

**Entanglement measures
(How much is it entangled?)
(Lecture of the Quantum Information class of
the Master in Quantum Science and
Technology)**

Géza Tóth

Theoretical Physics, University of the Basque Country (UPV/EHU), Bilbao, Spain
Donostia International Physics Center (DIPC), San Sebastián, Spain
IKERBASQUE, Basque Foundation for Science, Bilbao, Spain
Wigner Research Centre for Physics, Budapest, Hungary

UPV/EHU, Leioa
8, 15 February, 2024

1 Entanglement measures (How much is it entangled?)

- Motivation
 - A. General quantum operation
 - B. Local operations and classical communication (LOCC)
 - C. Entanglement of formation
 - D. Concurrence
 - E. Entanglement of distillation
 - F. Bound entanglement
 - G. Requirements for entanglement measures
 - H. Negativity

Entanglement measures

- After detecting entanglement, we have to ask how entangled the state is.
- It will turn out that entanglement is a resource.

1 Entanglement measures (How much is it entangled?)

- Motivation
- A. General quantum operation
- B. Local operations and classical communication (LOCC)
- C. Entanglement of formation
- D. Concurrence
- E. Entanglement of distillation
- F. Bound entanglement
- G. Requirements for entanglement measures
- H. Negativity

General quantum operation

- The general quantum operation is defined as

$$\varrho' = \sum_k E_k \varrho E_k^\dagger$$

with

$$\sum_k E_k^\dagger E_k = 1.$$

- E_k are Kraus operators.
- Generalized measurements, POVM (positive operator-valued measure).
- Special case: von Neumann measurements, when E_k are pairwise orthogonal projectors.
- Naimark's dilation theorem:
general operation =
von Neumann measurement on system+ancilla.

- 1 **Entanglement measures (How much is it entangled?)**
 - Motivation
 - A. General quantum operation
 - **B. Local operations and classical communication (LOCC)**
 - C. Entanglement of formation
 - D. Concurrence
 - E. Entanglement of distillation
 - F. Bound entanglement
 - G. Requirements for entanglement measures
 - H. Negativity

Local operations and classical communication (LOCC)

- LOCC are
 - local unitaries,
 - local von Neumann or POVM measurements,
 - local unitaries or measurements conditioned on measurement outcomes on the other party.
- Mathematical description of LOCC. Separable operations are a somewhat larger set, however, this set can easily be described.

$$\varrho' = \sum_k E_k^{(1)} \otimes E_k^{(2)} \varrho \left(E_k^{(1)} \otimes E_k^{(2)} \right)^\dagger$$

with

$$\sum_k \left(E_k^{(1)} \otimes E_k^{(2)} \right)^\dagger \left(E_k^{(1)} \otimes E_k^{(2)} \right) = 1.$$

Local operations and classical communication (LOCC) II

- Stochastic Local Operations and Classical Communication (SLOCC):

$$|\Psi\rangle' \leftarrow E_k^{(1)} \otimes E_k^{(2)} |\Psi\rangle$$

It happens with some probability, not deterministic.

- LOCC cannot create entanglement. Separable states remain separable under LOCC.
- LOCC can create correlations.

- 1 **Entanglement measures (How much is it entangled?)**
 - Motivation
 - A. General quantum operation
 - B. Local operations and classical communication (LOCC)
 - **C. Entanglement of formation**
 - D. Concurrence
 - E. Entanglement of distillation
 - F. Bound entanglement
 - G. Requirements for entanglement measures
 - H. Negativity

Entropy of entanglement

- The von Neumann entropy is defined as

$$S(\varrho) = -\text{Tr}(\varrho \log_2 \varrho).$$

- It can be written with the eigenvalues of the density matrix as

$$S(\varrho) = -\sum_{k=1}^d \lambda_k \log_2 \lambda_k.$$

- For a pure state we have $\lambda_k = \{1, 0, 0, \dots, 0\}$, and thus it is zero.
- Its maximal is for the completely mixed state for which $\lambda_k = \{\frac{1}{d}, \frac{1}{d}, \frac{1}{d}, \dots, \frac{1}{d}\}$, and its value is $\log_2 d$.
- For a bipartite pure state, the **entropy of entanglement** is

$$E_E(|\Psi\rangle) = S(\text{Tr}_1(|\Psi\rangle\langle\Psi|)).$$

That is, it is the von Neumann entropy of the reduced state is an entanglement measure.

Entropy of entanglement II

- Comments
 - It is one for two-qubit singlet states.
 - It is zero for product states.
 - It is invariant under $U_1 \otimes U_2$.

Entanglement of formation

- For mixed states, the entanglement of formation is the convex roof of the von Neumann entropy of the reduced state.

$$E_F = \min_{|\Psi_k\rangle, p_k} \sum_k p_k E_E(|\Psi_k\rangle),$$

- The optimization is over all decompositions of the state of the type

$$\varrho = \sum_k p_k |\Psi_k\rangle\langle\Psi_k|.$$

- E_F tells us, in the asymptotic limit, how many singlets we need to create the state.
- Is it easy to compute? No. For 2×2 systems, there is an explicit formula with the concurrence. For larger systems, there is not a general method.

