

Pauli component erasing operations

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Carlos' ideas

1 CP from eigenvalues

Choi matrix's eigenvalues of a 1-qubit Pauli Channel are

$$\lambda_\mu = 1 + \sum_{j=1}^3 a_j^\mu \tau_j \quad \mu = 0, 1, 2, 3; \quad a_j^\mu = \begin{cases} 1, & \mu = j \vee \mu = 0 \\ -1, & \mu \neq j \end{cases} . \quad (1)$$

Therefore, the inequalities needed to be satisfied for a 1-qubit unital Pauli channel in order to be CP may be expressed in the following compact expression:

$$\sum_{j=0}^3 a_j^\mu \tau_j \geq -1, \quad \mu = 1, 2, 3; \quad a_j^\mu = \begin{cases} 1, & \mu = j \\ -1, & \mu \neq j \end{cases} . \quad (2)$$

Now, Choi matrix's eigenvalues of an n-qubit Pauli Channel are

$$\lambda_{\mu_1, \dots, \mu_n} = 1 + \sum_{\substack{j_1, \dots, j_n=0 \\ (j_1, \dots, j_n \neq 0)}}^3 a_{j_1}^{\mu_1} \dots a_{j_n}^{\mu_n} \tau_{j_1, \dots, j_n} \quad \mu_l = 0, 1, 2, 3,$$

$$a_{j_l}^{\mu_l} = \begin{cases} 1, & \mu_l = j_l \vee j_l = 0 \vee \mu_1, \dots, \mu_n = 0 \\ -1, & \mu_l \neq j_l \end{cases}.$$
(3)

Therefore, the inequalities needed to be satisfied for the CP are

$$\sum_{\substack{j_1, \dots, j_n=0 \\ (j_1, \dots, j_n \neq 0)}}^3 a_{j_1}^{\mu_1} \dots a_{j_n}^{\mu_n} \tau_{j_1, \dots, j_n} \geq -1, \quad \mu_l = 0, 1, 2, 3; \quad a_{j_l}^{\mu_l} = \begin{cases} 1, & \mu_l = j_l \vee j_l = 0 \\ -1, & \mu_l \neq j_l \end{cases}, \quad (4)$$

where we used that $\lambda_{0, \dots, 0}$ is always non-negative.

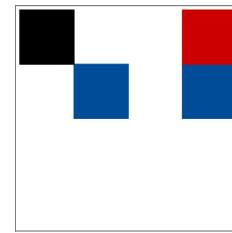
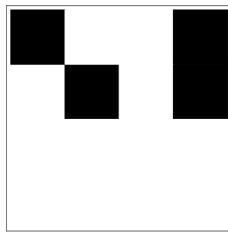
1.1 Another observation from this

Choi's matrix of 2 qubits is diagonal in Pauli product basis (Kraus operators). Does this follow in the general case????

2 General characterisation of PCE quantum channels

To avoid confusion

CP: Igual el canal totalmente despolarizante y el estado totalmente mixto tendrían el mismo diagrama. Quiza el borde se puede ser de diferente color JA: Me gustaría discutir antes si igual vale la pena hacer la distinción. Dado que al final la distinción sólo es una ayuda que se me ocurrió para explicar gráficamente el procedimiento de la concatenación. The figures we've been using (columns, boards, cubes) may represent both PCE operations (dynamics) and density matrices (kinematics). We will make a distinction between both representations with colors. B&W represent PCE operations, and colored figures represent density matrices in Pauli products basis.



(a) PCE operation that erases all Pauli components except for $r_{0,0}$, $r_{1,1}$, $r_{1,3}$, and $r_{0,3}$. (b) Density matrix in Pauli basis with all components equal to zero except for $r_{0,0}$, $r_{1,1}$, $r_{1,3}$, and $r_{0,3}$.

Hypothesis

Let us denote PCE_n the set of all PCE quantum channels for n qubits.

Hypothesis 1 *There exists a set $\Gamma_n \subset \text{PCE}_n$ that is sufficient (and necessary?) to generate the rest of elements in PCE_n as concatenations of different elements in Γ_n .*

Let us consider $\mathcal{E}_j \in \Gamma_n$ ($j = 1, \dots, 4^n - 1$), and $\Lambda \in \text{PCE}_n$. All Λ are a composition of \mathcal{E}_j ,

