Learning Marginals Suffices!

(Sample complexity of learning a quantum state & circuit complexity of creating a state)

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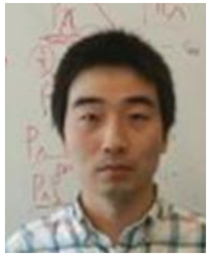

based on arXiv:2303.08938

Mathematical Picture Language @ Harvard
10/23/2023

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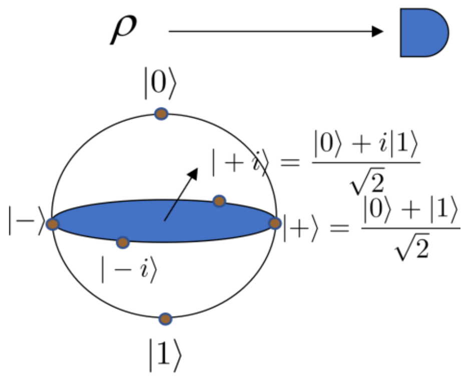
Reconstructing a quantum state

- Given multiple copies of the same quantum state, how do we learn the state?

  - **Quantum state tomography (QST)**

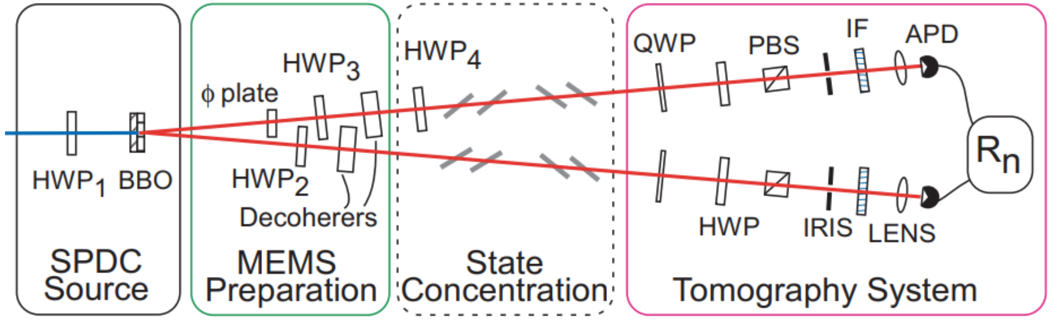
one qubit:



Bloch sphere

$$\rho = \frac{1}{2}(I + \vec{r}\cdot\vec{\sigma})$$

two qubits:



[Altepeter et al. PRL 2004]

$$\rho = \sum_{\mu,\nu} c_{\mu,\nu}\sigma_\mu \otimes \sigma_\nu \qquad \sigma_0 \equiv I$$

➔ Essentially, measure Pauli product expectation, e.g., $\sigma_x^{[1]} \otimes \sigma_y^{[2]} \otimes \cdots \sigma_z^{[n]}$

➔ QST also enables process tomography

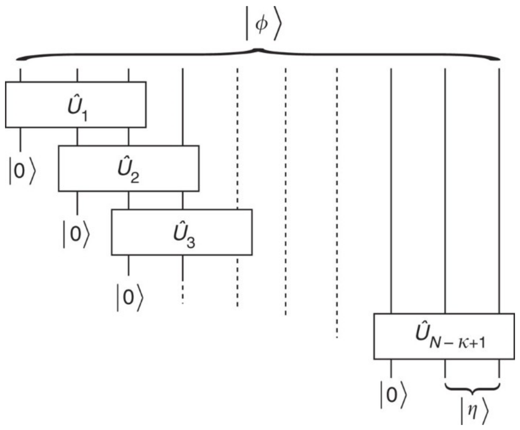
Exponential barrier to learn

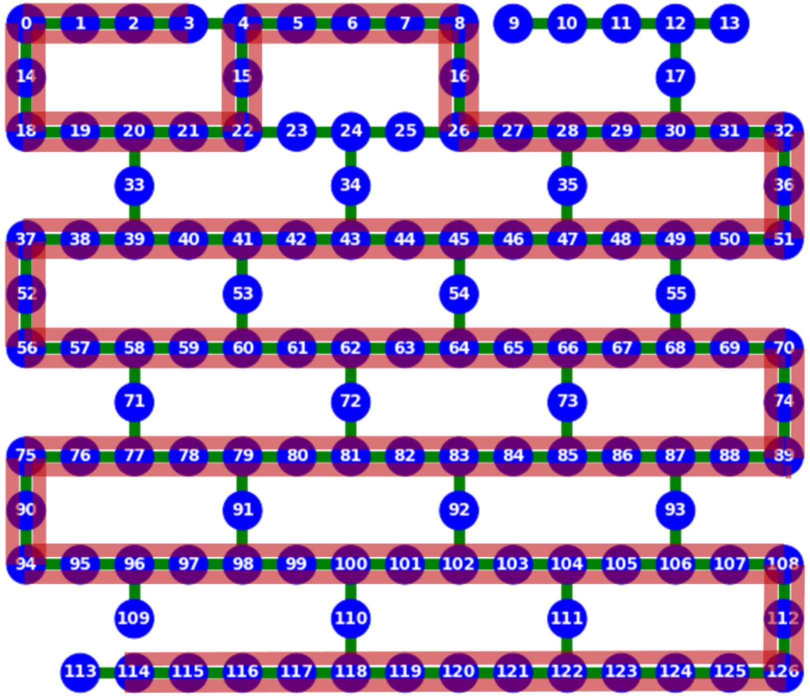
- Need to measure Pauli product expectation
  e.g., $\sigma_x^{[1]} \otimes \sigma_y^{[2]} \otimes \cdots \sigma_z^{[n]}$

  ➔ Exponentially many observables to measure ☹

  ➔ How many copies are needed?

