

Entanglement Classification using Knots

PH3203 Term Project

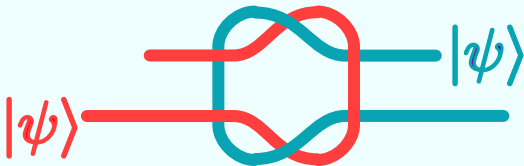
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Basic Theoretical Background

Introduction to Quantum Information

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- When a system is in a statistical ensemble of many pure states $\{|\psi_i\rangle\}$, with respective *classical* probabilities p_i , such a state is called a **Mixed State**. We represent such states using the density operator:

$$\rho = \sum_i p_i |\psi_i\rangle \langle \psi_i|$$

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- A quantum state ρ_{AB} is **separable** if it can be written as:

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- A state is **entangled** if it is not separable.

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- If all eigenvalues positive, then, in 2×2 or 2×3 systems, this implies the state is separable.

Classifying Entanglement using Knots

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$$C(\rho) = \max\{0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4\}$$

Here λ_i are the square root of the eigenvalues, in decreasing order, of the non-Hermitian matrix $\tilde{\rho}$ where $\tilde{\rho}$ is defined by:

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According to the Concurrence test, a state represented by the density operator ρ is separable iff $C(\rho) = 0$.

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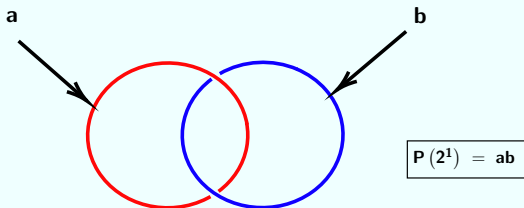
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- An n -variable monomial M is irrelevant if all of its variables are already present as an n -ring link of lesser-order monomials, built only with the variables of M , eg $ab + bc + abc$ is not valid as abc is irrelevant here.

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- From this, we can construct a link polynomial which is characterised by the given state.

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- 3 Full state $|\psi\rangle \rightarrow$ sum of individual such states. Trace out d and obtain density matrix of reduced system.

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- **Full state becomes:**

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- Qudit state, take $|Q_d\rangle = |1\rangle_d$
- **Full state becomes:** $|\psi_2\rangle = |2^1\rangle_{ac} \otimes |q_2\rangle_b \otimes |1\rangle_d$

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- Full state characterising the link: $|\psi\rangle = c_1 |\psi_1\rangle + c_2 |\psi_2\rangle$

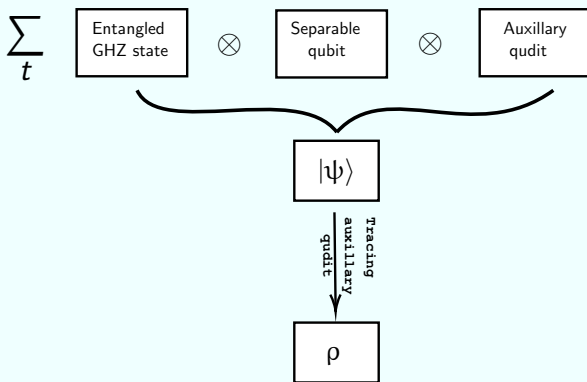


Figure: Schematic representation of the algorithm.

Demonstration of Algorithm

- **Full state characterising the link:** $|\psi\rangle = c_1 |\psi_1\rangle + c_2 |\psi_2\rangle$
- Then construct the density matrix accordingly for the state.

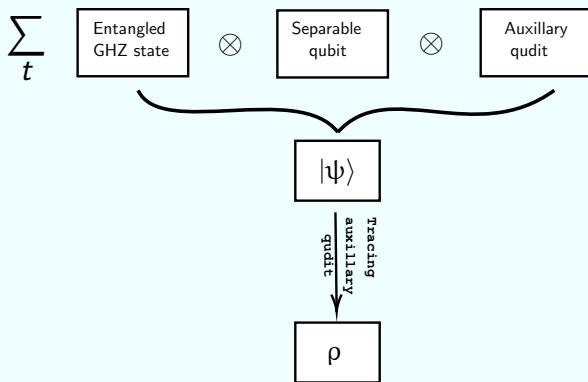


Figure: Schematic representation of the algorithm.