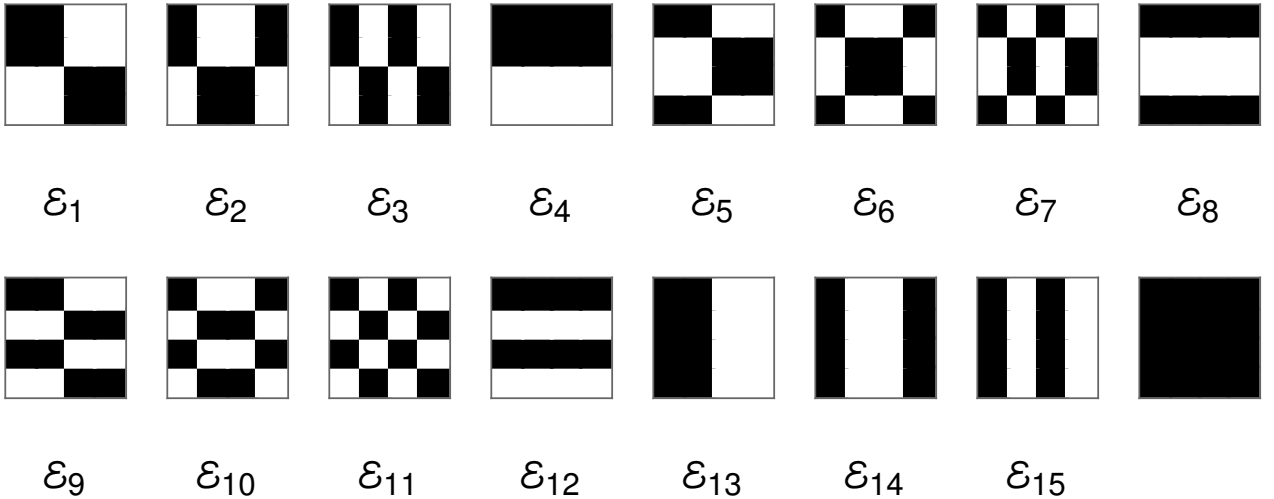
$$\underbrace{\mathcal{E}_{j_{2n}} \dots \mathcal{E}_{j_1}}_{k \text{ elements}} = \Lambda, \quad j_l \neq j_{l+1}, \quad k = 1, \dots, 2n. \quad (5)$$

A way to find Γ

PCE quantum channels in Γ_n may be found as the quantum channels defined by the the coefficients a_j^μ of the τ_i in the eigenvalues expression of Choi matrix, with $a_k^k = 0$ (instead of -1). Let us show the 2-qubits case as an example to illustrate this. The eigenvalues of Choi matrix of 2-qubits Pauli Channel are

