Harnessing Natural Compounds for Universal Quantum Computing

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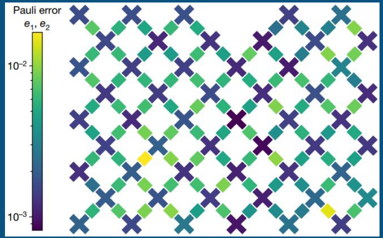
- Faculties

1. Quantum computing devices may be much easier to build than we thought
2. A branched DNA based universal quantum computing proposal

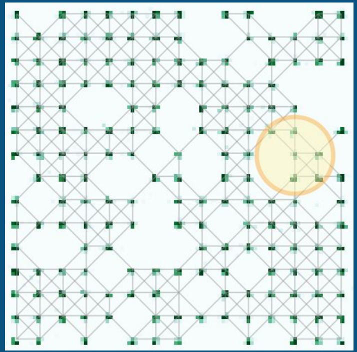
(work in progress)

Technical challenges of current schemes

- Scalability of system size
    - The “energy wall” problem



(Frank Arute et al. 2019)



(Ebadi et al. 2022)

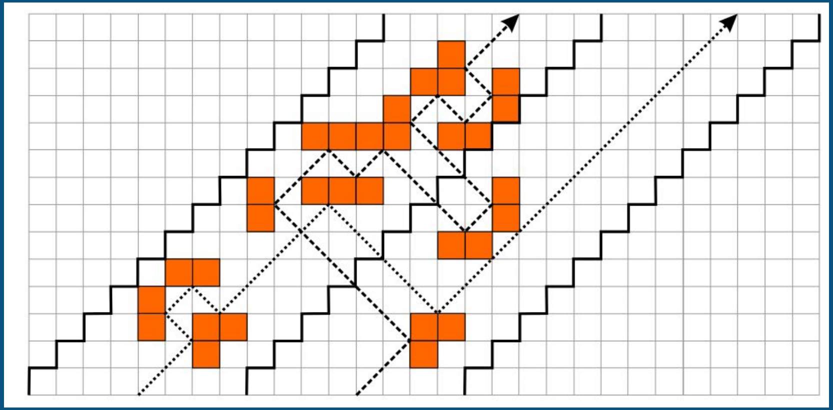
- Accurate quantum gates
    - Man made devices do not have have uniform high quality
    - External control inevitably induces noise
    - NOTE: Noisy quantum devices may be classically efficiently simulatable (arXiv:1810.03176, arXiv:2306.05804)

Easy ontrol

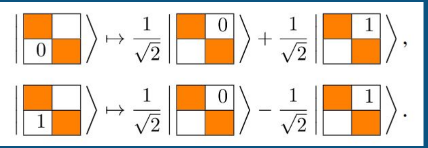
Robust to environmental noises

Physics like cellular automata

(Fredkin 1982, Margolus 1984, Arrighi 2011)



- Register: two dimensional grid
- Qubit: 4 states in each grid cell
- Quantum Gate: A reversible rule set of a 2x2 grid

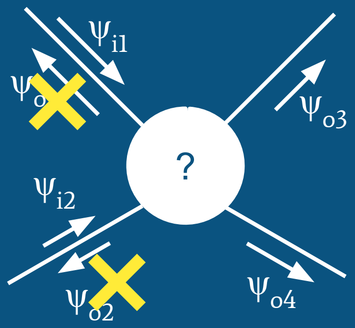


- Quantum Algorithm: encoded in the initial state

Problems

1. Unlikely to find the target Hamiltonian in nature (64 parameters)
2. Requires an external clock signal
3. Canvas size too big

Scattering based quantum computing



Scattering Center

No reflection

$$S = \left(\begin{array}{cc|cc} s_{11} & s_{12} & s_{13} & s_{14} \\ s_{21} & s_{22} & s_{23} & s_{24} \\ \hline s_{31} & s_{32} & s_{33} & s_{34} \\ s_{41} & s_{42} & s_{43} & s_{44} \end{array}\right)$$