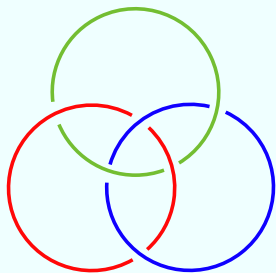
Some Examples...

Three Qubit System: 3^1 class

Pure State: $|3^1\rangle_{abc} = \frac{1}{\sqrt{2}} (|000\rangle_{abc} + |111\rangle_{abc})$

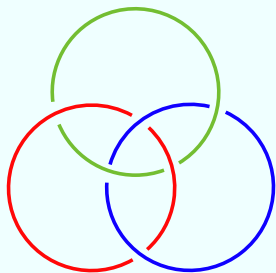
Three Qubit System: 3^1 class

Pure State: $|3^1\rangle_{abc} = \frac{1}{\sqrt{2}} (|000\rangle_{abc} + |111\rangle_{abc})$



Three Qubit System: 3^1 class

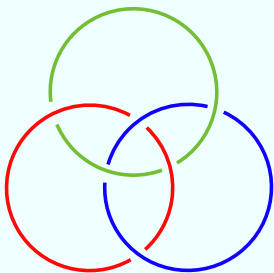
Pure State: $|3^1\rangle_{abc} = \frac{1}{\sqrt{2}} (|000\rangle_{abc} + |111\rangle_{abc})$



$$\rho_{abc} = \begin{bmatrix} 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 \end{bmatrix}$$

Three Qubit System: 3^1 class

Pure State: $|3^1\rangle_{abc} = \frac{1}{\sqrt{2}} (|000\rangle_{abc} + |111\rangle_{abc})$

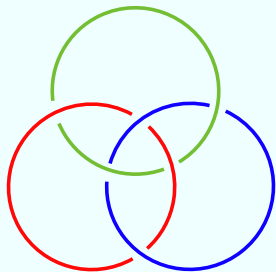


$$\rho_{abc} = \begin{bmatrix} 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 \end{bmatrix}$$

$$\rho_{abc}^{T_a} = \begin{bmatrix} 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.5 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 \end{bmatrix}$$

Three Qubit System: 3^1 class

Pure State: $|3^1\rangle_{abc} = \frac{1}{\sqrt{2}} (|000\rangle_{abc} + |111\rangle_{abc})$



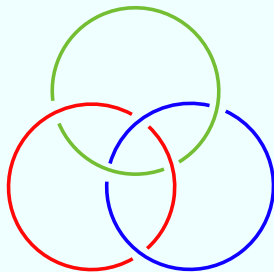
• **Eigenvalues:**
0.0, 0.5, -0.5

$$\rho_{abc} = \begin{bmatrix} 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 \end{bmatrix}$$

$$\rho_{abc}^{T_a} = \begin{bmatrix} 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.5 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 \end{bmatrix}$$

Three Qubit System: 3^1 class

Pure State: $|3^1\rangle_{abc} = \frac{1}{\sqrt{2}} (|000\rangle_{abc} + |111\rangle_{abc})$



- **Eigenvalues:**

0.0, 0.5, -0.5

- One eigenvalue is negative \rightarrow

**Tripartite
Entanglement**

$$\rho_{abc} = \begin{bmatrix} 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 \end{bmatrix}$$

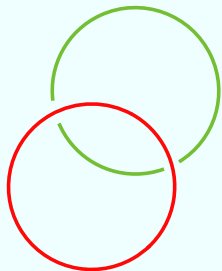
$$\rho_{abc}^{T_a} = \begin{bmatrix} 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.5 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 \end{bmatrix}$$

Three Qubit System: 3^1 class

Pure State: $|3^1\rangle_{abc} = \frac{1}{\sqrt{2}} (|000\rangle_{abc} + |111\rangle_{abc})$

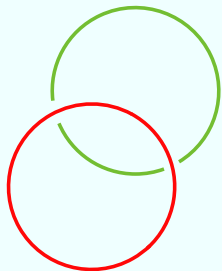
Three Qubit System: 3^1 class

Pure State: $|3^1\rangle_{abc} = \frac{1}{\sqrt{2}} (|000\rangle_{abc} + |111\rangle_{abc})$



