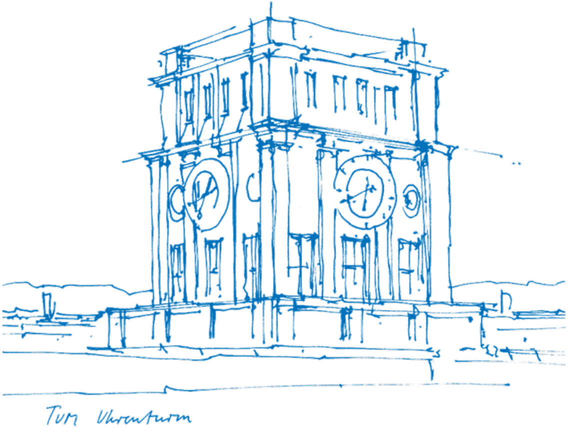
Clifford Tableaus and the Stabilizer Algorithm



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December 20th, 2024

Outline

1. Preliminary Definitions
2. Stabilizer Formalism
3. Stabilizer Algorithm

Pauli Matrices

$$I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

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Products of Pauli matrices:

$$I^2 = X^2 = Y^2 = Z^2 = I$$

$$IX = XI = X \qquad IY = YI = Y \qquad IZ = ZI = Z$$

$$XY = iZ \qquad YX = -iZ$$

$$YZ = iX \qquad ZY = -iX$$

$$ZX = iY \qquad XZ = -iY$$

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Group Theory

Group $(G, \cdot)$ is a non-empty set G with a binary group multiplication operation $" \cdot "$.

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- **Associativity:** $\forall g_1, g_2, g_3 \in G \implies g_1 \cdot (g_2 \cdot g_3) = (g_1 \cdot g_2) \cdot g_3$

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- **Identity:** $\exists e \in G$ such that $\forall g \in G \implies e \cdot g = g \cdot e = g$

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- **Identity:** $\exists e \in G$ such that $\forall g \in G \implies e \cdot g = g \cdot e = g$
- **Inverse:** $\forall g \in G \implies \exists g^{-1} \in G$ such that $g \cdot g^{-1} = g^{-1} \cdot g = e$

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Pauli Group

Definitions

$\mathcal{P}_n$ is defined as the group of n-qubit Pauli operators.
It consists of all tensor products of n Pauli matrices, with a phase factor ± 1 or $\pm i$.

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$$\mathcal{P}_1 = \{\pm I, \pm iI, \pm X, \pm iX, \pm Y, \pm iY, \pm Z, \pm iZ\}$$

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$$\mathcal{P}_n = \left\{ i^m \bigotimes_{j=1}^{n} \sigma_{k_j} \middle| m, k_j \in \{0,1,2,3\}, \sigma_0 = I, \sigma_1 = X, \sigma_2 = Y, \sigma_3 = Z \right\}$$

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Size of a Pauli Group: $|\mathcal{P}_n| = 4^{n+1}$

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Pauli Group
Operations

Given two Pauli operators $P = i^{m_P} \bigotimes_{j=1}^{n} P_j$ and $Q = i^{m_Q} \bigotimes_{j=1}^{n} Q_j$, their product, as necessitated by Group Definition, is:

$$P \cdot Q = i^{m_P + m_Q} \bigotimes_{j=1}^{n} P_j Q_j$$

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$$P \cdot Q = i^{m_P + m_Q} \bigotimes_{j=1}^{n} P_j Q_j$$

P commutes with Q if the number of indices j such that P_j anti-commutes with Q_j is even.

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Group Generators

A set of l elements $\{g_i\}_{1 \leq i \leq l}$ generates a group G if every element $g \in G$ can be written as a product of the generators.
In this case, the group G can be written in terms of its generators:

$$G = \langle g_i \mid i \in \mathbb{N}, 1 \leq i \leq l \rangle$$

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Examples:

$$\mathcal{P}_1 = \langle X, Z, iI \rangle$$
$$\langle X \rangle = \{I, X\}$$

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Outline

Stabilizer Groups

Definitions

- Element $g \in \mathcal{P}_n$ **stabilizes** $|\psi\rangle$ iff $g|\psi\rangle = |\psi\rangle$.
  $|\psi\rangle$ is eigenstate of g with eigenvalue $+1$.

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- $S \mathrel{\widehat{=}}$ Subgroup of the Pauli Group $\mathcal{P}_n$: $S \subseteq \mathcal{P}_n$.

- $V_S \mathrel{\widehat{=}}$ Set of n-qubit states stabilized by S:

$$V_S = \{|\psi\rangle \mid S \subseteq \mathcal{P}_n, \forall g \in S \text{ holds: } g|\psi\rangle = |\psi\rangle\}$$

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Stabilizer Groups

Properties

Not just any subgroup S of the Pauli group can be used as the stabilizer for a non-trivial vector space V_S.

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$$(-I) \in S \text{ and } (-I)\left|\psi\right\rangle = -\left|\psi\right\rangle \implies \left|\psi\right\rangle = \vec{0} \implies V_S = \left\{\vec{0}\right\} \text{ (trivial)}$$

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Conditions for S such that V_S not trivial:

- **Commutativity:** $\forall g_1, g_2 \in S$ holds: $g_1 g_2 = g_2 g_1$

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Conditions for S such that V_S not trivial:

- **Commutativity:** $\forall g_1, g_2 \in S$ holds: $g_1 g_2 = g_2 g_1$
- **Strict Identity:** $-I \notin S$, $iI \notin S$, $-iI \notin S$

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Stabilizer Conditions

Commutativity Proof

Let V_S be non-trivial and let $g_1, g_2 \in S$.

