Magic-induced computational separation in entanglement theory

Salvatore F.E. Oliviero

Talk based on: ArXiv: 2403.19610

YQIS 2024

Joint work with:

Andi Gu

Lorenzo Leone

SCUOLA NORMALE SUPERIORE

Motivations

Motivations

- What is the difference between **high magic** entanglement and **low magic** entanglement?

Motivations

- What is the difference between **high magic** entanglement and **low magic** entanglement?
- For states with no magic, estimate entanglement is easy.

Motivations

- What is the difference between **high magic** entanglement and **low magic** entanglement?
- For states with no magic, estimate entanglement is easy.
- **Operational approach**: let us study the difference for entanglement characterization and manipulation tasks.

Measures of Entanglement and Magic

How do we measure entanglement?

- Bipartition in a qubit system. $A|B$
- Reduced density matrix $\psi_A = \mathrm{tr}_B |\psi\rangle\langle\psi|$
- **von Neumann entropy**:

$$S_1(\psi_A) = -\mathrm{tr}(\psi_A \log \psi_A)$$

Measures of Entanglement and Magic

How do we measure entanglement?

- Bipartition in a qubit system. $A|B$
- Reduced density matrix $\psi_A = \mathrm{tr}_B\, |\psi\rangle\langle\psi|$
- **von Neumann entropy**:

$$S_1(\psi_A) = -\,\mathrm{tr}(\psi_A \log \psi_A)$$

How do we measure magic?

- Group of Pauli operators $P \in \mathcal{P}_n$
- Pauli subgroup *stabilizing* $|\psi\rangle$

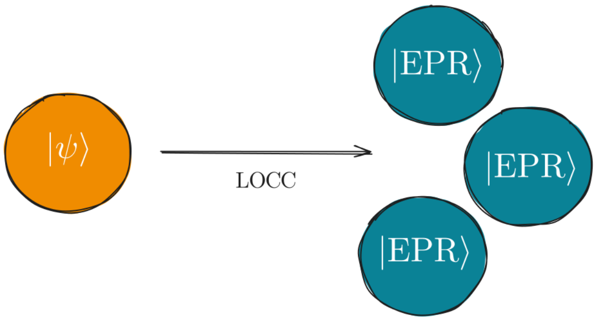
$$G_\psi = \{P : P|\psi\rangle = |\psi\rangle\}$$

- **Stabilizer nullity**

$$\nu(\psi) = n - \log|G_\psi|$$

Entanglement manipulation

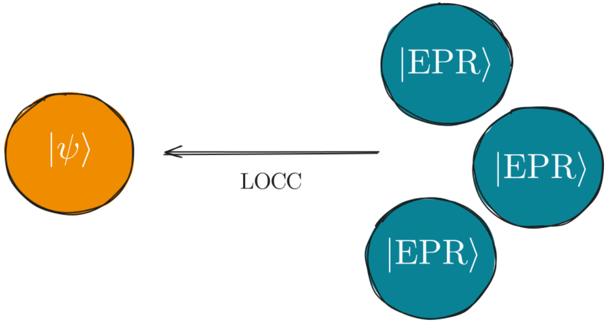
Task: via LOCC Alice and Bob want to distill a Bell pair from an entangled state $|\psi\rangle$



- For pure states the optimal number of Bell pair is the von Neumann entropy

$$M_+ = S_1(\psi_A)$$

Task: via LOCC Alice and Bob want to distill a state $|\psi\rangle$



- For pure states the optimal number of Bell pair is the von Neumann entropy

$$M_- = S_1(\psi_A)$$

Stabilizer States

- Consider k mutually commuting, and independent Pauli operators $S = \{P_1, \ldots, P_k\}$.

$$\sigma = \prod_{P \in S} \frac{I + P}{2}$$

- S is the generating set of the stabilizer group G (abelian subgroup of $\mathcal{P}_n$) associated with σ.

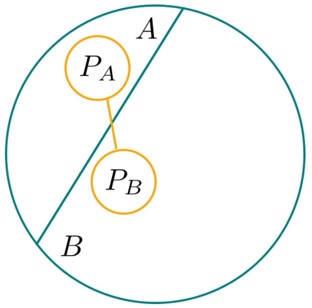
$$|G| = 2^{|S|} = 2^k$$

- Pure stabilizer states $|\sigma\rangle$ $\forall P \in G$, $P|\sigma\rangle = |\sigma\rangle$.