$$\begin{aligned}
\lambda_1 &= \tau_{0,0} + \tau_{0,1} - \tau_{0,2} - \tau_{0,3} + \tau_{1,0} + \tau_{1,1} - \tau_{1,2} - \tau_{1,3} - \tau_{2,0} - \tau_{2,1} + \tau_{2,2} + \tau_{2,3} - \tau_{3,0} - \tau_{3,1} + \tau_{3,2} + \tau_{3,3} \\
\lambda_2 &= \tau_{0,0} - \tau_{0,1} - \tau_{0,2} + \tau_{0,3} + \tau_{1,0} - \tau_{1,1} - \tau_{1,2} + \tau_{1,3} - \tau_{2,0} + \tau_{2,1} + \tau_{2,2} - \tau_{2,3} - \tau_{3,0} + \tau_{3,1} + \tau_{3,2} - \tau_{3,3} \\
\lambda_3 &= \tau_{0,0} - \tau_{0,1} + \tau_{0,2} - \tau_{0,3} + \tau_{1,0} - \tau_{1,1} + \tau_{1,2} - \tau_{1,3} - \tau_{2,0} + \tau_{2,1} - \tau_{2,2} + \tau_{2,3} - \tau_{3,0} + \tau_{3,1} - \tau_{3,2} + \tau_{3,3} \\
\lambda_4 &= \tau_{0,0} + \tau_{0,1} + \tau_{0,2} + \tau_{0,3} + \tau_{1,0} + \tau_{1,1} + \tau_{1,2} + \tau_{1,3} - \tau_{2,0} - \tau_{2,1} - \tau_{2,2} - \tau_{2,3} - \tau_{3,0} - \tau_{3,1} - \tau_{3,2} - \tau_{3,3} \\
\lambda_5 &= \tau_{0,0} + \tau_{0,1} - \tau_{0,2} - \tau_{0,3} - \tau_{1,0} - \tau_{1,1} + \tau_{1,2} + \tau_{1,3} - \tau_{2,0} - \tau_{2,1} + \tau_{2,2} + \tau_{2,3} + \tau_{3,0} + \tau_{3,1} - \tau_{3,2} - \tau_{3,3} \\
\lambda_6 &= \tau_{0,0} - \tau_{0,1} - \tau_{0,2} + \tau_{0,3} - \tau_{1,0} + \tau_{1,1} + \tau_{1,2} - \tau_{1,3} - \tau_{2,0} + \tau_{2,1} + \tau_{2,2} - \tau_{2,3} + \tau_{3,0} - \tau_{3,1} - \tau_{3,2} + \tau_{3,3} \\
\lambda_7 &= \tau_{0,0} - \tau_{0,1} + \tau_{0,2} - \tau_{0,3} - \tau_{1,0} + \tau_{1,1} - \tau_{1,2} + \tau_{1,3} - \tau_{2,0} + \tau_{2,1} - \tau_{2,2} + \tau_{2,3} + \tau_{3,0} - \tau_{3,1} + \tau_{3,2} - \tau_{3,3} \\
\lambda_8 &= \tau_{0,0} + \tau_{0,1} + \tau_{0,2} + \tau_{0,3} - \tau_{1,0} - \tau_{1,1} - \tau_{1,2} - \tau_{1,3} - \tau_{2,0} - \tau_{2,1} - \tau_{2,2} - \tau_{2,3} + \tau_{3,0} + \tau_{3,1} + \tau_{3,2} + \tau_{3,3} \\
\lambda_9 &= \tau_{0,0} + \tau_{0,1} - \tau_{0,2} - \tau_{0,3} - \tau_{1,0} - \tau_{1,1} + \tau_{1,2} + \tau_{1,3} + \tau_{2,0} + \tau_{2,1} - \tau_{2,2} - \tau_{2,3} - \tau_{3,0} - \tau_{3,1} + \tau_{3,2} + \tau_{3,3} \\
\lambda_{10} &= \tau_{0,0} - \tau_{0,1} - \tau_{0,2} + \tau_{0,3} - \tau_{1,0} + \tau_{1,1} + \tau_{1,2} - \tau_{1,3} + \tau_{2,0} - \tau_{2,1} - \tau_{2,2} + \tau_{2,3} - \tau_{3,0} + \tau_{3,1} + \tau_{3,2} - \tau_{3,3} \\
\lambda_{11} &= \tau_{0,0} - \tau_{0,1} + \tau_{0,2} - \tau_{0,3} - \tau_{1,0} + \tau_{1,1} - \tau_{1,2} + \tau_{1,3} + \tau_{2,0} - \tau_{2,1} + \tau_{2,2} - \tau_{2,3} - \tau_{3,0} + \tau_{3,1} - \tau_{3,2} + \tau_{3,3} \\
\lambda_{12} &= \tau_{0,0} + \tau_{0,1} + \tau_{0,2} + \tau_{0,3} - \tau_{1,0} - \tau_{1,1} - \tau_{1,2} - \tau_{1,3} + \tau_{2,0} + \tau_{2,1} + \tau_{2,2} + \tau_{2,3} - \tau_{3,0} - \tau_{3,1} - \tau_{3,2} - \tau_{3,3} \\
\lambda_{13} &= \tau_{0,0} + \tau_{0,1} - \tau_{0,2} - \tau_{0,3} + \tau_{1,0} + \tau_{1,1} - \tau_{1,2} - \tau_{1,3} + \tau_{2,0} + \tau_{2,1} - \tau_{2,2} - \tau_{2,3} + \tau_{3,0} + \tau_{3,1} - \tau_{3,2} - \tau_{3,3} \\
\lambda_{14} &= \tau_{0,0} - \tau_{0,1} - \tau_{0,2} + \tau_{0,3} + \tau_{1,0} - \tau_{1,1} - \tau_{1,2} + \tau_{1,3} + \tau_{2,0} - \tau_{2,1} - \tau_{2,2} + \tau_{2,3} + \tau_{3,0} - \tau_{3,1} - \tau_{3,2} + \tau_{3,3} \\
\lambda_{15} &= \tau_{0,0} - \tau_{0,1} + \tau_{0,2} - \tau_{0,3} + \tau_{1,0} - \tau_{1,1} + \tau_{1,2} - \tau_{1,3} + \tau_{2,0} - \tau_{2,1} + \tau_{2,2} - \tau_{2,3} + \tau_{3,0} - \tau_{3,1} + \tau_{3,2} - \tau_{3,3} \\
\lambda_{16} &= \tau_{0,0} + \tau_{0,1} + \tau_{0,2} + \tau_{0,3} + \tau_{1,0} + \tau_{1,1} + \tau_{1,2} + \tau_{1,3} + \tau_{2,0} + \tau_{2,1} + \tau_{2,2} + \tau_{2,3} + \tau_{3,0} + \tau_{3,1} + \tau_{3,2} + \tau_{3,3}.
\end{aligned} \tag{6}$$