Three Qubit System: 3^1 class

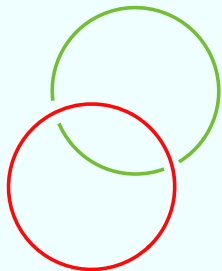
Pure State: $|3^1\rangle_{abc} = \frac{1}{\sqrt{2}} (|000\rangle_{abc} + |111\rangle_{abc})$



$$\rho_{ab} = \begin{bmatrix} 0.5 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.5 \end{bmatrix}$$

Three Qubit System: 3^1 class

Pure State: $|3^1\rangle_{abc} = \frac{1}{\sqrt{2}} (|000\rangle_{abc} + |111\rangle_{abc})$

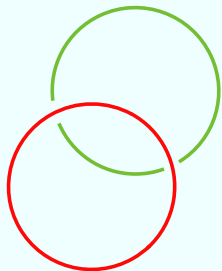


$$\rho_{ab} \begin{bmatrix} 0.5 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.5 \end{bmatrix}$$

$$\rho_{ab}^{Ta} \begin{bmatrix} 0.5 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.5 \end{bmatrix}$$

Three Qubit System: 3^1 class

Pure State: $|3^1\rangle_{abc} = \frac{1}{\sqrt{2}} (|000\rangle_{abc} + |111\rangle_{abc})$



$$\rho_{ab} = \begin{bmatrix} 0.5 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.5 \end{bmatrix}$$

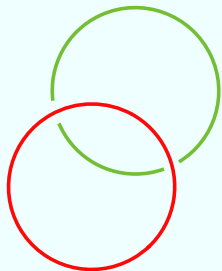
$$\rho_{ab}^{Ta} = \begin{bmatrix} 0.5 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.5 \end{bmatrix}$$

● **Eigenvalues:**

$0.0, 0.5 \geq 0$

Three Qubit System: 3^1 class

Pure State: $|3^1\rangle_{abc} = \frac{1}{\sqrt{2}} (|000\rangle_{abc} + |111\rangle_{abc})$



$$\rho_{ab} = \begin{bmatrix} 0.5 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.5 \end{bmatrix}$$

$$\rho_{ab}^{Ta} = \begin{bmatrix} 0.5 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.5 \end{bmatrix}$$

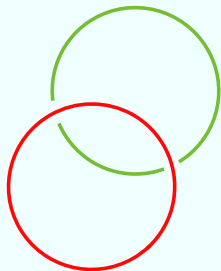
● **Eigenvalues:**

$$0.0, 0.5 \geq 0$$

● All eigenvalues are positive.

Three Qubit System: 3^1 class

Pure State: $|3^1\rangle_{abc} = \frac{1}{\sqrt{2}} (|000\rangle_{abc} + |111\rangle_{abc})$



$$\rho_{ab} = \begin{bmatrix} 0.5 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.5 \end{bmatrix}$$

$$\rho_{ab}^{Ta} = \begin{bmatrix} 0.5 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.5 \end{bmatrix}$$

• **Eigenvalues:**
 $0.0, 0.5 \geq 0$

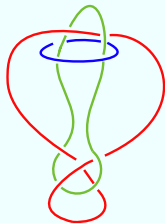
- All eigenvalues are positive.
- System completely **separable** after cut.

Three Qubit System: 3^2 class

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$

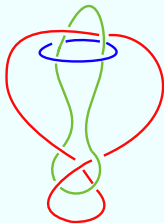
Three Qubit System: 3^2 class

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$



Three Qubit System: 3^2 class

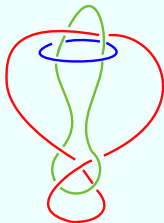
Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$



$$\rho_{abc} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

Three Qubit System: 3^2 class

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$

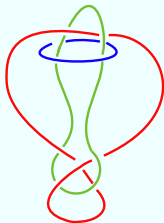


$$\rho_{abc} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

$$\rho_{abc}^{T_a} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.333 & 0.333 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

Three Qubit System: 3^2 class

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$



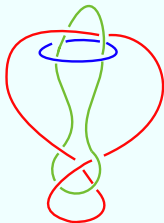
● Eigenvalues:

$-0.471, 0.0, 0.333, 0.471, 0.666$

$$\rho_{abc} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$
$$\rho_{abc}^{T_a} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.333 & 0.333 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

Three Qubit System: 3^2 class

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$



● Eigenvalues:

$-0.471, 0.0, 0.333, 0.471, 0.666$

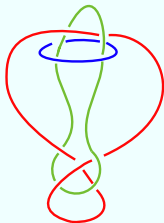
$$\rho_{abc} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

$$\rho_{abc}^{T_a} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.333 & 0.333 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

$$\rho_{abc}^{T_c} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 & 0.333 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

Three Qubit System: 3^2 class

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$



● Eigenvalues:

$-0.471, 0.0, 0.333, 0.471, 0.666$

$-0.333, 0.0, 0.127, 0.333, 0.872$

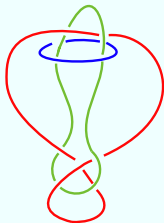
$$\rho_{abc} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

$$\rho_{abc}^{T_a} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.333 & 0.333 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

$$\rho_{abc}^{T_c} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 & 0.333 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

Three Qubit System: 3^2 class

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$



$$\rho_{abc} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

$$\rho_{abc}^{T_a} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.333 & 0.333 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

$$\rho_{abc}^{T_c} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 & 0.333 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.333 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

● Eigenvalues:

−0.471, 0.0, 0.333, 0.471, 0.666

−0.333, 0.0, 0.127, 0.333, 0.872

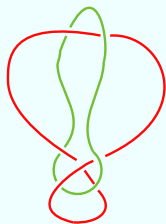
- One eigenvalue is negative → **Tripartite Entanglement**

Three Qubit System: 3^2 class: cut

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$

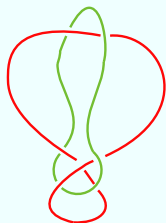
Three Qubit System: 3^2 class: cut

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$



Three Qubit System: 3^2 class: cut

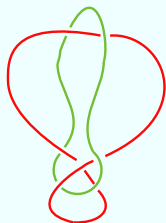
Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$



$$\rho_{ab} = \begin{bmatrix} 0.666 & 0.0 & 0.0 & 0.333 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

Three Qubit System: 3^2 class: cut

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$

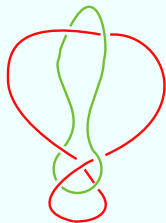


$$\rho_{ab} = \begin{bmatrix} 0.666 & 0.0 & 0.0 & 0.333 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

$$\rho_{ab}^{T_a} = \begin{bmatrix} 0.666 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.333 & 0.0 \\ 0.0 & 0.333 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

Three Qubit System: 3^2 class: cut

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$



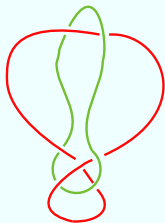
● **Eigenvalues:**
 $0.333, -0.333, 0.666$

$$\rho_{ab} = \begin{bmatrix} 0.666 & 0.0 & 0.0 & 0.333 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

$$\rho_{ab}^{T_a} = \begin{bmatrix} 0.666 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.333 & 0.0 \\ 0.0 & 0.333 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

Three Qubit System: 3^2 class: cut

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$



- **Eigenvalues:**

$0.333, -0.333, 0.666$

- One eigenvalue is negative \rightarrow **Tripartite Entanglement**

$$\rho_{ab} = \begin{bmatrix} 0.666 & 0.0 & 0.0 & 0.333 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.333 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$
$$\rho_{ab}^{T_a} = \begin{bmatrix} 0.666 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.333 & 0.0 \\ 0.0 & 0.333 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

Three Qubit System: 3^2 class: another cut

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$

Three Qubit System: 3^2 class: another cut

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$



Three Qubit System: 3^2 class: another cut

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$



$$\rho_{bc} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

Three Qubit System: 3^2 class: another cut

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$



$$\rho_{bc} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

$$\rho_{bc}^{T_b} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

Three Qubit System: 3^2 class: another cut

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$



● **Eigenvalues:**
0.0, 0.333, 0.666

$$\rho_{bc} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

$$\rho_{bc}^{T_b} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

Three Qubit System: 3^2 class: another cut

Pure State: $|3^2\rangle_{abc} = \frac{1}{\sqrt{3}} (|000\rangle_{abc} + |111\rangle_{abc} + |001\rangle_{abc})$



$$\rho_{bc} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

$$\rho_{bc}^{T_b} = \begin{bmatrix} 0.333 & 0.333 & 0.0 & 0.0 \\ 0.333 & 0.333 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.333 \end{bmatrix}$$