- All the properties of σ can be determined by looking at S.

Entanglement for stabilizer states

- Entanglement is completely determined by S.
- $S_A = \{P \in S | P = P_A \otimes I_B\}$
- $S_A = \{P \in S | P = I_A \otimes P_B\}$
- $S_{AB} = \{P \in S | P \notin S_A \cup S_B\}$



$$S_1(\sigma_A) = \frac{|S_{AB}|}{2}$$

Example

$$|\mathrm{EPR}\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

$$S_A = \{\}, S_B = \{\}, S_{AB} = \{XX, ZZ\}$$

$$S_1(\mathrm{tr}_B(|\mathrm{EPR}\rangle\langle\mathrm{EPR}|)) = 1$$

Fattal et al., *Entanglement in the stabilizer formalism*, ArXiv:quant-ph/0406168

Magic-States $=\nu$-compressible states

- Consider a state $|\psi\rangle$ with stabilizer nullity ν.
- We can associate a stabilizer group G generated by S.

$$|\psi\rangle\langle\psi| = \sum_{i=1}^{4^\nu} \mathrm{tr}(h_i \psi) h_i \prod_{P \in S} \frac{I+P}{2}$$

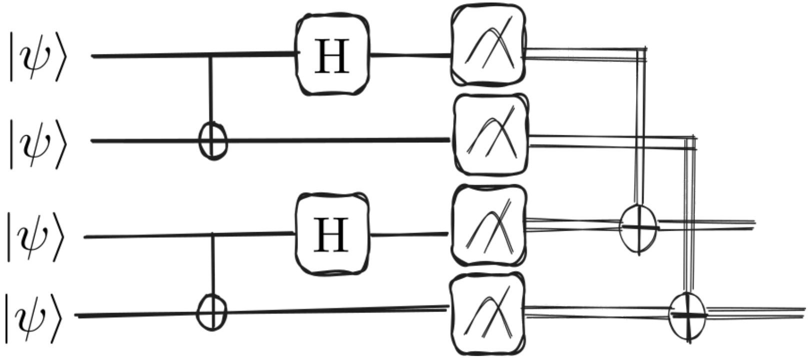
- $|\psi\rangle$ is ν-compressible because it can always be written as $|\psi\rangle = C(|0\rangle_{n-\nu} \otimes |\phi\rangle_\nu)$
- **Fact:** the stabilizer group G can be learned efficiently.

Leone et al., *Learning t-doped stabilizer states*, Quantum 8, 1361 (2024).

Learning algorithm for G

Algorithm:
Input $O((n+\log(1/\delta))\epsilon)$ copies of $|\psi\rangle$, $\epsilon, \delta \in (0,1)$
Output Stabilizer set $\hat{S}$.

1. Perform Bell difference Sampling. The span of the samples is $S^{\perp}$
2. $S = \mathrm{Ker}(S^{\perp})$ (Gaussian Elimination)



Grewal et al., *Efficient Learning of Quantum States Prepared With Few Non-Clifford Gates*, ArXiv: 2305

Learning algorithm for G

Algorithm:
Input $O((n + \log(1/\delta))\epsilon)$ copies of $|\psi\rangle$, $\epsilon, \delta \in (0, 1)$
Output Stabilizer set $\hat{S}$.

1. Perform Bell difference Sampling. The span of the samples is $S^{\perp}$
2. $S = \mathrm{Ker}(S^{\perp})$ (Gaussian Elimination)

Grewal et al., *Efficient Learning of Quantum States Prepared With Few Non-Clifford Gates*, ArXiv: 2305

Learning algorithm for G

Algorithm:
Input $O((n + \log(1/\delta))\epsilon)$ copies of $|\psi\rangle$, $\epsilon, \delta \in (0, 1)$
Output Stabilizer set $\hat{S}$.