- 1 **Entanglement measures (How much is it entangled?)**
 - Motivation
 - A. General quantum operation
 - B. Local operations and classical communication (LOCC)
 - C. Entanglement of formation
 - **D. Concurrence**
 - E. Entanglement of distillation
 - F. Bound entanglement
 - G. Requirements for entanglement measures
 - H. Negativity

Entanglement of formation

- For two qubits, E_F can be calculated explicitly (Wootters, 1997).
- Special case: for pure states the concurrence is

$$C(|\Psi\rangle) = |\langle\Psi|\tilde{\Psi}\rangle| = 2|a_{11}a_{22} - a_{12}a_{21}|,$$

where

$$|\Psi\rangle = \begin{pmatrix} a_{11} \\ a_{12} \\ a_{21} \\ a_{22} \end{pmatrix}.$$

- It is related to the linear entropy of the reduced state.

$$C = \sqrt{2(1 - \text{Tr}(\rho_{\text{red}}^2))}, \quad (1)$$

where

$$\rho_{\text{red}} = \text{Tr}_2(|\Psi\rangle\langle\Psi|). \quad (2)$$

Entanglement of formation II

- Now we have to compute E_F from C .
- We also need that

$$\epsilon(c) = H_2\left(\frac{1 + \sqrt{1 - c^2}}{2}\right).$$

Here

$$H_2 = -x \log_2 x - (1 - x) \log_2 (1 - x).$$

- Then, E_F can be obtained as

$$E_F(\varrho) = \epsilon(C(\varrho)).$$

Entanglement of formation III

- For mixed states, the **concurrence** is defined as

$$C(\varrho) = \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4),$$

where λ_k 's are, in a decreasing order, the eigenvalues of

$$R = \sqrt{\sqrt{\varrho} \tilde{\varrho} \sqrt{\varrho}},$$

and

$$\tilde{\varrho} = (\sigma_y \otimes \sigma_y) \varrho^* (\sigma_y \otimes \sigma_y).$$

- 1 **Entanglement measures (How much is it entangled?)**
 - Motivation
 - A. General quantum operation
 - B. Local operations and classical communication (LOCC)
 - C. Entanglement of formation
 - D. Concurrence
 - **E. Entanglement of distillation**
 - F. Bound entanglement
 - G. Requirements for entanglement measures
 - H. Negativity

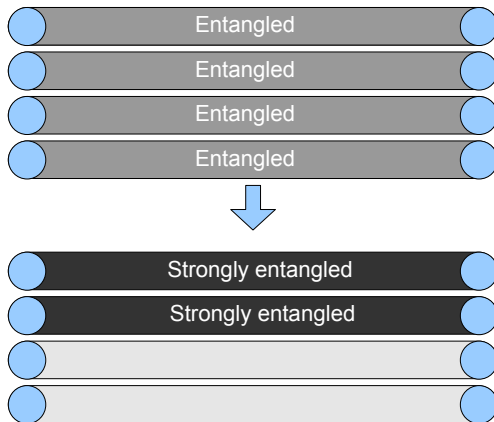
Entanglement of distillation

- E_D tells us, how many singlets we can obtain from the state with LOCC. In general,

$$E_F \geq E_D.$$

- Note that local operation and classical communication means that we have several copies and we can act on the copies locally.

Entanglement of distillation II



1 Entanglement measures (How much is it entangled?)

- Motivation
- A. General quantum operation
- B. Local operations and classical communication (LOCC)
- C. Entanglement of formation
- D. Concurrence
- E. Entanglement of distillation
- F. Bound entanglement
- G. Requirements for entanglement measures
- H. Negativity

Bound entanglement

- There are states that need entangled particles to be created, but singlets cannot be distilled from them.
- All PPT entangled states are like that. (That is, all entangled states that are not detected by the Peres-Horodecki criterion.)

Bound entanglement II

- Next, we will prove this. First we show that PPT state remain PPT under LOCC. Under LOCC we have

$$\varrho' = \sum_k E_k^{(1)} \otimes E_k^{(2)} \varrho \left(E_k^{(1)} \otimes E_k^{(2)} \right)^\dagger$$

We also have

$$(\varrho')^{T2} = \sum_k E_k^{(1)} \otimes ((E_k^{(2)})^\dagger)^T \varrho^{T2} (E_k^{(1)})^\dagger \otimes (E_k^{(2)})^T$$

Here we used that $(AB)^T = B^T A^T$ and $A^\dagger = (A^*)^T$.

- We can see that if $\varrho^{T2} \geq 0$ then $(\varrho')^{T2} \geq 0$. Thus the PPT states remain PPT under LOCC.

R., P., M., and K. Horodecki, *Rev. Mod. Phys.* 81, 865 (2009).

(Click on the link above, see "G. Bound entanglement - when distillability fails" on page 44.)

Bound entanglement III

- Let us again remember the flip operator

$$F|k\rangle|l\rangle = |l\rangle|k\rangle$$

It has eigenvalues ± 1 .