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Let V_S be non-trivial and let $g_1, g_2 \in S$.

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$$|\psi\rangle = g_1 g_2 |\psi\rangle = -g_2 g_1 |\psi\rangle = -|\psi\rangle \iff |\psi\rangle = \vec{0} \implies V_S \text{ is trivial.}$$

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Strict Identity Proof

Let V_S be non-trivial.

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$$
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(-I) \in S &\implies |\psi\rangle = (-I)\,|\psi\rangle = -\,|\psi\rangle &\iff |\psi\rangle = \vec{0} &\implies V_S \text{ is trivial.}\\
(iI) \in S &\implies |\psi\rangle = (iI)\,|\psi\rangle = i\,|\psi\rangle &\iff |\psi\rangle = \vec{0} &\implies V_S \text{ is trivial.}\\
(-iI) \in S &\implies |\psi\rangle = (-iI)\,|\psi\rangle = -i\,|\psi\rangle &\iff |\psi\rangle = \vec{0} &\implies V_S \text{ is trivial.}
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$-I \in S$, $iI \in S$, $-iI \in S$ lead to contradictions.

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Check Matrix
Structure

Suppose $S = \langle g_i \mid i \in \mathbb{N}, 1 \leq i \leq l \rangle$.

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H_S is an $l \times 2n$ binary matrix whose rows correspond to the generators g_1 through g_l.

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Example: $$l \left\{ \begin{bmatrix} \underbrace{\begin{matrix} 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{matrix}}_{n} & \Bigg| & \underbrace{\begin{matrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{matrix}}_{n} \end{bmatrix} \right.$$

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- Row i corresponds to generator $g_i \in S$.

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More explicitly, with $h_{i,j}$ denoting the element of H_S at row i and column j:

- If g_i contains I on the j^{th} qubit $\implies h_{i,j} = 0$ and $h_{i,n+j} = 0$.

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- If g_i contains Z on the j^{th} qubit $\implies h_{i,j} = 0$ and $h_{i,n+j} = 1$.
- If g_i contains Y on the j^{th} qubit $\implies h_{i,j} = 1$ and $h_{i,n+j} = 1$.

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Check Matrix

Example Steane Code

For Readability tensor product operator signs are left out. $\sigma_i \sigma_j$ corresponds to $\sigma_i \otimes \sigma_j$.

$$\left[\begin{array}{ccccccc|ccccccc} 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{array}\right] \widehat{=}$$

Generator	Operator
g_1	$I\,I\,I\,X\,X\,X\,X$
g_2	$I\,X\,X\,I\,I\,X\,X$
g_3	$X\,I\,X\,I\,X\,I\,X$
g_4	$I\,I\,I\,Z\,Z\,Z\,Z$
g_5	$I\,Z\,Z\,I\,I\,Z\,Z$
g_6	$Z\,I\,Z\,I\,Z\,I\,Z$

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Unitary Operations
Main Revelation

Suppose U is a unitary operator, $|\psi\rangle \in V_S$ and $g \in S$.

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$\implies$ If we can describe a state by its stabilizers, we can easily compute the stabilizers of the state that emerges from the previous state under a unitary operation.

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Unitary Operations
Advantages for Computation

For certain special unitary operations U this transformation of the generators takes on a particularly appealing form.

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(Unkown) State $|\psi\rangle$ stabilized by X.

$\longrightarrow$ Apply Hadamard gate H to $|\psi\rangle$.

$\Longrightarrow$ Resulting (Unkown) state $|\psi'\rangle$ stabilized by Z.

Unitary Operations
Transformation under Conjugation

Operation	Input	Output
CX	X_1	X_1X_2
	X_2	X_2
	Z_1	Z_1
	Z_2	Z_1Z_2
H	X	Z
	Z	X
S	X	Y
	Z	Z

Operation	Input	Output
X	X	X
	Z	$-Z$
Y	X	$-X$
	Z	$-Z$
Z	X	$-X$
	Z	Z

[2] Michael A Nielsen and Isaac L Chuang. *Quantum computation and quantum information*. Cambridge university press, 2010

Measurement

Main Principles

We want to measure observable $g \in \mathcal{P}_n$ of state $|\psi\rangle$, stabilized by $\langle g_i \mid i \in \mathbb{N}, 1 \leq i \leq l \rangle$.

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Deterministic case

g commutes with all g_i and assume g does not have a global phase.

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$$\forall i \text{ holds: } g_i g |\psi\rangle = g g_i |\psi\rangle = g |\psi\rangle \implies g|\psi\rangle \in V_S$$

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In both cases the measurement does not disturb the state of the system, and leaves the stabilizer invariant.

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Because g has eigenvalues ± 1, the measurement operators are: $M_{\pm g} = \frac{I \pm g}{2}$

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Measurement probabilities:

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$$p(+1) = p(-1) \text{ and } p(+1) + p(-1) = 1 \implies p(+1) = p(-1) = \frac{1}{2}$$

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Outline

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