Now, taking all $\tau_{i,j}$ with coefficients -1 equal to zero one is led to 16 elements of PCE_2 (one for each eigenvalue):

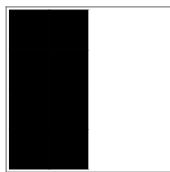
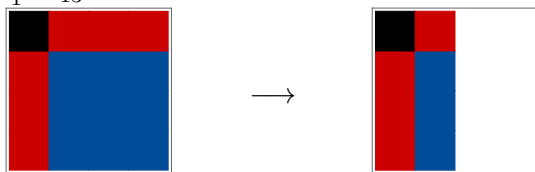


The first 15 elements are the elements of Γ_2 .

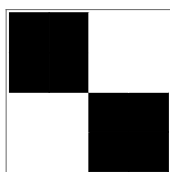
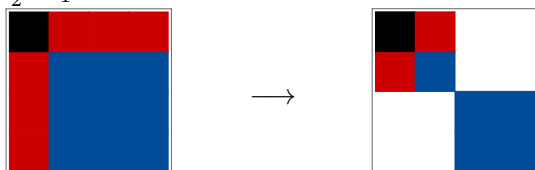
For the sake of completeness let us show how to construct all elements in PCE_2 from Γ_2 . Recall that PCE_2 can be ordered in equivalence classes with PCE quantum channels that are connected via particle swaps and local permutations of basis.

- **8 components:**

– $C_1^8: \mathcal{E}_{13}$

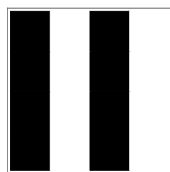
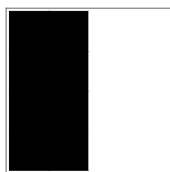
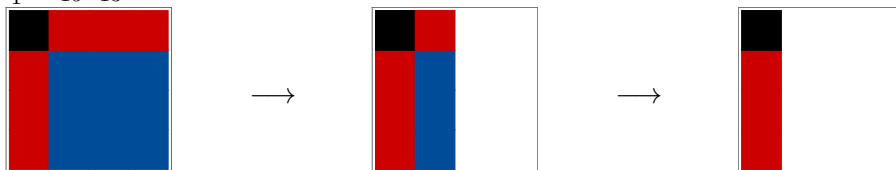


– $C_2^8: \mathcal{E}_1$

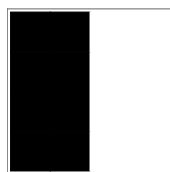
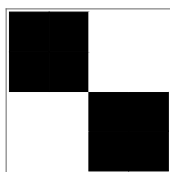
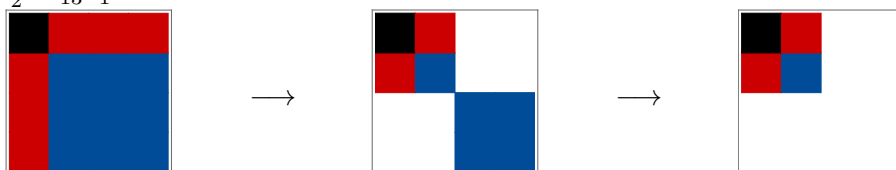


• 4 components:

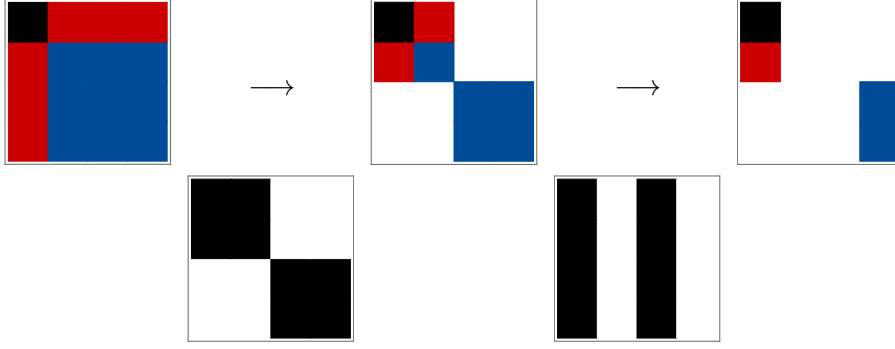
– $C_1^4: \mathcal{E}_{15}\mathcal{E}_{13}$