U^T (upper right block), U (lower left block)

S-matrix is unitary

$$SS^\dagger = 1$$

Time-reversal symmetry

$$S = S^T$$

Multi-particle quantum walk

Time evolution governed by a Hamiltonian that being the Laplacian of a unweighted graph

(Ambainis 2007, Andrew 2009, 2013)

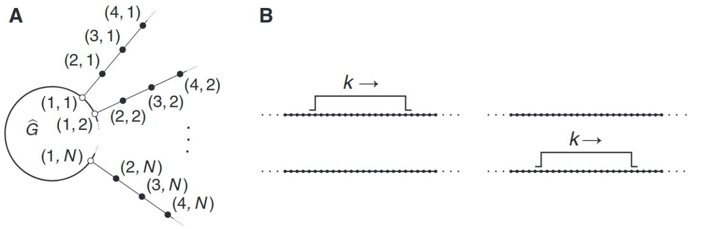


Fig. 1. (**A**) The infinite graph G. The vertices labeled $(1, j)$ belong to $\hat{G}$. (**B**) Encoded $|0\rangle$ (left) and $|1\rangle$ (right).

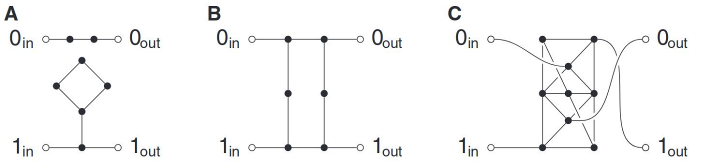
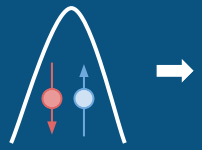


Fig. 2. (**A**) Phase gate at $-\pi/4$. (**B**) Basis-changing gate at $-\pi/4$. (**C**) Hadamard gate at $-\pi/2$.

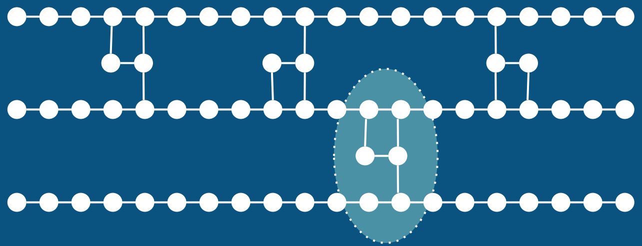
- Register: a translational invariant chain
- Qubit: a Fermionic/Bosonic mode propagating on the chain.
- Quantum Gate: An unweighted graph as scattering centers.
- Quantum Algorithm: encoded in the graph structure

Imagine: Branched DNA as a candidate

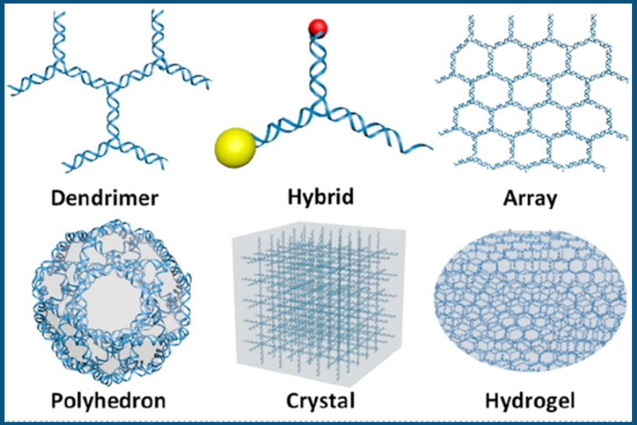
Qubit: an electronic mode with two spins



Register: a DNA double-strand



Quantum Gate: structures



Can create complex topology, very stable, can store billions of bits! (Dong 2020, Doricchi 2022)

Everyone can make an order on Taobao to synthesis a DNA sequence

Natural Hamiltonians are weighted!