- Compromises to make progress:
  - Compressed sensing for low-rank states: $O(r2^n n^2)$ observables needed [Gross et la. PRL 2010]
  - Matrix-product-state inspired: few-qubit QST + unitary to successively disentangle qubits ➔ linear [Cramer et al. Nat. Comm. 2010]



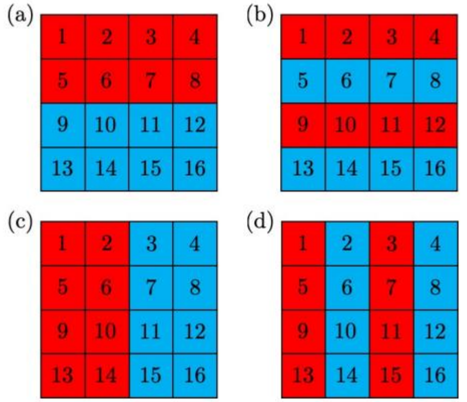


3^{102} different kinds of measurements would have been needed for a 102-qubit experiment in [Yu, Zhao & Wei, PRR 2023]

Learn only restricted observables is plausible

- Quantum overlapping tomography [Cotler& Wilczek PRL 2019] : to learn (up to) k-local Paulis, i.e., only k non-identity, e.g., $\sigma_x^{[1]} \otimes \sigma_y^{[2]} \otimes \cdots \otimes \sigma_z^{[k]} \otimes I \otimes \cdots I$
  - $\sim n^k$ reduced density matrices (i.e. quantum marginals) to measure
  - $e^{O(k)} n^k$ measurements (i.e. samples) needed

  There is a specific overlapping tomography protocol in [Yu 2020] , using O(10^k log(m)/λ^2) samples for *m* different k-qubit reduced density matrices accurate up to a trace norm parameter λ.



Four perfect hash functions; red=0; blue=1; nonidentical pair (I,j) has at least one function with i & j different colors

[Cotler & Wilczek]

- Quantum shadow tomography [Huang, Kueng & Preskill, Nat Phys 2020]
  - Goal: to predict M different observables $\{O_i\}$ of the state
  - Order log(M) measurements suffice:

$$N \geq \text{(order)} \log(M) \max_i ||O_i||^2_{\text{shadow}} / \epsilon^2 \qquad \text{for } k\text{-local } O\text{: } ||O_i||^2_{\text{shadow}} \leq 4^k ||O_i||^2_\infty$$

Quantum marginals and numerical ranges

- N-representability problem is QMA-complete:

  Fermions: [Liu, Christandl & Verstraete, PRL 2007]

  Spins: [Kitaev, Shen & Vyalyi 2002, …]

  Bosons: [Wei, Mosca & Nayak, PRL 2010]

Given a set of quantum marginals, is there a global state that is compatible with them?

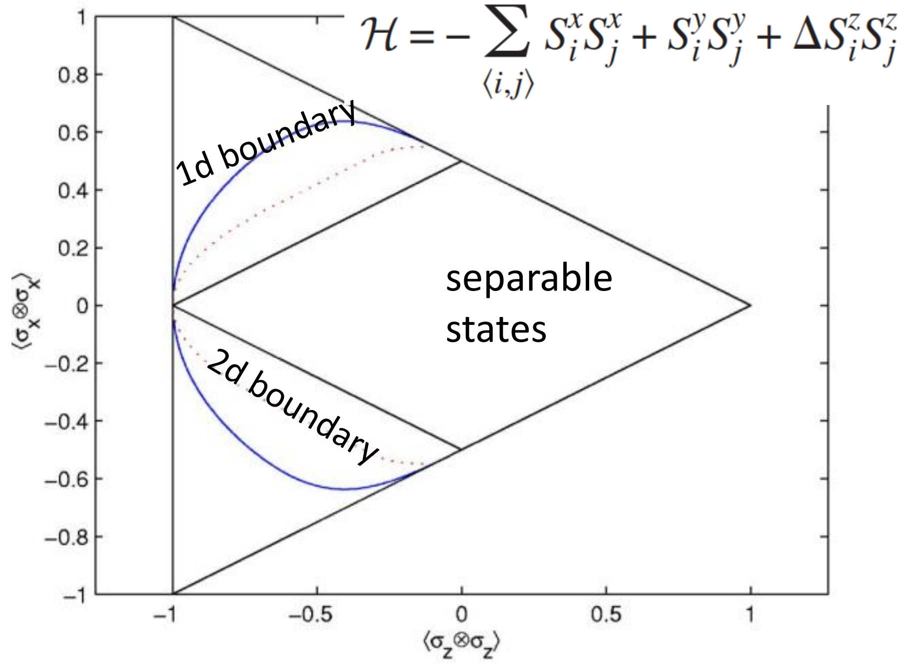
[Coulson 1960, Coleman 1973…]

- Its solution would allow solving general ground-state energy problems:

$$E_0 = \min_{\rho'_{s_i} s; |\psi\rangle} \sum_{s_i} \mathrm{tr}[H_{s_i}(\rho_{s_i})] \qquad H = \sum_i H_{S_i}$$

$$\rho_{S_i} = \mathrm{tr}_{n-S_i} \, |\psi\rangle\langle\psi|$$

- Numerical ranges of few-body operators provide useful insight into many-body physics



[Verstraete & Cirac, PRB 2006]

Are there states we can learn well?

- Quantum overlapping tomography & shadow tomography abandon complete characterization for a quantum state, but to learn/predict some observables

- Learning a generic state is exponentially hard, but is there a subset of physically relevant states that we can learn well?