1. Perform Bell difference Sampling. The span of the samples is $S^{\perp}$
2. $S = \mathrm{Ker}(S^{\perp})$ (Gaussian Elimination)

- The group $\hat{G} \equiv \langle \hat{S} \rangle$ contains G.
- $|\psi\rangle$ is ϵ-close in trace distance to some state with a stabilizer group $\hat{G}$.
- Runtime $O(n^2(n + \log(1/\delta))\epsilon)$

Grewal et al., *Efficient Learning of Quantum States Prepared With Few Non-Clifford Gates*, ArXiv: 2305

Entanglement vs Magic-dominated

Entanglement-dominated

$$S_1(\psi_A) = \omega(\nu)$$

Magic-dominated

$$S_1(\psi_A) = O(\nu)$$

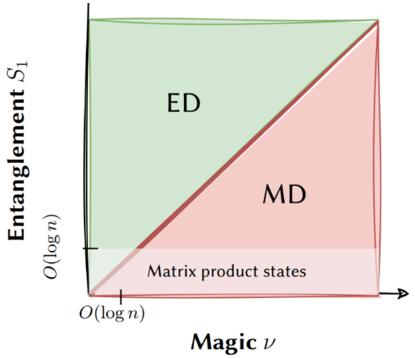
Entanglement vs Magic-dominated

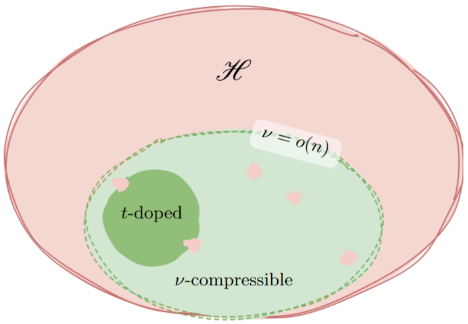
Entanglement-dominated

$$S_1(\psi_A) = \omega(\nu)$$

Magic-dominated

$$S_1(\psi_A) = O(\nu)$$





Stabilizer Entanglement

Stabilizer Entanglement

- Let $|\psi\rangle$ be a state with stabilizer nullity ν, stabilizer group G and generating set S.
- One can always: $S = S_A \cup S_B \cup S_{AB}$

Stabilizer Entanglement

- Let $|\psi\rangle$ be a state with stabilizer nullity ν, stabilizer group G and generating set S.
- One can always: $S = S_A \cup S_B \cup S_{AB}$

Stabilizer Entanglement $E(\psi_A) = \frac{|S_{AB}|}{2}$

Stabilizer Entanglement

- Let $|\psi\rangle$ be a state with stabilizer nullity ν, stabilizer group G and generating set S.
- One can always: $S = S_A \cup S_B \cup S_{AB}$

Stabilizer Entanglement $E(\psi_A) = \frac{|S_{AB}|}{2}$

Bounds with entanglement entropy

Stabilizer Entanglement

- Let $|\psi\rangle$ be a state with stabilizer nullity ν, stabilizer group G and generating set S.
- One can always: $S = S_A \cup S_B \cup S_{AB}$

Stabilizer Entanglement $E(\psi_A) = \frac{|S_{AB}|}{2}$

Bounds with entanglement entropy

$$E(\psi_A) - \frac{\nu}{2} \leq S_1(\psi_A) \leq E(\psi_A) + \frac{\nu}{2}$$

Stabilizer Entanglement

- Let $|\psi\rangle$ be a state with stabilizer nullity ν, stabilizer group G and generating set S.
- One can always: $S = S_A \cup S_B \cup S_{AB}$

Stabilizer Entanglement $E(\psi_A) = \frac{|S_{AB}|}{2}$

Bounds with entanglement entropy

$$E(\psi_A) - \frac{\nu}{2} \leq S_1(\psi_A) \leq E(\psi_A) + \frac{\nu}{2}$$

- $E(\psi_A)$ can be estimated efficiently $O(n^2)$
- ν can be estimated efficiently $O(n)$

Efficient entanglement characterization for entanglement-dominated tasks

Efficient entanglement characterization for entanglement-dominated tasks

- **Task:** Aim is to check whether $S_1(\psi_A) = \Theta(f(n_A))$.

Efficient entanglement characterization for entanglement-dominated tasks

- **Task:** Aim is to check whether $S_1(\psi_A) = \Theta(f(n_A))$.
- ψ is entanglement dominated iff $E(\psi_A) = \omega(\nu)$

Efficient entanglement characterization for entanglement-dominated tasks

- **Task:** Aim is to check whether $S_1(\psi_A) = \Theta(f(n_A))$.
- ψ is entanglement dominated iff $E(\psi_A) = \omega(\nu)$
- Given a entanglement class $f(n_A)$, if $E(\psi_A) = f(n_A)$ then $S_1(\psi_A) = f(n_A) + o(f(n_A))$.

