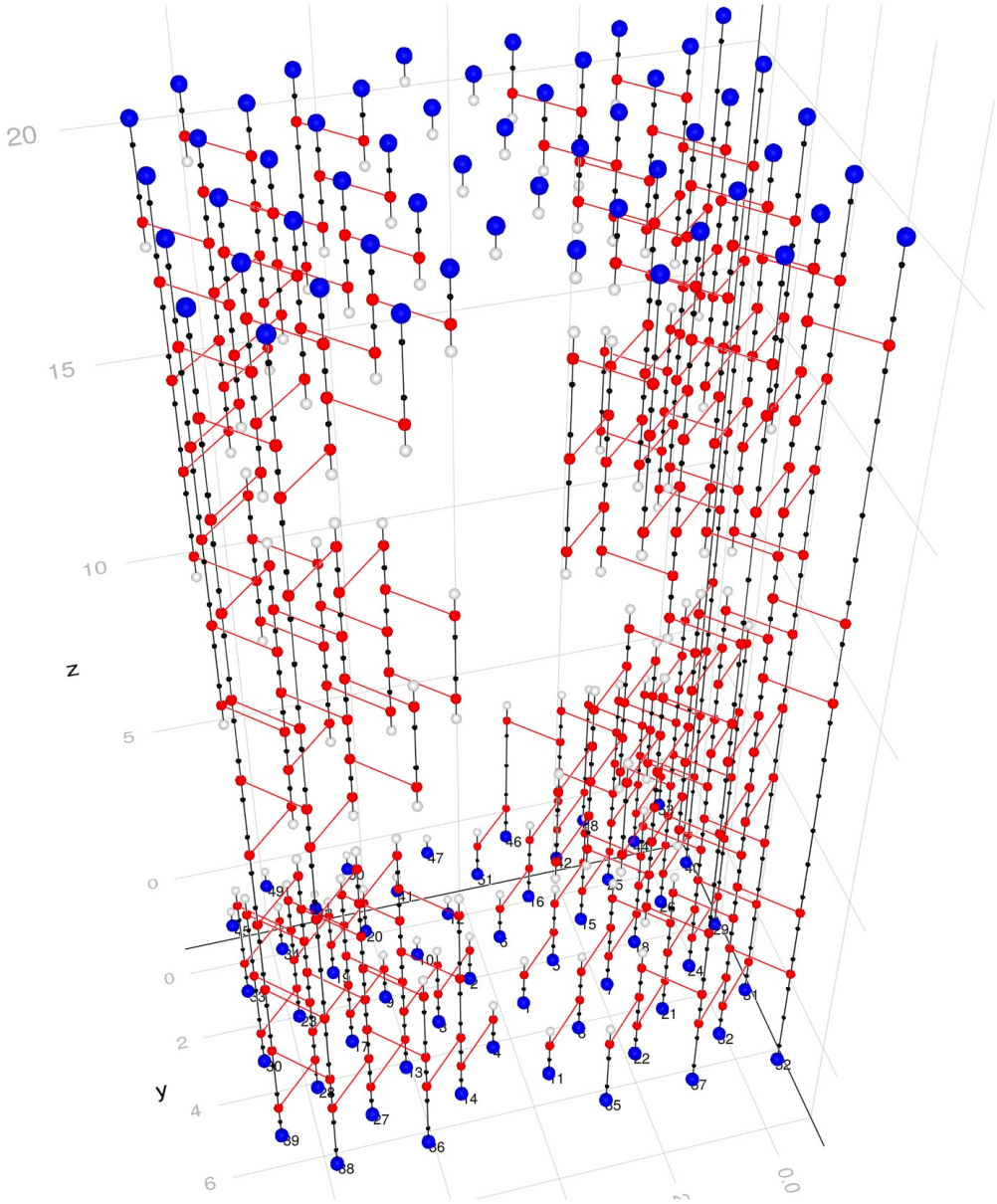
```julia
using XEB

D = 20  # circuit depth
layout = google_layout_53(53, D)

# left part and right part
L = sort!([52, 37, 35, 32, 22, 11, 31, 21, 8, 24, 7, 1,
    29, 18, 5, 26, 15, 6, 40, 25, 16, 44, 42, 51, 53, 48, 46])
R = setdiff(1:53, L)

# add noises and simplify the circuit
cuts = XEB.generate_cut(layout, L, 1, D)
XEB.simplify!(layout, cuts)

# visualize the tensor network
XEB.plot3d(layout)
```



Can we do better?