  Yes! (1) Unique ground states of local Hamiltonians with gap &
  (2) Output state of a short-depth quantum circuit

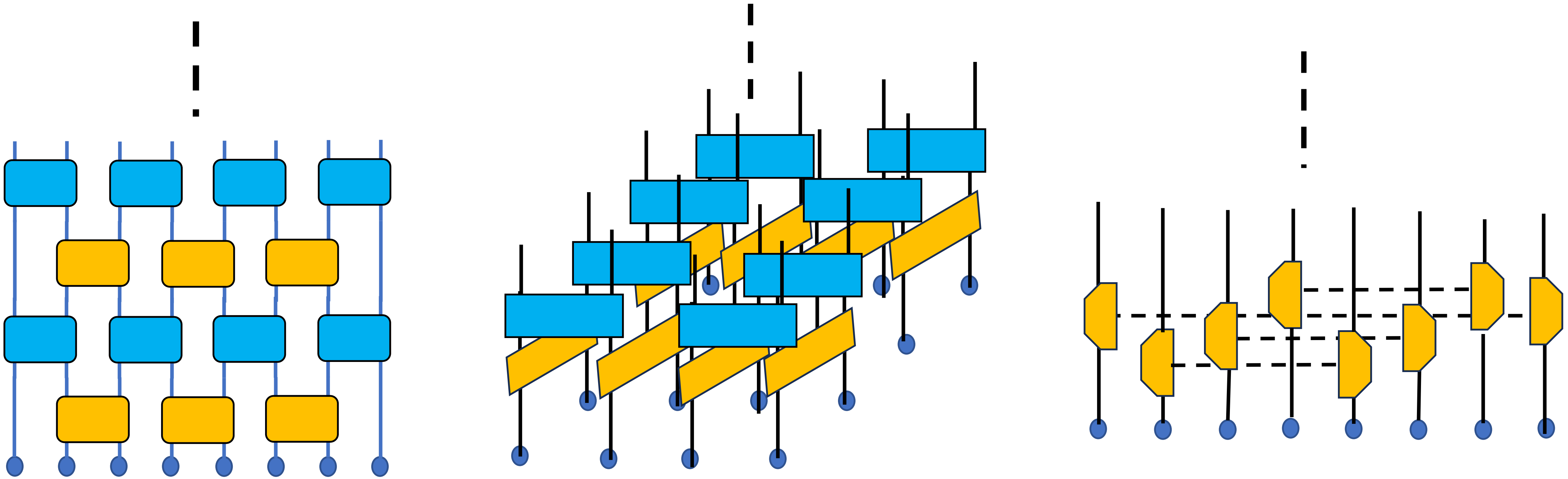
→ For these (restricted) states, we don't need to know all n-point correlators, but just some reduced density matrices (marginals) → Learning marginals suffices!

Example circuits

Nearest-neighbor gates in 1D

Nearest-neighbor gates in 2D

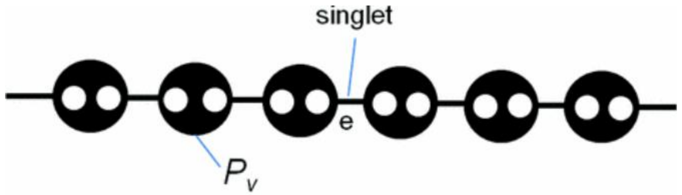
Non-local but 2-lcaol gates



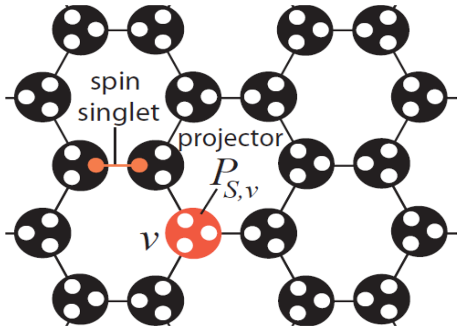
➔ We would like to learn output of these circuits

Example Hamiltonians

- Affleck-Kennedy-Lieb-Tasaki (AKLT) Hamiltonians [AKLT '87,'88] :



$$H_{1D} = \sum_i \hat{P}^{(S=2)}_{i,i+1} = \frac{1}{2} \sum_{\text{edge } \langle i,j \rangle} \left[\vec{S}_i \cdot \vec{S}_j + \frac{1}{3} (\vec{S}_i \cdot \vec{S}_j)^2 + \frac{2}{3} \right]$$



$$H_{2D} = \sum_{\text{edge } \langle i,j \rangle} \hat{P}^{(S=3)}_{i,j}$$

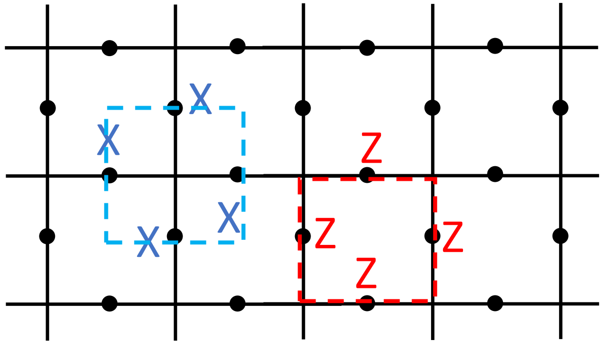
$$= \sum_{\text{edge } \langle i,j \rangle} \left[\vec{S}_i \cdot \vec{S}_j + \frac{116}{243} (\vec{S}_i \cdot \vec{S}_j)^2 + \frac{16}{243} (\vec{S}_i \cdot \vec{S}_j)^3 + \frac{55}{108} \right]$$

[gapped: Poma & Wei, PRL 2020;
Lemm, Sandivik &Wang, PRL 2020]

- Kitaev's toric code Hamiltonian [Kitaev '03] :

$$\hat{H} = -\sum_v A_v - \sum_p B_p,$$

$$A_v = \prod_{j \in v} \sigma_x^{[j]} \qquad B_p = \prod_{j \in \partial(p)} \sigma_z^{[j]}$$



Learning and circuit complexities

We will be interested in

(1) The minimum number of copies of the same quantum state necessary to reconstruct the state (which depends on the type of measurement, e.g. Pauli vs. Clifford) [we use Pauli's]
≈: the learning complexity of a quantum state

(2) The minimum depth of the quantum circuit necessary to implement a state [we use 2-local gates]
≈: the circuit complexity of a quantum state