1. A “natural” gate must be arbitrary: We probably can not get any specific gate. Instead, the gate given by the nature must be arbitrary. And this arbitrary gate can very accurate.
2. Only one gate: We probably can not get two gates that simultaneously transparent to a particle at a certain momentum k.

The compiling problem

1995: almost any single arbitrary gate (n ≥ 2) is universal! However, we do not know any efficient compiling algorithm. Naive linear time compiling

$$\varepsilon_g \sim 1/d$$

2021: Adam Bouland et al designed the first inverse-free Solovay-Kitaev algorithm! The compiling algorithm has polylog complexity

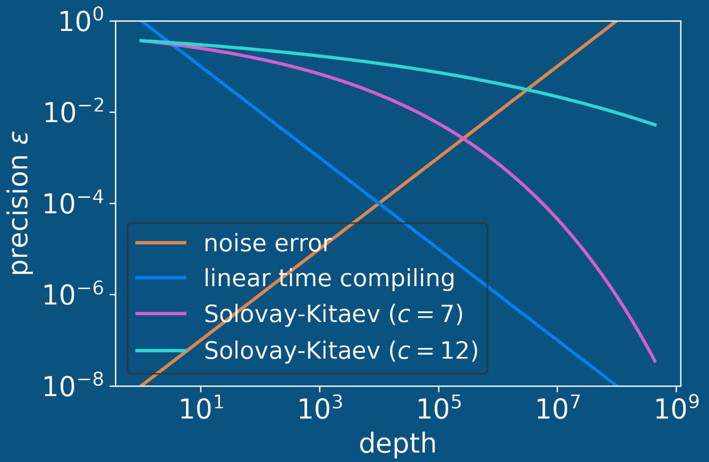
$$\varepsilon_g \sim \exp(-d^{1/c}),\ c \approxeq 12\ (7)$$

for two qubit gate compiling. Problem solved?

Compile with 2-qubit gates: U (≠ SWAP * U * SWAP)

Noise error : d * 10^{-8}

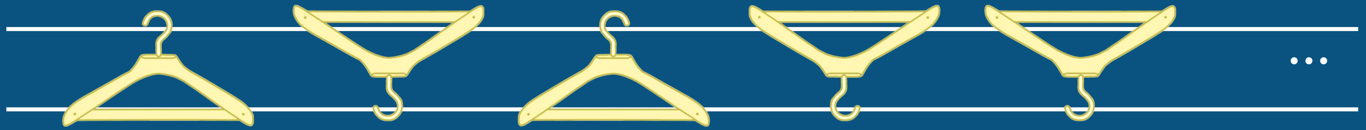
Compiling error : ε_g



Brute-force compiling in time-reversible scattering-based computing scheme

- Identify an arbitrary unitary gate U from a natural structure to high precision

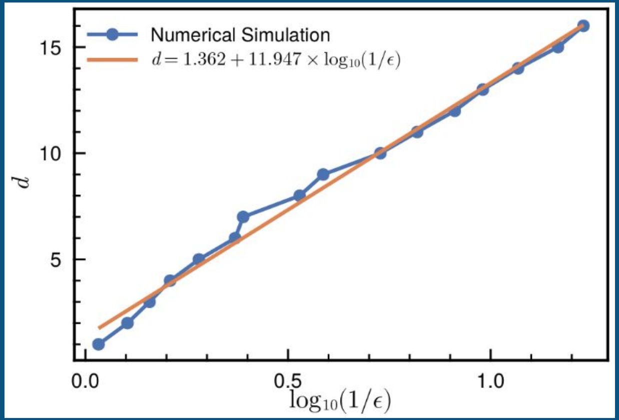
- Compile any two qubit gate to $\{U, U^T, U^S, U^{ST}\}$