- **Eigenvalues:**

0.0, 0.333, 0.666

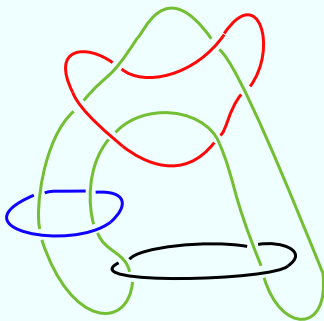
- No eigenvalue is negative \rightarrow **Separable**

Four Qubit System

Link Class: 4^{20}

Link polynomial: $abc + abd + ac$

$$|\psi_{20}\rangle = |3^1\rangle_{abc} |0\rangle_d |0\rangle_e + |3^1\rangle_{abd} |0\rangle_c |1\rangle_e + |2^1\rangle_{ac} |10\rangle_{bd} |2\rangle_e.$$



a: green b: black c: red d: blue

Four Qubit System

$$\hat{\rho}_{abcd} = \frac{\text{Tr}_e(|\psi_{20}\rangle \langle \psi_{20}|)}{\sqrt{\langle \psi_{20} | \psi_{20} \rangle}}.$$

We need to check for Four-partite entanglement. So we have to compute the eigenvalues of the partial transpose with respect to each subsystem.

$\hat{\rho}_{abcd}^{T_a}$: Eigenvalues: $-0.270, -0.103, 0.000, 0.103, 0.270, 0.333$

$\hat{\rho}_{abcd}^{T_b}$: Eigenvalues: $-0.186, 0.000, 0.167, 0.209, 0.333, 0.477$

$\hat{\rho}_{abcd}^{T_c}$: Eigenvalues: $-0.236, 0.000, 0.064, 0.167, 0.236, 0.333, 0.436$

$\hat{\rho}_{abcd}^{T_d}$: Eigenvalues: $-0.167, 0.000, 0.033, 0.167, 0.259, 0.541$

Four Qubit System

$$\hat{\rho}_{abcd} = \frac{\text{Tr}_e(|\psi_{20}\rangle \langle \psi_{20}|)}{\sqrt{\langle \psi_{20} | \psi_{20} \rangle}}.$$

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$\hat{\rho}_{abcd}^{T_d}$: Eigenvalues: $-0.167, 0.000, 0.033, 0.167, 0.259, 0.541$

As the eigenvalues are negative, it has **FOUR PARTITE ENTANGLEMENT**.

Four Qubit System

All Possible Partial Traces:

Partial Trace with respect to system a :

$$\hat{\rho}_{bcd} = \begin{bmatrix} 0.333 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.166 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.166 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.333 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

As this is a diagonal matrix, we can say directly that after measuring a , the rest of the system b,c,d becomes **separable**.

Four Qubit System

Partial Trace with respect to system b :

Four Qubit System

Partial Trace with respect to system b :

• $\hat{\rho}_{acd}^{T_a}$:

Eigenvalues: $-0.167, 0.000, 0.167, 0.167, 0.333, 0.500$.

Four Qubit System

Partial Trace with respect to system b :

- $\hat{\rho}_{acd}^{T_a}$:

Eigenvalues: — 0.167, 0.000, 0.167, 0.167, 0.333, 0.500.

- $\hat{\rho}_{acd}^{T_c}$:

Eigenvalues: — 0.167, 0.000, 0.167, 0.167, 0.333, 0.500.

Four Qubit System

Partial Trace with respect to system b :

- $\hat{\rho}_{acd}^{T_a}$:

Eigenvalues: $-0.167, 0.000, 0.167, 0.167, 0.333, 0.500$.

- $\hat{\rho}_{acd}^{T_c}$:

Eigenvalues: $-0.167, 0.000, 0.167, 0.167, 0.333, 0.500$.