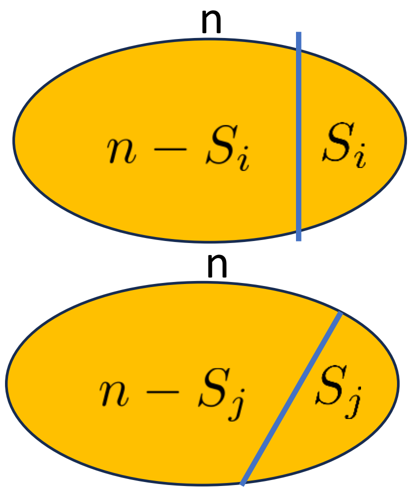
Key results: We show that the marginals (reduced density matrices) uniquely determine quantum states with low circuit complexity. Moreover, the determination procedure is robust against the potential noise of the marginals (such as statistical noise in the measurement). Our result also bridges quantum circuit complexity and ground states of gapped local Hamiltonians.

Outline

- ❑ Introduction
- ❑ Some properties of unique ground states and their quantum marginals
- ❑ Learning output of a shallow quantum circuit
- ❑ Lower bound on quantum state complexity
- ❑ Conclusion

UDA notion and unique ground states

- Unique ground states of local Hamiltonians are always uniquely determined by their local reduced density matrices among all mixed states (UDA)



  - We use ψ_{S_i} to denote the reduced density matrices of pure state ψ supported on sites in S_i, i.e. $\psi_{S_i} \equiv \mathrm{Tr}_{n-S_i}(|\psi\rangle\langle\psi|)$

- A pure state ψ is UDA with respect to a set of multi-sites $\{S_i\}_{i=1}^{m}$ (interaction graph)

If for any mixed state ρ : $\rho_{s_i} = \psi_{s_i}, \forall 1 \leq i \leq m \implies \rho = |\psi\rangle\langle\psi|$

[note similar notion of being uniquely determined by marginals among all pure states (UDP) can be defined]

Example: $|W_4\rangle = a_1|0001\rangle + a_2|0010\rangle + a_3|0100\rangle + a_4|1000\rangle$ [Parashar& Rana, PRA 2009]

Is UDA by all 2-body reduced density matrices

$|\mathrm{GHZ}_4\rangle = a|0000\rangle + b|1111\rangle$ not UDA (nor UDP)

There exist states that are UDP but not UDA [Xin et al. PRL2017]

UDA and unique ground states

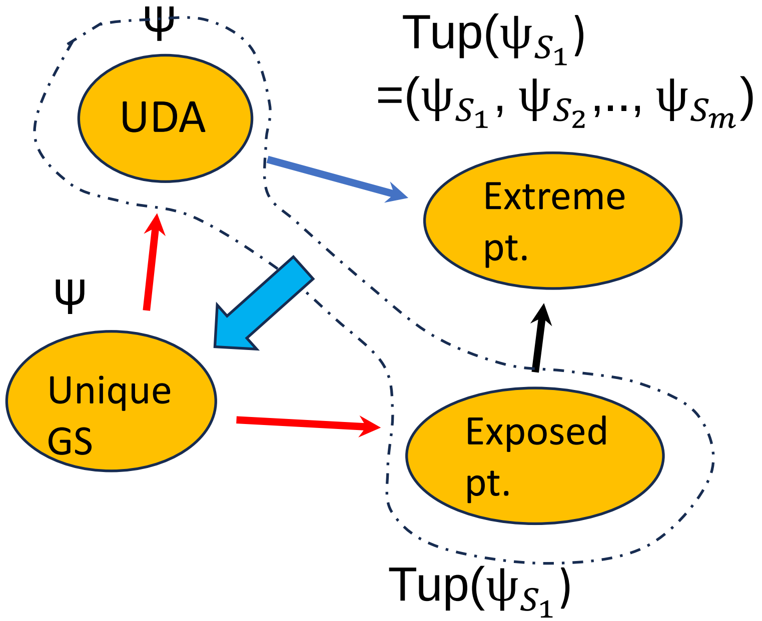
(i) A quantum state |ψ⟩ is UDA by its k-local reduced density matrices on the interaction graph G only if the tuple of its reduced density matrices is an extreme point of R={(σ_{S_1}, σ_{S_2},.., σ_{S_m})}

(ii) A quantum state |φ⟩ is the unique ground state of a Hamiltonian with the interaction graph G only if the tuple of its reduced density matrices is an exposed point of R

(iii) A quantum state |φ⟩ is the unique ground state of a Hamiltonian with the interaction graph G only if it is UDA by its reduced density matrices on the interaction graph G.

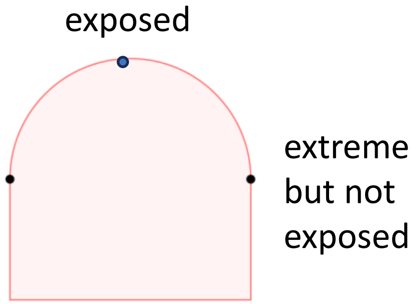
If a pure state is UDA and its tuple of reduced density matrices (over some interaction graph G) is also an exposed point, it is a unique ground state of some local Hamiltonian with the same interaction graph

Note: An exposed point does not always imply UDA, nor UDP.



Note: UDA $\not\Rightarrow$ Unique GS

[Karuvade et al. PRA 2019]



[Wikipedia]

Robust fingerprint of ground state: tuple of reduced density matrices

Lemma. Let $|\psi\rangle$ be the unique ground state of a k-local Hamiltonian H with gap $\Delta > 0$ and interaction graph $G = \{s_1, \cdots, s_m\}$, for any state ρ, one of the following conditions must be satisfied:

$$H = \sum_i H_{S_i} \ (0 \leq H_{S_i} \leq I_{S_i})$$

1. $||\psi - \rho||_1 < \varepsilon$;
2. $||\psi_{si} - \rho_{si}||_1 > \Delta \varepsilon^2/2m$ for some i.

where m is number of terms, $\psi \equiv |\psi\rangle\langle\psi|$ and ψ_{s_i} denotes the marginal supported on subsystem s_i

➔ Sufficient to perform tomography of all the k-local reduced density matrices with precision $\Delta\varepsilon^2/2m$ for trace norm to determine the unique ground state ψ of some k-local Hamiltonian up to precision ε in trace norm.