Estimate linear XEB without sampling

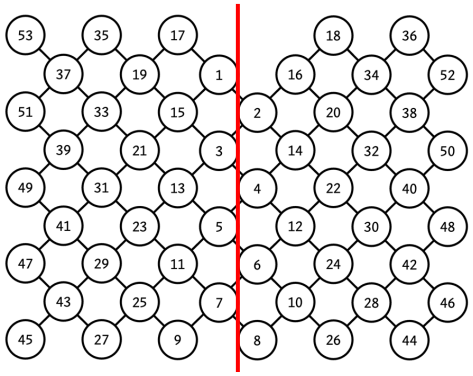
Original method (requires sampling)

1. Sample a random quantum circuit
2. Compute the output probability distribution with a tensor network (closed bound dimension 4 + open bound dimension 2)
3. Compute XEB from the probability distribution
4. Take average over all samples

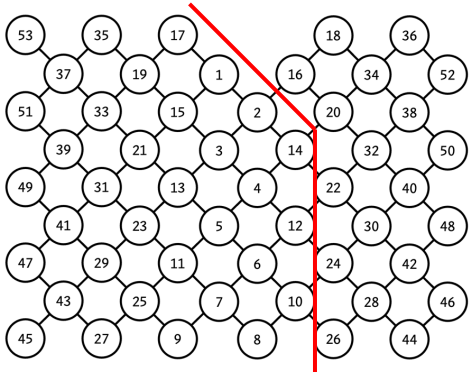
New method (without sampling)

1. Using the ZX-calculus to represent XEB as a tensor network (closed bound dimension 3 + no open indices)
2. Contract this tensor network and get XEB