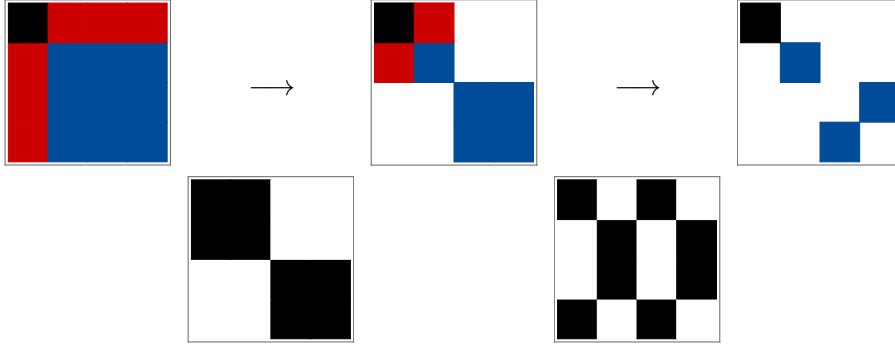
– $C_2^4: \mathcal{E}_{13}\mathcal{E}_1$



– $C_3^4: \mathcal{E}_{15}\mathcal{E}_1$

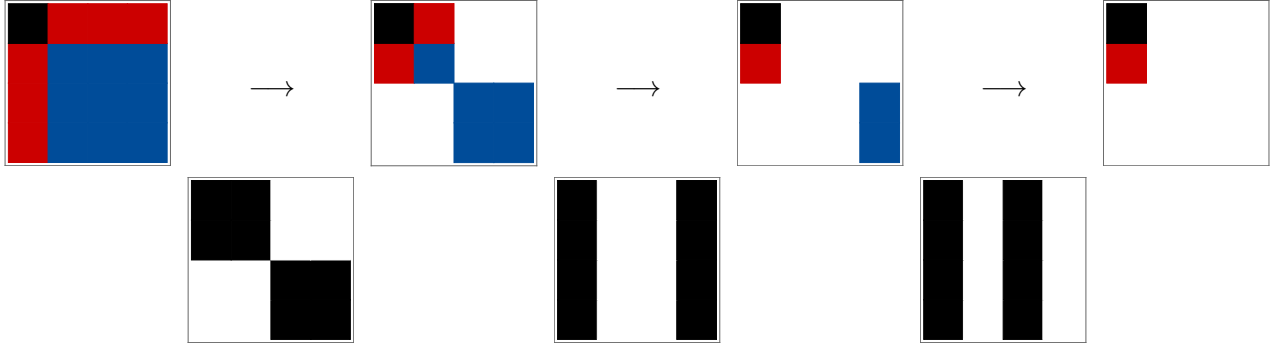


– $C_4^4: \mathcal{E}_7\mathcal{E}_1$

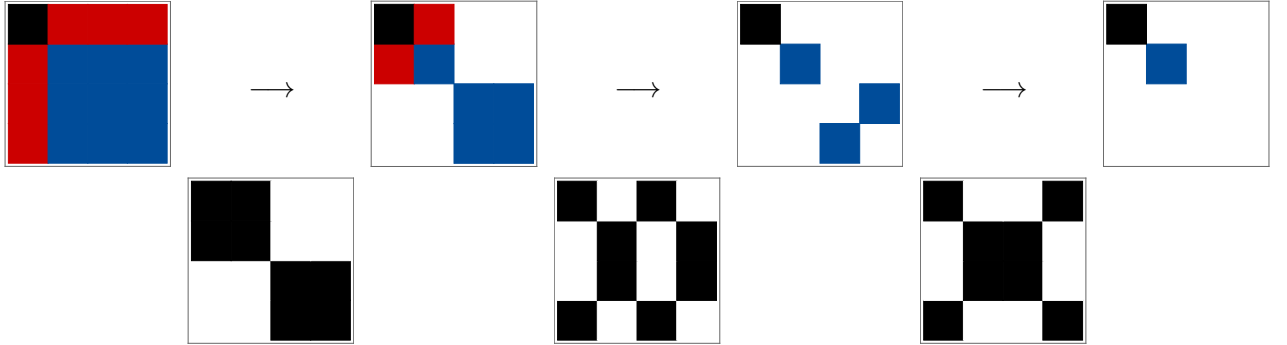


• 2 components:

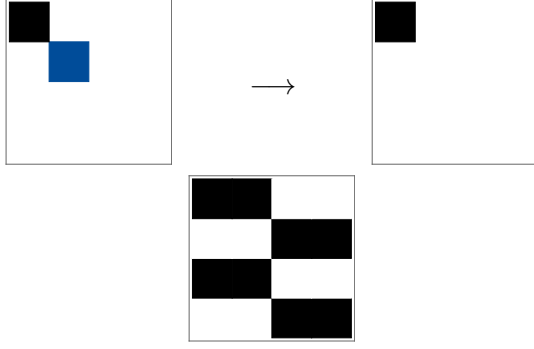
– $C_1^2: \mathcal{E}_{15}\mathcal{E}_{14}\mathcal{E}_1$