Note: There is a specific overlapping tomography protocol in [Yu 2020] , which uses $O(10^k \log(m)/\epsilon^2)$ samples for the tomography of m different k-qubit reduced density matrices accurate up to a trace norm parameter ϵ.

Proof of Lemma

Lemma. Let $|\psi\rangle$ be the unique ground state of a k-local Hamiltonian H with gap $\Delta > 0$ and interaction graph G = $\{s_1, \cdots, s_m\}$, for any state ρ, one of the following conditions must be satisfied:

1. $||\psi - \rho||_1 < \varepsilon$; 2. $||\psi_{si} - \rho_{si}||_1 > \Delta\, \varepsilon^2/2m$ for some i.

$H = \sum_i H_{S_i}\ (0 \leq H_{S_i} \leq I_{S_i})$

where m is number of terms, $\psi \equiv |\psi\rangle\langle\psi|$ and ψ_{s_i} denotes the marginal supported on subsystem s_i

Proof. From the ground state and the gap:

$$H \geq E_0|\psi\rangle\langle\psi| + (E_0 + \Delta)(I - |\psi\rangle\langle\psi|) = (E_0 + \Delta)I - \Delta|\psi\rangle\langle\psi|$$

If scenario 1 does NOT hold:

$$||\psi - \rho||_1 \geq \epsilon \overset{*}{\Longrightarrow} \mathrm{tr}(|\psi\rangle\langle\psi|\rho) \leq 1 - \frac{||\psi - \rho||_1^2}{2^2} \leq 1 - \frac{\epsilon^2}{4}$$

$$\Rightarrow \sum_{s_i} \mathrm{tr}[H_{s_i}(\rho_{s_i} - \psi_{s_i})] = \mathrm{tr}[H(\rho - \psi)] \geq (\Delta(1 - \mathrm{tr}(|\psi\rangle\langle\psi|\rho)) \geq \frac{\Delta\epsilon^2}{4}$$

Thus, $\mathrm{tr}[H(\rho - \psi)] = \sum_{s_i} \mathrm{tr}[H_{s_i}(\rho_{s_i} - \psi_{s_i})] \geq \dfrac{\Delta\epsilon^2}{4}$

*note: $||\rho||_1 = \mathrm{Tr}\sqrt{\rho\rho^\dagger} = 2\max_{P \leq I} \mathrm{tr}(\rho P)$

$\Rightarrow$ At least one $||\rho_{s_i} - \psi_{s_i}||_1 \geq \dfrac{\Delta\epsilon^2}{2m}$

*Use: $1 - F(\rho, \sigma) \leq \frac{1}{2}||\rho - \sigma||_1 \leq \sqrt{1 - F(\rho, \sigma)^2}$

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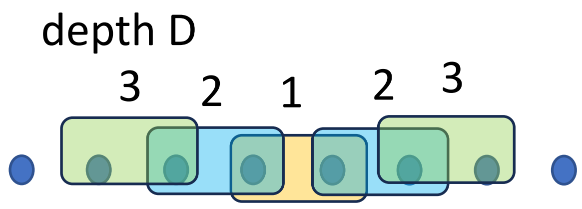
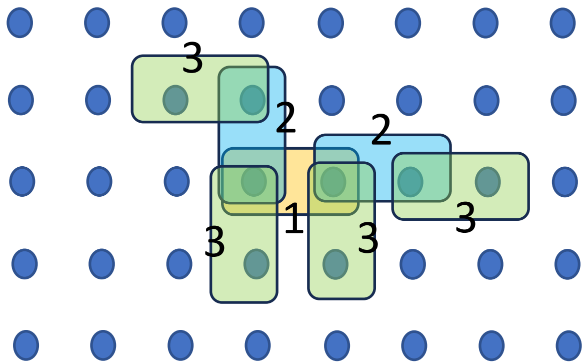
Output of a short-depth quantum circuit

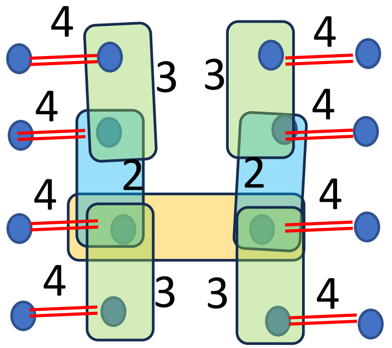
The output state $|\psi_D\rangle$ of an n-qubit quantum circuit with depth $D \geq 1$ is the unique ground state of a k-local frustration-free Hamiltonian with a gap at least 1.
Moreover, $k = 2^D$, if the gates are not geometrically local; $k = 2D$ for a chain;
$k = \gamma_2(D)$ for the square lattice.