- $\hat{\rho}_{acd}^{T_d}$:

Eigenvalues: $0.000, 0.000, 0.000, 0.167, 0.230, 0.603$.

Four Qubit System

Partial Trace with respect to system b :

• $\hat{\rho}_{acd}^{T_a}$:

Eigenvalues: $-0.167, 0.000, 0.167, 0.167, 0.333, 0.500$.

• $\hat{\rho}_{acd}^{T_c}$:

Eigenvalues: $-0.167, 0.000, 0.167, 0.167, 0.333, 0.500$.

• $\hat{\rho}_{acd}^{T_d}$:

Eigenvalues: $0.000, 0.000, 0.000, 0.167, 0.230, 0.603$.

Negative eigenvalues suggest, a and cd are entangled, and c and ad are entangled.

Four Qubit System

Partial Trace with respect to system b :

- $\hat{\rho}_{acd}^{T_a}$:

Eigenvalues: $-0.167, 0.000, 0.167, 0.167, 0.333, 0.500$.

- $\hat{\rho}_{acd}^{T_c}$:

Eigenvalues: $-0.167, 0.000, 0.167, 0.167, 0.333, 0.500$.

- $\hat{\rho}_{acd}^{T_d}$:

Eigenvalues: $0.000, 0.000, 0.000, 0.167, 0.230, 0.603$.

Negative eigenvalues suggest, a **and** cd **are entangled**, and c **and** ad **are entangled**. We can not say anything about the subsystem d and ac .

Four Qubit System

Partial Trace with respect to system b :

Q. How to conclude anything about the separability of the subsystem d and ac ?

Four Qubit System

Partial Trace with respect to system b :

Q. How to conclude anything about the separability of the subsystem d and ac ?

Computing eigenstates of ρ_{acd} :

$$\begin{bmatrix} 0 \\ 0 \\ 1.0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1.0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1.0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ -1.0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1.0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1.0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0.525 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -0.850 \\ 0 \end{bmatrix}, \begin{bmatrix} 0.850 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0.525 \\ 0 \end{bmatrix}$$

Four Qubit System

Partial Trace with respect to system b :

Q. How to conclude anything about the separability of the subsystem d and ac ?

Computing eigenstates of ρ_{acd} :

$$\begin{bmatrix} 0 \\ 0 \\ 1.0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1.0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1.0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ -1.0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1.0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1.0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0.525 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -0.850 \\ 0 \end{bmatrix}, \begin{bmatrix} 0.850 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0.525 \\ 0 \end{bmatrix}$$

If we can show that these vectors are separable as $|v_{ac}\rangle \otimes |v_d\rangle$, then that will show that the ac and d are separable.

Four Qubit System

Partial Trace with respect to system b :

Consider,

$$\begin{bmatrix} 0 \\ 0 \\ 1.0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = |0\rangle_a |0\rangle_c |0\rangle_d.$$

So this vector is separable in this form $|v_{ac}\rangle \otimes |v_d\rangle$.

Similarly, we can say all the vectors of this form are separable.

Four Qubit System

Partial Trace with respect to system b :

Consider,

$$\begin{bmatrix} 0.525 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -0.850 \\ 0 \end{bmatrix} = 0.525 |0\rangle_a \otimes |0\rangle_c \otimes |0\rangle_d - 0.850 |1\rangle_a \otimes |1\rangle_c \otimes |0\rangle_d$$

This can be written as,

$$\begin{aligned} & (0.525 |0\rangle_a \otimes |0\rangle_c - 0.850 |1\rangle_a \otimes |1\rangle_c) \otimes |0\rangle_d . \\ & = |v_{ac}\rangle \otimes |v\rangle_d \end{aligned}$$

So, ac and d are separable.

Four Qubit System

Partial Trace with respect to system c :

Four Qubit System

Partial Trace with respect to system c :

• $\hat{\rho}_{abd}^{T_a}$:

Eigenvalues: $-0.167, 0.000, 0.167, 0.167, 0.167, 0.333$.

Four Qubit System

Partial Trace with respect to system c :

- $\hat{\rho}_{abd}^{T_a}$:

Eigenvalues: — 0.167, 0.000, 0.167, 0.167, 0.167, 0.333.