Efficient entanglement characterization for entanglement-dominated tasks

- **Task:** Aim is to check whether $S_1(\psi_A) = \Theta(f(n_A))$.
- ψ is entanglement dominated iff $E(\psi_A) = \omega(\nu)$
- Given a entanglement class $f(n_A)$, if $E(\psi_A) = f(n_A)$ then $S_1(\psi_A) = f(n_A) + o(f(n_A))$.
- Therefore, one estimates $S_1(\psi_A)$ up to a $o(1)$ relative error.

Efficient entanglement characterization for entanglement-dominated tasks

- **Task:** Aim is to check whether $S_1(\psi_A) = \Theta(f(n_A))$.
- ψ is entanglement dominated iff $E(\psi_A) = \omega(\nu)$
- Given a entanglement class $f(n_A)$, if $E(\psi_A) = f(n_A)$ then $S_1(\psi_A) = f(n_A) + o(f(n_A))$.
- Therefore, one estimates $S_1(\psi_A)$ up to a $o(1)$ relative error.
- Notice that, the above procedure holds even for states with $\nu = o(n)$.

Efficient entanglement distillation for entanglement-dominated task

Theorem There exists a bipartite Clifford unitary that distills a number of Bell pair equals to

$$M_+ = E(\psi_A) - \nu/2$$

which, for entanglement dominated states, is asymptotically (in n) optimal: $M_+/S_1(\psi_A) = 1 - o(1)$. Moreover, the unitary, can be found by $O(n)$ queries to $|\psi\rangle$.

Efficient entanglement distillation for entanglement-dominated task

Theorem There exists a bipartite Clifford unitary that distills a number of Bell pair equals to

$$M_+ = E(\psi_A) - \nu/2$$

which, for entanglement dominated states, is asymptotically (in n) optimal: $M_+/S_1(\psi_A) = 1 - o(1)$. Moreover, the unitary, can be found by $O(n)$ queries to $|\psi\rangle$.

Proof Sketch: $S = S_A \cup S_B \cup S_{AB}$, $|S| \geq n - \nu$

- We can complete the stabilizer group S to a maximal one S^c, describing a stabilizer state $|S^c\rangle$.
- For S^c there exists a unitary $U_A \otimes U_B$ Clifford that distills up to $|S^c_{AB}|/2$ Bell pairs.
- Applying the same unitary on $|\psi\rangle$, it transforms $S \to S'$ obtaining M_+ Bell pairs:

$$M_+ \geq \frac{|S_{AB}| - \nu}{2} = E(\psi_A) - \nu/2$$

Efficient entanglement dilution for entanglement-dominated task

Theorem For any state $|\psi\rangle$ in the ED phase there exists a stabilizer LOCC protocol for dilution that requires a number of Bell pairs equal to

$$M_- = E(\psi_A) + \nu/2$$

which, for entanglement dominated states, is asymptotically (in n) optimal: $M_- / S_1(\psi_A) = 1 + o(1)$, and ν bits of classical communication.

Efficient entanglement dilution for entanglement-dominated task

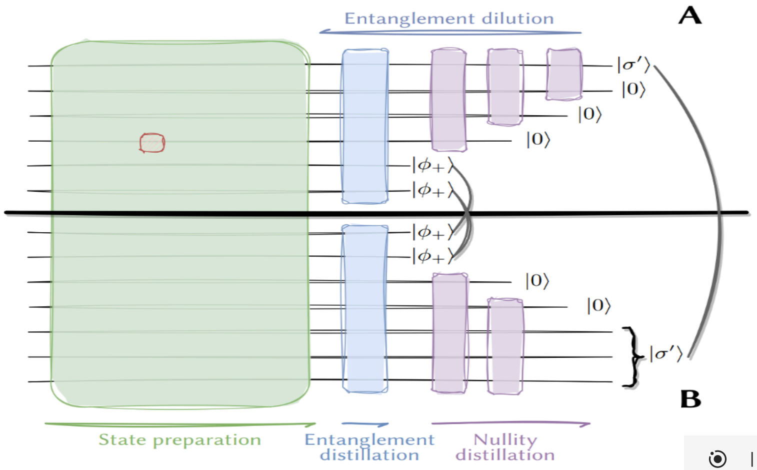
Theorem For any state $|\psi\rangle$ in the ED phase there exists a stabilizer LOCC protocol for dilution that requires a number of Bell pairs equal to

$$M_- = E(\psi_A) + \nu/2$$

which, for entanglement dominated states, is asymptotically (in n) optimal: $M_-/S_1(\psi_A) = 1 + o(1)$, and ν bits of classical communication.