Light cone contains linear number of points (k=2D)



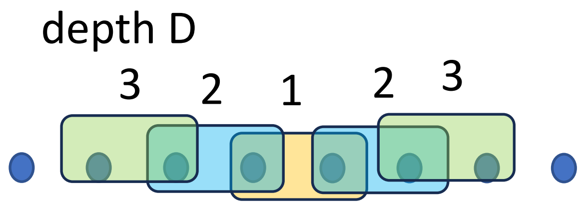
Light cone contains quadratic number of points k= $\gamma_2(D) = O(D^2)$



Light cone contains exponential number of points k= 2^D

- Initial state is |00…0>, unique ground state of $H_0 = \sum_{i=1}^{n} H_{0,i} = -\sum_i |0\rangle_i\langle 0|$ with gap 1
- D-layer circuit: $\mathcal{U}_D \equiv U_D \ldots U_2 U_1$ turns 1-local $H_{0,i}$ to at most k(D)-local, preserving gap

When multiple terms share same support



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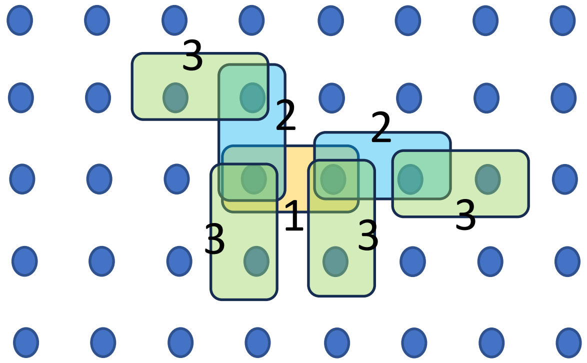

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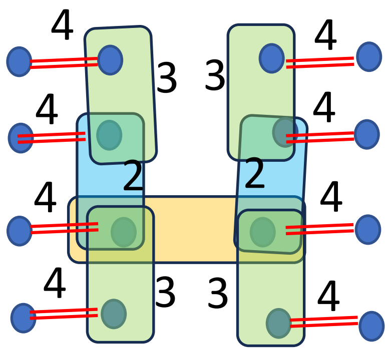


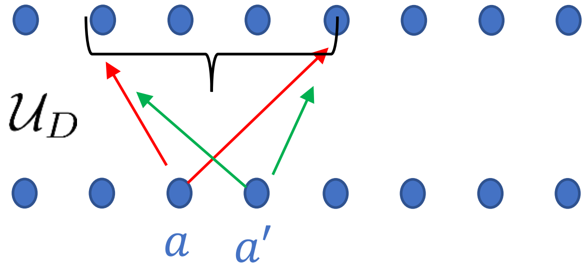
Light cone contains exponential number of points k= 2^D

- Initial state is |00…0>, unique ground state of $H_0 = \sum_i H_{0,i} = -\sum_i |0\rangle_i\langle 0|$ with gap 1
- D-th circuit: $\mathcal{U}_D \equiv U_D \dots U_2 U_1$ turns 1-local $H_{0,i}$ to at most k(D)-local, preserving gap

❖ When more than one terms in $\mathcal{U}_D H_0 \mathcal{U}_D^\dagger$ share same support, replace those by a single one

$$\mathcal{U}_D \left(I_{S_i} - |0\cdots0\rangle\langle0\cdots0|_{S_i}\right)\mathcal{U}_D^\dagger$$

where any single site $a \in S_i$ propagate by $\mathcal{U}_D$ to same final support



Closeness to output of shallow circuits

Theorem: Suppose n-qubit $|\psi\rangle$ has circuit complexity at most D. For any state (possibly mixed) ρ, one of the following conditions must be satisfied:

1. $||\psi - \rho||_1 < \varepsilon$;

2. $||\psi_s - \rho_s||_1 > \varepsilon^2/2n$ for some $s \subseteq \{0, \cdots, n-1\}$ with $|s| = k(D)$.

Note: $\psi = |\psi\rangle\langle\psi|$

➔ Intuitive picture: For an output of a short-depth quantum circuit, any state is either close to it or "far" from it which is detectable by quantum marginals

Proof: from our previous **Lemma** setting gap $\Delta=1$, and number m of terms in the Hamiltonian $m \leq n$ (i.e. number of qubits)

Recall

Lemma. Let $|\psi\rangle$ be the unique ground state of a k-local Hamiltonian H with gap $\Delta > 0$ and interaction graph $G = \{s_1, \cdots, s_m\}$, for any state ρ, one of the following conditions must be satisfied:
1. $||\psi - \rho||_1 < \varepsilon$; 2. $||\psi_{si} - \rho_{si}||_1 > \Delta\, \varepsilon^2/2m$ for some i.

Sample complexity for shallow-circuit output

Theorem. To accomplish the quantum state tomography for depth-D circuit output with precision ε,

1. $O(n^2 \cdot 10^k \log \binom{n}{k} / \varepsilon^4)$ suffices, if we do not know the circuit structure;
2. $O(n^2 \cdot 10^k \log(n) / \varepsilon^4)$ suffices, if we know the circuit structure,

where $k=k(D)$

(1) one-dimension: $k=2D$; (2) two dimensions: $k=\gamma_2(D) = O(D^2)$; (3) non-local: $k= 2^D$

Proof:

Employ the overlapping tomography protocol in [Yu 2020] , that uses $O(10^k \log(m)/\gamma^2)$ samples for *m* different *k*-qubit reduced density matrices accurate up to a trace norm parameter λ.

1. Set $m = \binom{n}{k}, \lambda = \varepsilon^2/(2n)$

2. Set $m = n, \lambda = \varepsilon^2/(2n)$

For polynomial samples, how deep can D be?

If we only have polynomial number of samples, poly(n,1/ε), we can probe output of a quantum circuit with depth D with precision ε, if

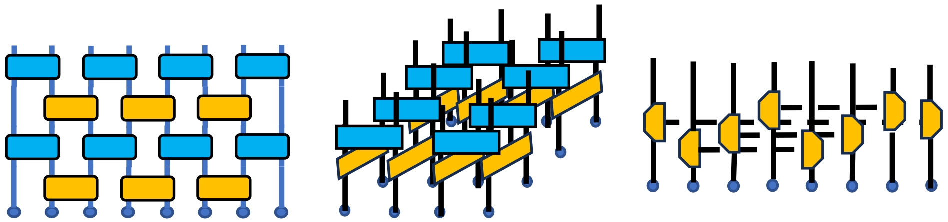
1. For one dimension (nearest-neighbor gates): $D = O(\log n)$
2. For two dimensions (nearest-neighbor gates): $D = O(\sqrt{\log n})$
3. For gates geometrically non-local: $D \leq \log(\log n) + O(1)$

Proof:

1. 10^k to be poly(n) ➔ that is k=2D=O(log n)
2. For 2-dim, $k \sim D^2$, D has to be $O(\sqrt{\log(n)})$
3. For general case, $k=2^D$, D has to be log(log n).