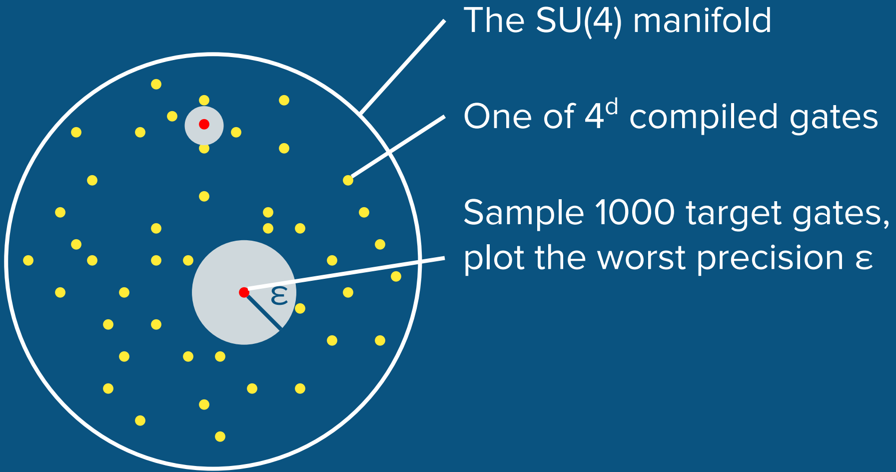
U U^S U^T U^{ST} U^S

$= \mathrm{SWAP} \cdot U \cdot \mathrm{SWAP}$

Result



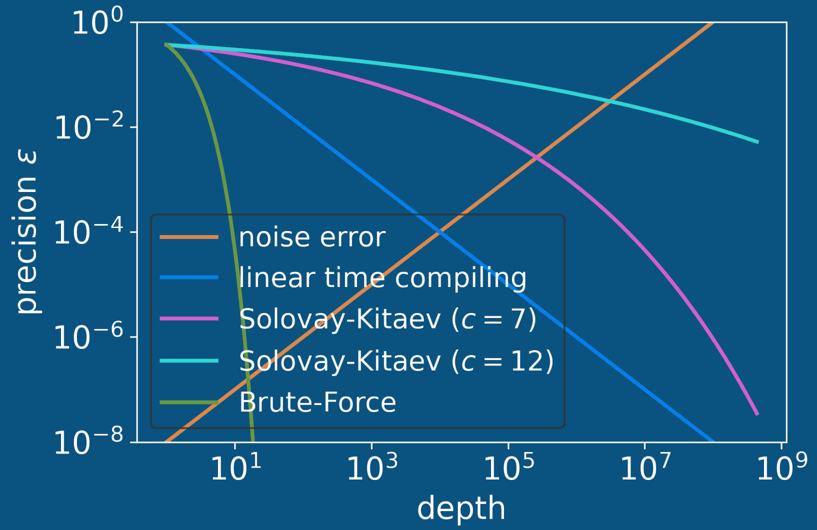
Operator infidelity ε = 1 - |Tr(U⁺T)|/4



Nearly perfectly uniform, the theoretical optimal scaling should be d ~ 13 * $\log_{10}(1/\varepsilon)$

With the improved brute-force search, we can reach doubled depth and ε^2 precision

Arbitrary unitary gate can be very efficiently compiled!



Brute-force compiling (this work)

$\varepsilon_g \sim \exp(-d)$

Summary: Universal quantum computing may be much easier than we thought

~~Clifford + T and compile with S-K algorithm~~ Use the gate that nature favors!

Manufacture + precision control + error correction ➔ Characterize + utilize

Advantages (branched DNA as an example):

1. The circuit can scale up to billions of gates,
2. Almost perfect gate, with uniform quality
3. Very energy efficient
4. Very stable under room temperature, can keep information for >100, 000 years
5. Coherence time is less likely to be an issue

New issues:

1. Systematic study of the electronic properties of branched DNA compounds.
2. An qubit input and readout scheme.
3. A scalable optimal compiling algorithm.

Thanks

Collaborators

Yu-Sheng Zhao
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Xia-Kun Chu
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Bio-molecule expert

Due to the political issues, some collaborators are not listed.

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