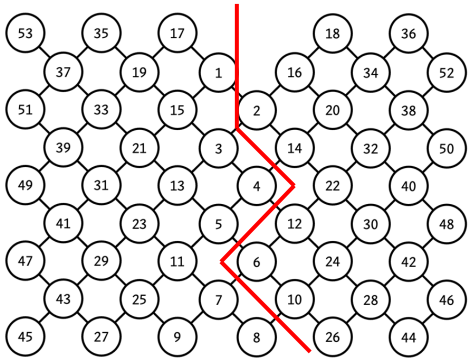
Different cuts



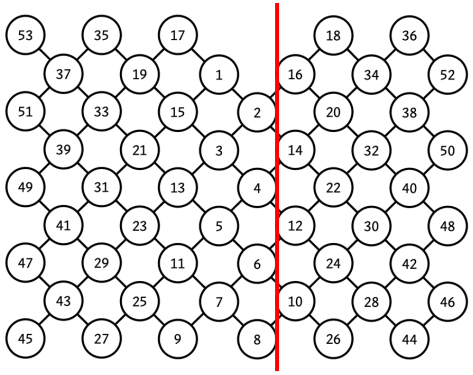
$\chi = 1.523\times10^{-8}$



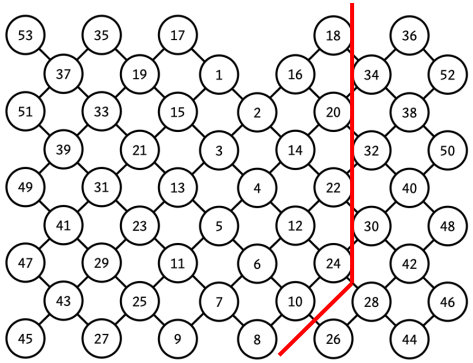
$\chi = 1.554\times10^{-8}$



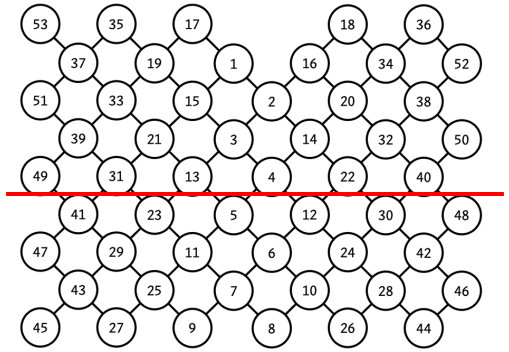