Circuit complexity

- ❑ We define the circuit complexity of a quantum state to be the minimum depth of the quantum circuit (using 2-local gates) necessary to implement the state (from an initial |00…0⟩ state)



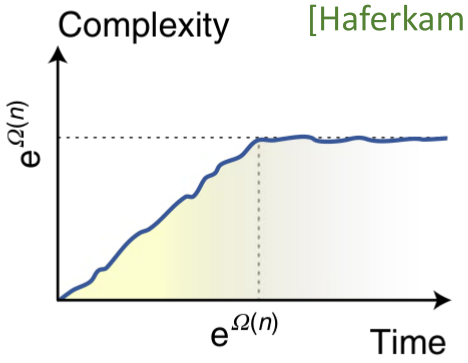
- ➢ Complexity emerges as an important quantity in holography, AdS/CFT and black holes

"Complexity = Volume" — The volume of Einstein-Rosen bridges corresponds to the complexity of the CFT on the boundary of an AdS space [Stanford & Susskind, PRD 2014]

"Complexity = Action" — Quantum complexity of a holographic state is dual to the action of a certain spacetime region [Brown et al., PRL 2016]

- ➢ Random unitary circuits for evolution of generic quantum systems

Complexity for unitary U, implemented from blocks of two-qubit random-Haar gates, grows linearly until the number of gates ~ $T \geq 4^n - 1$



[Haferkamp et al. Nat. Phys. 2022]

Testing circuit complexity of a state

- Check if given poly copies of an n-qubit state ρ, can it be approximated by a depth-D circuit?

That is to distinguish between:

1. $||\psi - \rho|| < \epsilon^2/6n$ for some quantum state $|\psi\rangle$ with circuit complexity ≤ D;
2. $||\psi - \rho|| > \epsilon$ for any quantum state $|\psi\rangle$ with circuit complexity ≤ D

"Algorithm" Input: n-qubit ρ & D ➔ Output: case 1 or 2

Step 1: Do overlapping tomography to obtain all $\{\tilde{\rho}_S\}$ with $|S| \leq k$ to precision $\epsilon^2/6n$

Step 2: Compute and check if a state $|\psi\rangle$ w. circuit depth ≤ D exists such that $||\psi_s - \tilde{\rho}_s||_1 < \frac{\epsilon^2}{3n}$ for all S with $|S| \leq k$

If ψ exists → case 1; otherwise, case 2

[May not be easy to do though]

Testing circuit complexity

Theorem. For an unknown *n*-qubit quantum state ρ, and a given circuit depth D, $O(n^2 \cdot 10^k \log \binom{n}{k} / \varepsilon^4)$ samples (with k=k(D)) suffice to distinguish between the two cases:

1. $||\psi - \rho|| < \varepsilon^2/6n$ for some quantum state $|\psi\rangle$ with circuit complexity ≤ D;
2. $||\psi - \rho|| > \varepsilon$ for any quantum state $|\psi\rangle$ with circuit complexity ≤ D

➔ Perform overlapping tomography on ρ to obtain k-marginals $\tilde{\rho}_S$ with $|S| \leq k$, up to precision $\varepsilon^2/6n$.

For case 1: $$||\psi_S - \tilde{\rho}_S|| < ||\psi_S - \rho_S|| + ||\tilde{\rho}_S - \rho_S||$$
$$\leq ||\psi - \rho|| + ||\tilde{\rho}_S - \rho_S|| < \frac{\varepsilon^2}{6n} + \frac{\varepsilon^2}{6n} = \frac{\varepsilon^2}{3n}$$

➔ The state ψ can be obtained from running/computing depth-D variational circuit and minimizing the trace norm

For case 2: Assume we can obtain a ϕ such that $||\phi_S - \tilde{\rho}_S|| < \frac{\varepsilon^2}{3n}$

Then $$||\phi_S - \rho_S|| < ||\phi_S - \tilde{\rho}_S|| + ||\tilde{\rho}_S - \rho_S||| < \frac{\varepsilon^2}{3n} + \frac{\varepsilon^2}{6n} = \frac{\varepsilon^2}{2n}$$

➔ $||\phi - \rho|| < \varepsilon$ → Contradicts assumption of case 2, thus ϕ does NOT exist.

Outline

- ❑ Introduction
- ❑ Some properties of unique ground states and their quantum marginals
- ❑ Learning output of a shallow quantum circuit
- ❑ Lower bound on quantum state complexity
- ❑ Conclusion

Lower bound on quantum state complexity

Theorem. If $|\psi\rangle$ is not UDA by its r local reduced density matrices, its circuit complexity is at least: (1) $\lceil(r+1)/2\rceil$ for 1-d chain; (2) max D: such that $\gamma_2(D) \leq r+1$ on the square lattice; (3) $\log(r+1)$ for non-geometrical circuits

Proof. Output is unique GS of k(D)-local Hamiltonian ➔ UDA on k-local interaction graph and we have k > r

Example. Take the GHZ state $|\psi\rangle = 1/\sqrt{2}\,(|0\rangle^{\otimes n} + |1\rangle^{\otimes n})$ as an example, it is not UDA by its $n-1$ reduced density matrices:

$$\rho_{n-1} = \frac{1}{2}(|\underbrace{0\ldots0}_{n-1}\rangle\langle 0\ldots0| + |\underbrace{1\ldots1}_{n-1}\rangle\langle 1\ldots1|)$$

which is also the (n-1)-qubit marginal of

$$\rho_n = \frac{1}{2}(|\underbrace{0\ldots00}_{n}\rangle\langle 0\ldots00| + |\underbrace{1\ldots11}_{n}\rangle\langle 1\ldots11|)$$