– $C_2^2: \mathcal{E}_6\mathcal{E}_7\mathcal{E}_1$



- **1 component:** $\mathcal{E}_9\mathcal{E}_6\mathcal{E}_7\mathcal{E}_1$



Hypothesis 2 *Only n elements in Γ_n are sufficient to generate the remaining elements.*

2.1 Numerical Results

Hypothesis 1 has strong numerical support. The search for PCE quantum channels has been done in two different ways:

1. Using the inequalities in (4) to test CP of all PCE operations (even the ones that do not follow the power-of-2 rule).
2. Using hypothesis 1.

Both methods have analyzed the cases of 1, 2, 3 and partially 4 qubits. Both of them get the same results.

Qubits	Number of components invariant								
	1	2	4	8	16	32	64	128	256
1	1	3	1						
2	1	15	35	15	1				
3	1	63	651	1395	651	1			
4	1	255	10795	97155?	????	97155	10795	255	1

Tested with both methods

Tested only with inequalities

Tested only with concatenation hypothesis

3 Things to do and questions to answer

1. This characterization may explain the power-of-2 rule. It is quite obvious (in the figures representation) that the concatenation always erases half of the number of non-zero components. A proof for that is missing.
2. Analytic proof for (4).
3. Analytic proof that (5) is necessary and sufficient to find all elements in PCE_n .
4. Analytic proof that taking $-1 \rightarrow 0$ for a_k^k leads to CP. I suggest using particle swaps and local basis permutation in order to reduce the problem to n inequalities.
5. Find a way to count PCE channels.

4 Progress

4.1 An idea to prove equation (3)

A density matrix of 1 qubit in Pauli matrices basis is written as

$$\rho = \frac{1}{2} \sum_{i=0}^3 r_i \sigma_i, \quad (7)$$

where σ_i are a 2×2 identity plus Pauli matrices. For 2 qubits, in the general case, the density matrix cannot be written as

$$\rho = \frac{1}{4} \left(\sum_{i=0}^3 r_i \sigma_i \otimes \sum_{j=0}^3 r_j \sigma_j \right) \quad (8)$$

because a 2-qubits state is not separable, in general. Therefore, the density matrix is written as

$$\rho = \frac{1}{4} \sum_{i,j=0}^3 r_{i,j} \sigma_{i,j}. \quad (9)$$

In some sense, expanding (8)

$$\frac{1}{4} \left(\sum_{i=0}^3 r_i \sigma_i \otimes \sum_{j=0}^3 r_j \sigma_j \right) = \frac{1}{4} \left(\mathbb{1}_4 \otimes \mathbb{1}_4 + \mathbb{1} \otimes \sum_{j=1}^3 r_j \sigma_j + \sum_{i=1}^3 r_i \sigma_i \otimes \mathbb{1} + \sum_{i=1}^3 r_i \sigma_i \otimes \sum_{j=1}^3 r_j \sigma_j \right) \quad (10)$$

makes us a hint realize that, in the general case, the components of 2-qubits density matrix in tensor products of Pauli matrices basis are

$$r_i r_j \rightarrow r_{i,j}, \quad r_i \rightarrow r_{i,0}, \quad r_j \rightarrow r_{0,j}. \quad (11)$$

It follows that n -qubits density matrix is

$$\rho = \frac{1}{2^n} \sum_{j_1, \dots, j_n=0}^3 r_{j_1, \dots, j_n} \sigma_{j_1} \otimes \dots \otimes \sigma_{j_n}, \quad (12)$$

therefore,

$$r_{j_1} \dots r_{j_k} \dots r_{j_n} \rightarrow r_{j_1, \dots, j_n}, \quad r_{j_k} \rightarrow r_{0, \dots, j_k, \dots, 0}, \quad (13)$$

where

$$r_{j_1} \dots r_{j_k} \dots r_{j_n} \neq r_{j_1, \dots, j_n}, \quad r_{j_k} \neq r_{0, \dots, j_k, \dots, 0}, \quad (14)$$