- The maximally entangled state

$$|\Psi_{\text{me}}\rangle = \frac{1}{\sqrt{d}} \sum_{k=1}^d |k\rangle|k\rangle.$$

Bound entanglement IV

- We can show that

$$|\Psi_{\text{me}}\rangle\langle\Psi_{\text{me}}| = \frac{1}{d} \sum_{k,l} |k\rangle\langle l| \otimes |k\rangle\langle l|,$$

$$|\Psi_{\text{me}}\rangle\langle\Psi_{\text{me}}|^{T_1} = \frac{1}{d} \sum_{k,l} |k\rangle\langle l| \otimes |l\rangle\langle k| \equiv \frac{F}{d},$$

where $|l\rangle$ are real orthonormal vectors.

- Now we show that PPT states have a small overlap with the maximally entangled state. For PPT states, the fidelity with respect to the maximally entangled state is

$$\text{Tr}(|\Psi_{\text{me}}\rangle\langle\Psi_{\text{me}}|\varrho) = \text{Tr}(|\Psi_{\text{me}}\rangle\langle\Psi_{\text{me}}|^{T_1}\varrho^{T_1}) = \frac{1}{d}\text{Tr}(F\varrho^{T_1}) \leq \frac{1}{d},$$

since $\varrho^{T_1} \geq 0$ and F has ± 1 eigenvalues.

Bound entanglement IV

- Thus, PPT states have a small fidelity with respect to the maximally entangled state. Even LOCC operations cannot increase this.
- A simple product state can reach $1/d$

$$\text{Tr}(|\Psi_{\text{me}}\rangle\langle\Psi_{\text{me}}||11\rangle\langle 11|) = \frac{1}{d}.$$

- 1 **Entanglement measures (How much is it entangled?)**
 - Motivation
 - A. General quantum operation
 - B. Local operations and classical communication (LOCC)
 - C. Entanglement of formation
 - D. Concurrence
 - E. Entanglement of distillation
 - F. Bound entanglement
 - **G. Requirements for entanglement measures**
 - H. Negativity

Requirements for entanglement measures

- 1 To each density matrix it assigns a nonnegative number. Typically, the maximally entangled state has $\log d$.
- 2 $E(\varrho) = 0$ for separable states.
- 3 E does not increase on average under LOCC.

$$E(\varrho) \leq \sum_k p_k E\left(\frac{A_k \varrho A_k^\dagger}{\text{Tr}(A_k \varrho A_k^\dagger)}\right). \quad (3)$$

- 4 For pure states, it has the same value as the entanglement entropy.
- Entanglement monotone: 1,2,3.
 - Entanglement measure: 1,2,4 and does not increase under deterministic LOCC, i.e.,

$$E(\varrho') \leq E(\varrho); \quad \varrho' = \sum_k A_k \varrho A_k^\dagger \quad (\text{POVM}). \quad (4)$$

- 1 **Entanglement measures (How much is it entangled?)**
 - Motivation
 - A. General quantum operation
 - B. Local operations and classical communication (LOCC)
 - C. Entanglement of formation
 - D. Concurrence
 - E. Entanglement of distillation
 - F. Bound entanglement
 - G. Requirements for entanglement measures
 - H. Negativity

Trace norm

- Let us consider the singular decomposition of a matrix

$$A = U\Sigma V^\dagger, \quad (5)$$

where

$$\Sigma = \text{diag}(\sigma_1, \sigma_2, \sigma_3, \dots, \sigma_d) \quad (6)$$

and $\sigma_k > 0$.

- Then the trace norm is

$$\|A\|_1 = \text{Tr}\left(\sqrt{AA^\dagger}\right) = \sum_k \sigma_k. \quad (7)$$

- The Hilbert-Schmidt norm is

$$\|A\|_2 = \text{Tr}\left(AA^\dagger\right) = \sum_k \sigma_k^2. \quad (8)$$

Negativity

- Example for a monotone: negativity

$$N(\varrho) = \frac{\|\varrho^{T1}\| - 1}{2}.$$

Trace norm= sum of singular values.

- For Hermitian matrices, it is the same as sum of eigenvalues.

$$N(\varrho) = \frac{\sum_k |\lambda_k| - 1}{2}.$$

- Note that $\sum_k \lambda_k = 1$. Then, assume that the first M eigenvalues are negative, the rest is positive. We get

$$N(\varrho) = \frac{\sum_{k=1}^M -\lambda_k + \sum_{k=M+1}^d \lambda_k - \sum_k \lambda_k}{2}.$$

Negativity II

- Hence,

$$N(\varrho) = \sum_{k=1}^M |\lambda_k|.$$

That is, the absolute value of the sum of the negative eigenvalues of the partial transpose.

- Clearly, it is zero for PPT states. Thus, it is zero for all separable states.
- Not as meaningful as the Entanglement of Formation, but can be calculated on any system sizes.
- It fulfills certain conditions on how it changes under LOCC. It does not increase under deterministic LOCC.