$\chi = 1.525\times10^{-8}$



$\chi = 1.508\times10^{-8}$



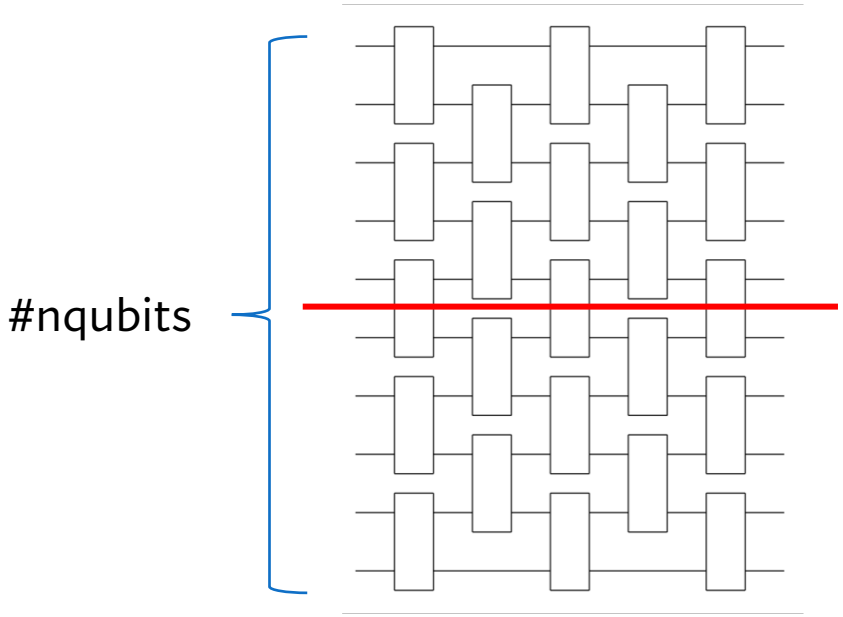
$\chi = 1.229\times10^{-8}$

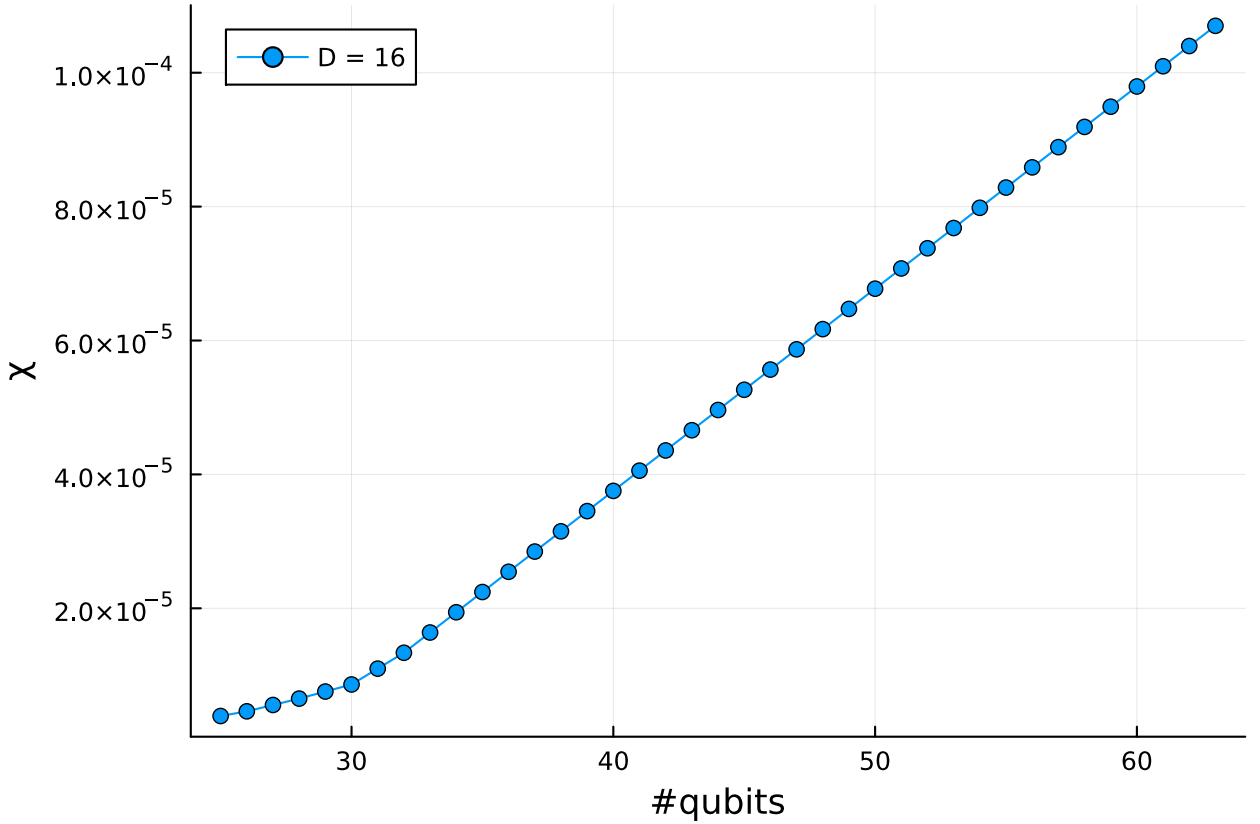


$\chi = 1.684\times10^{-8}$

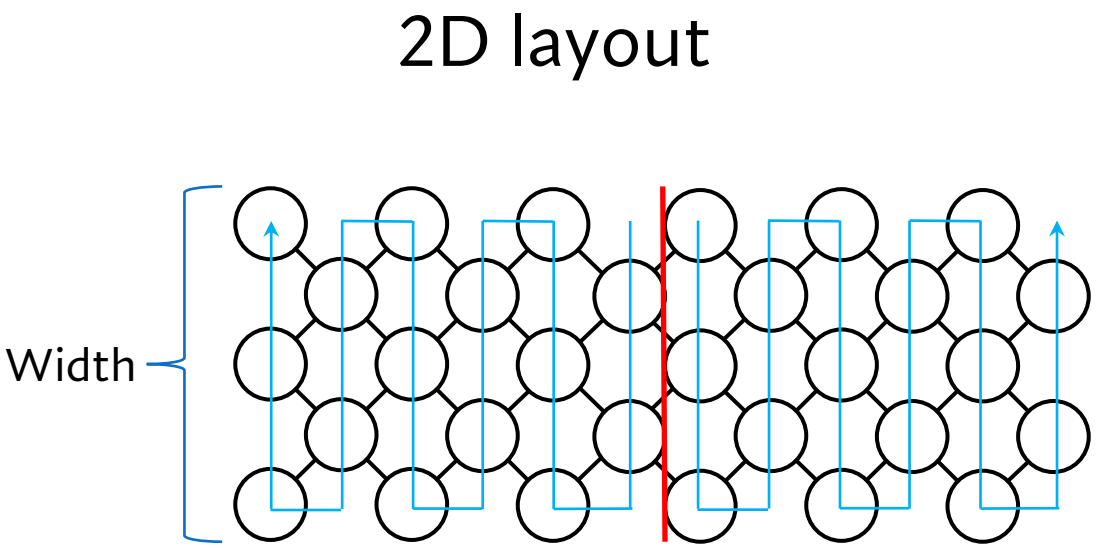