Now, the state $\rho_{\mathcal{E}}$ isomorphic to the Choi matrix $D_{\mathcal{E}}$ (is this written ok?) of a 1-qubit PCE channel \mathcal{E} is

$$\rho_{\mathcal{E}} = \sum_{i=0}^3 \lambda_i |\sigma_i\rangle\langle\sigma_i|, \quad (15)$$

where $|\sigma_i\rangle$ are the vectorized σ_i and λ_i are (this has been shown analytically)

$$\begin{aligned} \lambda_0 &= \frac{1}{4}(1 + \tau_1 + \tau_2 + \tau_3), & \lambda_1 &= \frac{1}{4}(1 + \tau_1 - \tau_2 - \tau_3), \\ \lambda_2 &= \frac{1}{4}(1 - \tau_1 + \tau_2 - \tau_3), & \lambda_3 &= \frac{1}{4}(1 - \tau_1 - \tau_2 + \tau_3). \end{aligned} \quad (16)$$

I claim that, in the same sense of (13), the eigenvalues of $\rho_{\mathcal{E}}$ of n -qubits PCE quantum channel \mathcal{E} are of the form

$$\lambda_{j_1} \dots \lambda_{j_k} \dots \lambda_{j_n} \rightarrow \lambda_{j_1, \dots, j_n}, \quad \lambda_{j_k} \rightarrow \lambda_{0, \dots, j_k, \dots, 0}, \quad (17)$$

where λ_k are the eigenvalues (16).

5 Number of PCE channels by the ratio of components left invariant

- 1/2 of total components invariant:

$$4^n - 1 \tag{18}$$

- 1/4 of total components invariant:

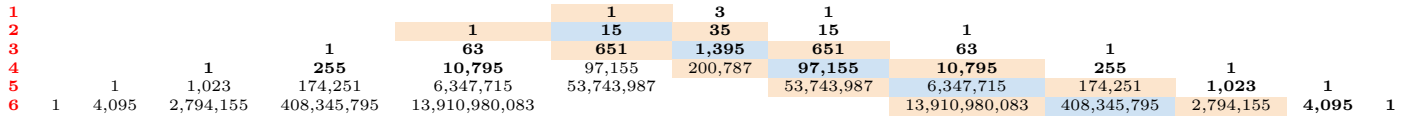
$$\frac{\binom{4^n-1}{2}}{3}, \quad (19)$$

- 1/8 of total components invariant:

$$\frac{\binom{4^n-1}{3} - \binom{4^n-1}{2}/3}{28} \quad (20)$$

- 1/16 of total components invariant:

$$\frac{\binom{4^n-1}{4} - 35 \binom{\binom{4^n-1}{3} - \binom{4^n-1}{2}/3}{28}}{840} \quad (21)$$



6 2 qubits: hermanitos

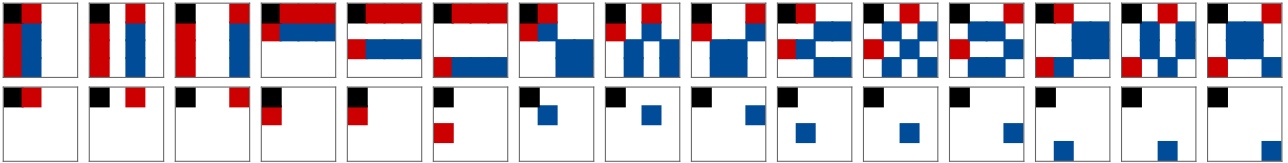


Figure 2: Los hermanitos de 2 qubits. La fila de arriba muestra al hermano mayor del canal que tiene exactamente abajo.

Estos hermanitos tienen la siguiente forma

$$\Phi = \mathcal{E}_i \otimes \mathcal{E}_j + (1 - \mathcal{E}_i) \otimes (1 - \mathcal{E}_j), \quad (22)$$

donde \mathcal{E}_i son el canal identidad y los 3 canales PCE que mapean la esfera de Bloch hacia alguno de los 3 ejes cartesianos.

En general, un canal cuántico PCE ϕ que deja invariantes únicamente dos componentes, $\tau_{0,\dots,0}$ y otra τ_{j_1,\dots,j_n} , tiene un ‘hermano mayor PCE’ Φ que deja invariantes $4^n - 1$ componentes que es de la forma

$$\Phi = \sum_{i=0}^{i \leq n/2} \sum_{j \in \mathcal{S}_{n,i}^n, j_i=1}^n \bigotimes \Omega j_i, \quad (23)$$

donde \mathcal{S}_{2i}^n es el conjunto que contiene a todos los subconjuntos con $2i$ elementos del conjunto $\{1, 2, 3, \dots, n\}$ y

$$\Omega_{j_i} = \begin{cases} \mathcal{E}_{j_i}, & j_i \notin j \\ \mathbb{1} - \mathcal{E}_{j_i}, & j_i \in j. \end{cases} \quad (24)$$