- $\hat{\rho}_{abd}^{T_b}$:

Eigenvalues: — 0.103, 0.000, 0.167, 0.270, 0.333, 0.333.

Four Qubit System

Partial Trace with respect to system c :

- $\hat{\rho}_{abd}^{T_a}$:

Eigenvalues: — 0.167, 0.000, 0.167, 0.167, 0.167, 0.333.

- $\hat{\rho}_{abd}^{T_b}$:

Eigenvalues: — 0.103, 0.000, 0.167, 0.270, 0.333, 0.333.

- $\hat{\rho}_{abd}^{T_d}$:

Eigenvalues: — 0.069, 0.000, 0.167, 0.167, 0.333, 0.402.

Four Qubit System

Partial Trace with respect to system c :

• $\hat{\rho}_{abd}^{T_a}$:

Eigenvalues: $-0.167, 0.000, 0.167, 0.167, 0.167, 0.333$.

• $\hat{\rho}_{abd}^{T_b}$:

Eigenvalues: $-0.103, 0.000, 0.167, 0.270, 0.333, 0.333$.

• $\hat{\rho}_{abd}^{T_d}$:

Eigenvalues: $-0.069, 0.000, 0.167, 0.167, 0.333, 0.402$.

Negative eigenvalues suggest, **a and bd are entangled, b and ad are entangled.** and **d and ab are entangled.**

Four Qubit System

Partial Trace with respect to system d :

Four Qubit System

Partial Trace with respect to system d :

• $\hat{\rho}_{abc}^{T_d}$:

Eigenvalues: — 0.208, 0.000, 0.074, 0.167, 0.300, 0.333,

Four Qubit System

Partial Trace with respect to system d :

• $\hat{\rho}_{abc}^{T_a}$:

Eigenvalues: — 0.208, 0.000, 0.074, 0.167, 0.300, 0.333,

• $\hat{\rho}_{abc}^{T_b}$:

Eigenvalues: — 0.122, 0.000, 0.167, 0.167, 0.333, 0.455.

Four Qubit System

Partial Trace with respect to system d :

• $\hat{\rho}_{abc}^{T_a}$:

Eigenvalues: — 0.208, 0.000, 0.074, 0.167, 0.300, 0.333,

• $\hat{\rho}_{abc}^{T_b}$:

Eigenvalues: — 0.122, 0.000, 0.167, 0.167, 0.333, 0.455.

• $\hat{\rho}_{abc}^{T_c}$:

Eigenvalues: — 0.167, 0.000, 0.167, 0.333, 0.333, 0.333.

Four Qubit System

Partial Trace with respect to system d :

• $\hat{\rho}_{abc}^{T_a}$:

Eigenvalues: $-0.208, 0.000, 0.074, 0.167, 0.300, 0.333,$

• $\hat{\rho}_{abc}^{T_b}$:

Eigenvalues: $-0.122, 0.000, 0.167, 0.167, 0.333, 0.455.$

• $\hat{\rho}_{abc}^{T_c}$:

Eigenvalues: $-0.167, 0.000, 0.167, 0.333, 0.333, 0.333.$

Negative eigenvalues suggest, **a and bc are entangled, b and ac are entangled.** and **c and ab are entangled.**

Four Qubit System

Partial Trace with respect to system ab :

$$\hat{\rho}_{cd} = \begin{bmatrix} 0.5 & 0 & 0 & 0 \\ 0 & 0.166 & 0 & 0 \\ 0 & 0 & 0.333 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}.$$

So, c and d are separated.

Four Qubit System

Partial Trace with respect to system bc :

$$\hat{\rho}_{ad} = \begin{bmatrix} 0.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0.333 & 0 \\ 0 & 0 & 0 & 0.166 \end{bmatrix}.$$

So, a and d are separated.

Four Qubit System

Partial Trace with respect to system cd :

$$\hat{\rho}_{ab} = \begin{bmatrix} 0.333 & 0 & 0 & 0 \\ 0 & 0.166 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 \end{bmatrix}.$$

So, a and b are separated.

Four Qubit System

Partial Trace with respect to system ad :

$$\hat{\rho}_{bc} = \begin{bmatrix} 0.333 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0.333 & 0 \\ 0 & 0 & 0 & 0.333 \end{bmatrix}.$$

So, b and c are separated.