Different number of qubits

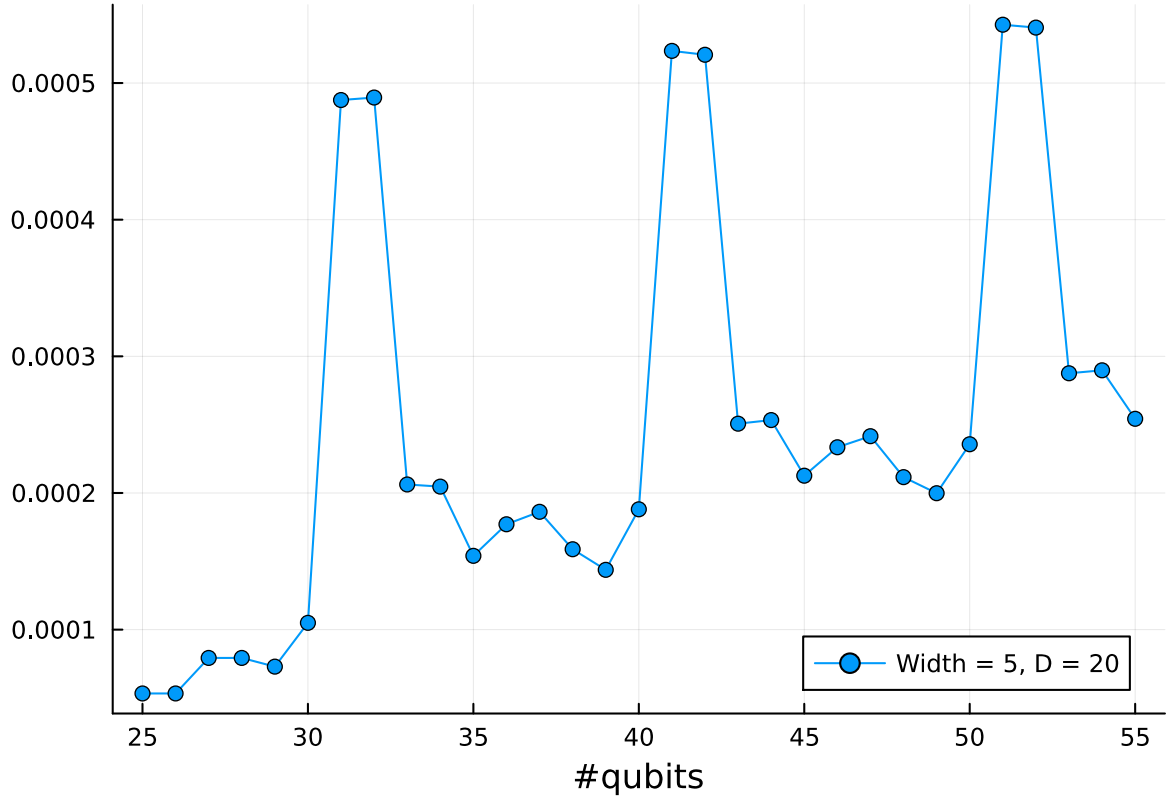
1D layout





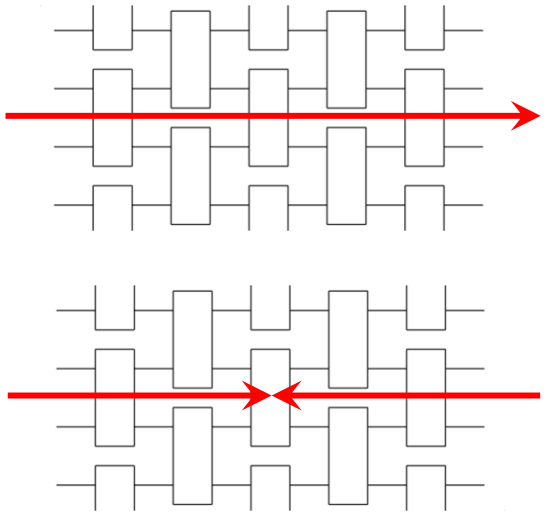
Different number of qubits

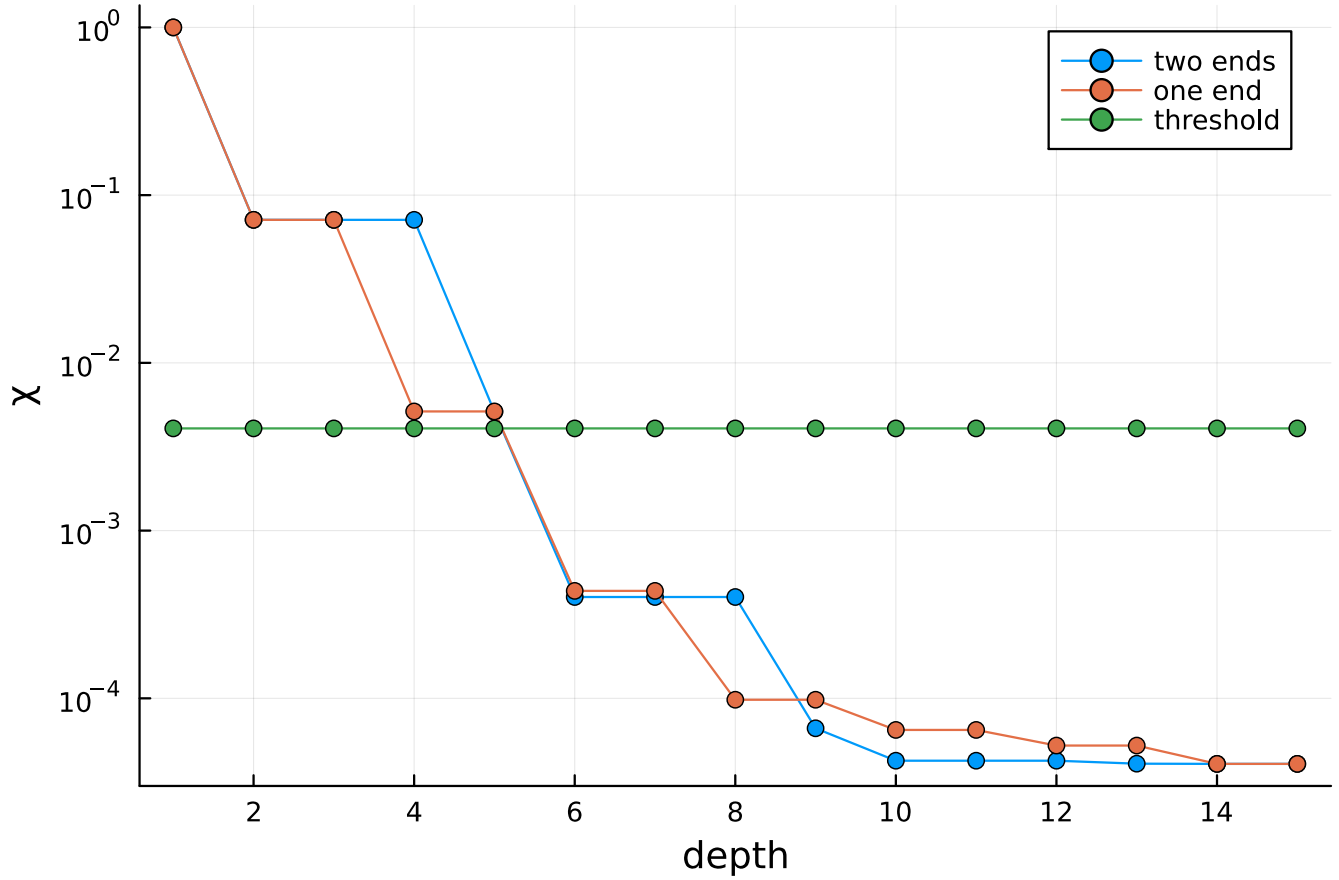




Different depth of cuts

Cutting orders





Conclusion

- Still difficult to get better XEB on a laptop
- Can outdo experiments if qubit number increase
- Julia is a developed platform for tensor networks

Acknowledgment

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Thank you!