Proof Sketch :

- B runs locally the distillation protocol. Obtaining the state $|\sigma'\rangle$
- Teleport of $\nu/2$ qubits of $|\sigma'\rangle$ to A.
- Application of local Cliffords on A and B. *Equivalent to revert distillation*.



No-go for magic dominated states

Theorem Any efficient state-agnostic protocol that can estimate $S_1(\psi_A)$ within $\omega(1)$ relative error for all MD states. It can distills at most a fraction of $o(1)$ Bell pairs from a magic-dominated state, and diluite more than a fraction of $\omega(1)$ Bell pairs from a magic-dominated state.

No-go for magic dominated states

Theorem Any efficient state-agnostic protocol that can estimate $S_1(\psi_A)$ within $\omega(1)$ relative error for all MD states. It can distills at most a fraction of $o(1)$ Bell pairs from a magic-dominated state, and diluite more than a fraction of $\omega(1)$ Bell pairs from a magic-dominated state.

Proof Sketch: Pseudorandom states encoded as magic-states

- Consider the following magic dominated state $|\psi\rangle = |0\rangle_{n-\nu} \otimes |\phi_{AB}\rangle_\nu$, with $\nu = \Theta(\log^c(n))$ with $c > 1$
- Two possible choices either $|\phi_{AB}\rangle_\nu$ is an Haar random state or $|\phi_{AB}\rangle_\nu$ is a pseudo entangled state
- Haar random states have maximal entropy of entanglement $S_1(\phi^H_{AB}) \sim \Theta(\log^c n)$, while $S_1(\phi^P_{AB}) = \Theta(\log^{c'} n)$, an efficient algorithm that achieves $M_+/S_1 = \Omega(1)$ fraction of distillable Bell pairs would distinguish pseudo random states from Haar. Consequently, the maximal number of extractable Bell pairs obeys $M_+/S_1 = o(1)$

Computational phase transition in entanglement manipulation

Entanglement-Dominated

$$S_1(\psi_A) = \omega(\nu)$$

- Entanglement can be measured up to $o(1)$ relative error, even if volume law.
- There exists (and can be efficiently found) an efficient and state-agnostic deterministic LOCC that distills an optimal number of Bell pair.
- There exists a optimal efficient and state-agnostic LOCC protocol that diluite a ED state.

Magic-Dominated

$$S_1(\psi_A) = O(\nu)$$

- No sample-efficient algorithm to estimate the von Neumann entropy $S_1(\psi_A)$ within a relative error at least $\omega(1)$.
- No sample-efficient algorithm that distills more than a $o(1)$ vanishing fraction of Bell pairs with respect to the optimal amount.
- No sample-efficient algorithm can dilute $|\psi\rangle$ using less than $\omega(S_1)$ Bell pairs for general MD states

Future directions

- Generalizing the result to a more robust measure of magic?
- A Computational phase transition in magic-state distillation?
    - From pseudomagic, we know that there is no-agnostic and efficient algorithm that distill more than $O(\log M(\psi))$ magic states for general states.
    - Is the magic-dominated phase useful for agnostic and efficient magic-state distillation?
- Generalization to the CV case. Analizing the connection between non-Gaussianity and Entanglement.

Future directions

- Generalizing the result to a more robust measure of magic?
- A Computational phase transition in magic-state distillation?
  - From pseudomagic, we know that there is no-agnostic and efficient algorithm that distill more than $O(\log M(\psi))$ magic states for general states.
  - Is the magic-dominated phase useful for agnostic and efficient magic-state distillation?
- Generalization to the CV case. Analizing the connection between non-Gaussianity and Entanglement.

Thanks for your attention!