Four Qubit System

Partial Trace with respect to system bd :

$$\hat{\rho}_{ac} = \begin{bmatrix} 0.5 & 0 & 0 & 0.166 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0.166 & 0 \\ 0.166 & 0 & 0 & 0.333 \end{bmatrix}.$$

Four Qubit System

Partial Transpose with respect to a :

$$\hat{\rho}_{ac}^{T_a} = \begin{bmatrix} 0.5 & 0 & 0 & 0 \\ 0 & 0 & 0.166 & 0 \\ 0 & 0.166 & 0.166 & 0 \\ 0 & 0 & 0 & 0.333 \end{bmatrix}.$$

Eigenvalues are : -0.103, 0.270, 0.333, 0.500.

So, a and c are entangled.

Four Qubit System

Partial Trace with respect to system ac :

$$\hat{\rho}_{bd} = \begin{bmatrix} 0.333 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0 \\ 0 & 0 & 0 & 0.166 \end{bmatrix}.$$

So, b and d are separated.

Four Qubit System

Result:

- After tracing out a , rest of the system b, c, d becomes separable.
- After tracing out b , a and cd remain entangled, c and ad remain entangled, and ac and d are separable.
- After tracing out c , a and bd , b and ad , and d and ab remain entangled.
- After tracing out d , a and bc , b and ac , and c and ab remain entangled.
- After tracing out ab , c and d are separable.
- After tracing out bc , a and d are separable.
- After tracing out cd , a and d are separable.
- After tracing out ad , b and c are separable.
- After tracing out bd , a and c are entangled.
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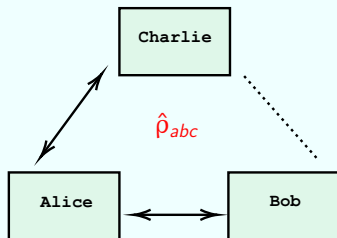
So, the polynomial is $abc + abd + ac$.

Application to Qubit Networks

- Different parties possessing entangled qubits, want to perform protocols with certain restrictions.

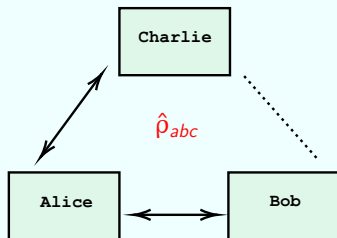
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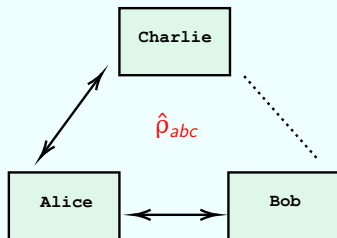
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Application to Qubit Networks

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- If density operator of the subsystem consisting the parties wanting to perform the protocol is separable, then the protocol cannot be performed successfully.
- If another party (not participating in the protocol) does not divulge information about their local operations, then results of the protocol cannot be correlated.



Application to Qubit Networks

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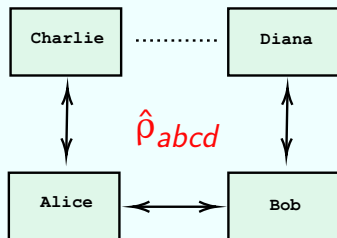
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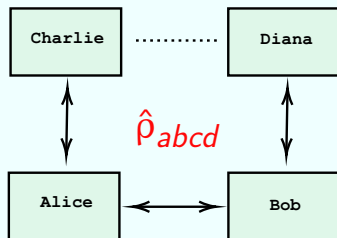
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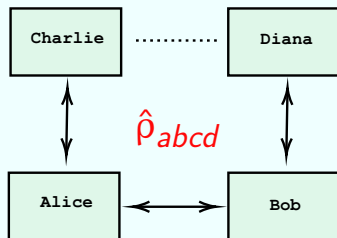


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 $P(a, b, c, d) = abc + abd + ac \longrightarrow$

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We can easily see that the polynomial describing this network is $P(a, b, c, d) = abc + abd + ac \rightarrow$ a state can immediately be constructed from the algorithm.

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Thank you!