➔ Circuit complexity is at least n/2 if only nearest neighbor on 1D geometry; $O(\sqrt{n})$ for 2-dim; log(n) if any two local gates can be applied

Intrinsic topological states

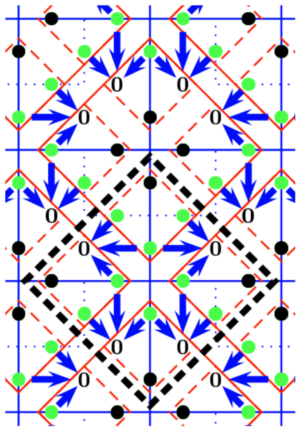
- These are long-ranged entangled states that cannot be created by a finite-depth quantum circuit from a product state

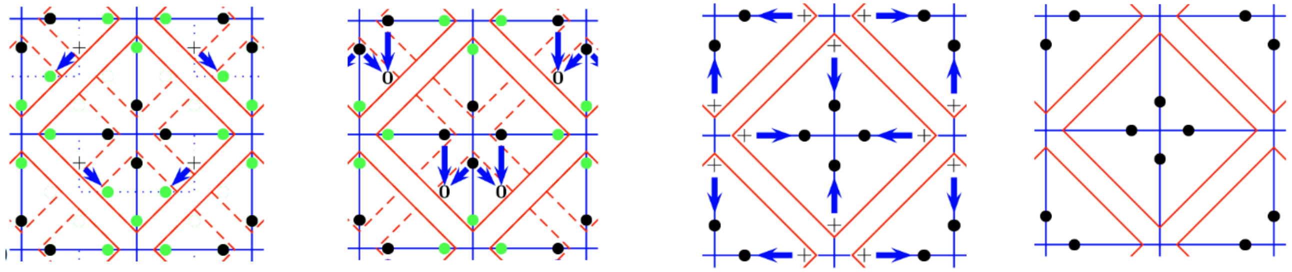
[Chen, Gu & Wen, PRB 2010]

  - n-qubit GHZ state is such an example: $|\psi\rangle = 1/\sqrt{2}\,(|0\rangle^{\otimes n} + |1\rangle^{\otimes n})$

  - Kitaev's toric code → can be exactly renormalized via log(n)-depth non-local gates

[Aguado &Vidal, PRL 2008]





→ Unfortunately, does not lead to a useful bound on locality k ☹
[expect to measure logical operators, linear size of the lattice]

  - Levin-Wen string-nets → can also be renormalized via log(n)-depth non-local gates

[Koenig, Reichardt &Vidal, PRB 2009]

Symmetry-protected topological states

- ❑ These are short-ranged entangled states that can be created by a finite-depth D quantum circuit from a product state (without respecting the symmetry); but cannot if symmetry is respected

[Chen, Gu & Wen, PRB 2010]

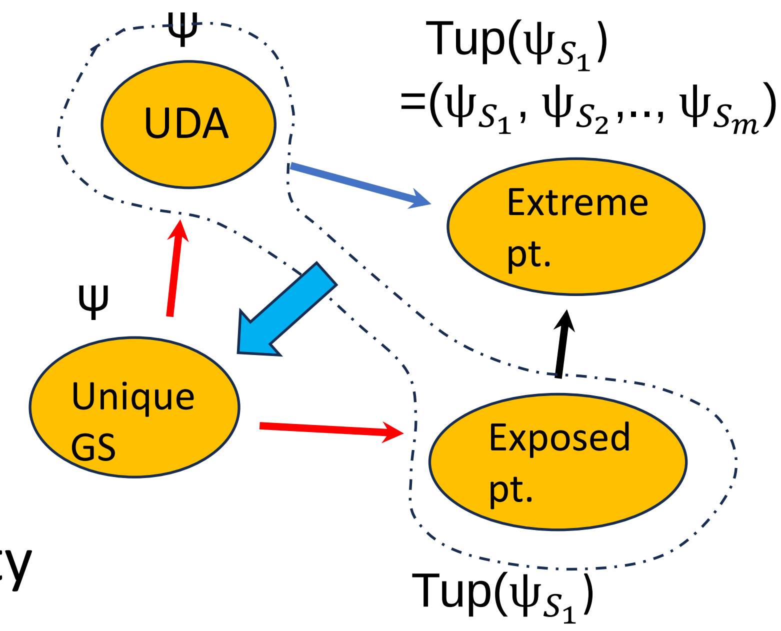
  - ➔ These states can be uniquely determined by their k(D)-local marginals
  - ➔ UDA is a property for short-ranged entangled phases!

- ❑ Even with symmetry respected, finite-depth non-local gates can disentangle them!

[Stephen et al., arXiv 2022]

Conclusion

- Properties of unique ground states & their quantum marginals
- Learning marginals of the output of a shallow quantum circuit suffices to determine the global state
- UDA and lower bound on quantum state complexity
- Future: explicit bounds for intrinsic topological states; extension to longer-depth circuits; inclusion of measurements?



Announcement: Faculty Search

Stony Brook University

➢ Yang Institute for Theoretical Physics (YITP) has two tenure track positions

(1) QIS theory :

Required qualifications: PhD degree or foreign equivalent in theoretical physics or closely related field, with an established record of outstanding independent research, including experience in the broad area of quantum information science--including, but not limited to, various approaches of quantum computation and information processing, quantum information theory interfacing with many-body physics, complexity and other theoretical physics, quantum error correction and mitigation, quantum simulations and algorithms that advance quantum advantage.

https://apply.interfolio.com/132644

(2) Theoretical Physics:

PhD degree or foreign equivalent in theoretical physics or closely related field, with an established record of outstanding independent research, including experience in fundamental areas of quantum field theory and/or string theory, broadly defined, possibly in addition to other topics in theoretical physics.

https://apply.interfolio.com/132647

* For full consideration, applications must be submitted by November 20, 2023