For example, let us elaborate the example for the 3 and 4 qubits generators. First, the PCE generators for 3 qubits are

$$\begin{aligned} \Phi_{j_1, j_2, j_3} &= \sum_{i=0}^{i \leq 3/2} \sum_{j \in \mathcal{S}_{2i}^3} \bigotimes_{j_i=1}^3 \Omega_{j_i} \\ &= \mathcal{E}_{j_1} \otimes \mathcal{E}_{j_2} \otimes \mathcal{E}_{j_3} + (\mathbb{1} - \mathcal{E}_{j_1}) \otimes (\mathbb{1} - \mathcal{E}_{j_2}) \otimes \mathcal{E}_{j_3} \\ &\quad + (\mathbb{1} - \mathcal{E}_{j_1}) \otimes \mathcal{E}_{j_2} \otimes (\mathbb{1} - \mathcal{E}_{j_3}) + \mathcal{E}_{j_1} \otimes (\mathbb{1} - \mathcal{E}_{j_2}) \otimes (\mathbb{1} - \mathcal{E}_{j_3}). \end{aligned} \quad (25)$$

The 4 qubits PCE generators are

$$\begin{aligned} \Phi_{j_1, j_2, j_3, j_4} &= \sum_{i=0}^{i \leq 2} \sum_{j \in \mathcal{S}_{2i}^4} \bigotimes_{j_i=1}^4 \Omega_{j_i} \\ &= \mathcal{E}_{j_1} \otimes \mathcal{E}_{j_2} \otimes \mathcal{E}_{j_3} \otimes \mathcal{E}_{j_4} + (\mathbb{1} - \mathcal{E}_{j_1}) \otimes (\mathbb{1} - \mathcal{E}_{j_2}) \otimes \mathcal{E}_{j_3} \otimes \mathcal{E}_{j_4} \\ &\quad + (\mathbb{1} - \mathcal{E}_{j_1}) \otimes \mathcal{E}_{j_2} \otimes (\mathbb{1} - \mathcal{E}_{j_3}) \otimes \mathcal{E}_{j_4} + (\mathbb{1} - \mathcal{E}_{j_1}) \otimes \mathcal{E}_{j_2} \otimes \mathcal{E}_{j_3} \otimes (\mathbb{1} - \mathcal{E}_{j_4}) \\ &\quad + \mathcal{E}_{j_1} \otimes (\mathbb{1} - \mathcal{E}_{j_2}) \otimes (\mathbb{1} - \mathcal{E}_{j_3}) \otimes \mathcal{E}_{j_4} + \mathcal{E}_{j_1} \otimes (\mathbb{1} - \mathcal{E}_{j_2}) \otimes \mathcal{E}_{j_3} \otimes (\mathbb{1} - \mathcal{E}_{j_4}) \\ &\quad + \mathcal{E}_{j_1} \otimes \mathcal{E}_{j_2} \otimes (\mathbb{1} - \mathcal{E}_{j_3}) \otimes (\mathbb{1} - \mathcal{E}_{j_4}) \\ &\quad + (\mathbb{1} - \mathcal{E}_{j_1}) \otimes (\mathbb{1} - \mathcal{E}_{j_2}) \otimes (\mathbb{1} - \mathcal{E}_{j_3}) \otimes (\mathbb{1} - \mathcal{E}_{j_4}). \end{aligned} \quad (26)$$

David's ideas

7 Alejo's ideas

7.1 Eigenvalues of the Choi matrix

It is possible to show that the eigenvalues of the Choi matrix associated to a Pauli channel of N qubits may be written in a compact form as

$$\lambda_{\vec{\mu}\vec{\nu}} = \sum_{\vec{m}\vec{n}} (-1)^{\vec{\mu} \cdot \vec{m} + \vec{\nu} \cdot \vec{n}} \tau_{\vec{m}\vec{n}}, \quad (27)$$

where $\tau_{\vec{m}\vec{n}}$ are the channel coefficients, the dimension of the “vector indices” is N and each vector element may attain the values 0 or 1. For instance, for $N = 1$ we have

$$\lambda_{\mu\nu} = \sum_{m,n=0}^1 (-1)^{\mu m + \nu n} \tau_{m,n}. \quad (28)$$

7.2 Analytical derivation of conditions for PCE channels

Is it possible to infer the whole set of conditions (rules) a PCE channel must satisfy from the general expression for the eigenvalues of the Choi matrix (Eq. 27)? Work in progress...

7.3 Extremal channels

It can be shown that PCE channels correspond to the extremal points in the polytope of trace preserving channels and non-negative τ coefficients for the case $M = 1$. For $N > 1$, in addition to the set of PCE channels, there are other “extremal channels”, it there anything special around them?