

Magic States Distillation Using Quantum Expander Codes.

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1 Good Codes With Large Λ .

Definition 1.1. Let $M \in \mathbb{F}_2^{k \times n}$ upper triangular matrix such that $k < n$. We say that M has the 1-stairs property if $M_{ij} = 1$ any $j < i$.

Claim 1.1. Any $M \in \mathbb{F}_2^{k \times n}$ upper triangular matrix can be turn into upper triangular matrix that has the 1-stairs property by elementary operation.

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 1 & 1 & 1 & 1 & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 1 & 1 & 1 & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & 1 & 1 & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & 0 & 1 & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix}$$

Proof. Consider the following algorithm: Let M be our initial matrix. We iterate over the rows from left to right. In the i th iteration, we check for any row $j < i$ if $M_{ji} = 1$. If not, we set M to be the matrix obtained by adding the i th row to the j th row. Since M is an upper triangular matrix, adding the i th row does not change any entry M_{js} for $s < i$. Therefore, the obtained matrix is still an upper triangular matrix and the entries at M_{js} for $j, s < i$ remain the same, namely 1 if and only if $j \leq s$.

Continuing with the process eventually yields, after k iterations, a matrix with the 1-stair property. \square

Claim 1.2. Let C be a $[n, k, d]$ binary linear code, and let Λ be subcode $\Lambda \subset C$ at dimension k' and distance d' . Then there exists a code $C' = [\leq 2n, \geq k - k'/2, d]$ and a subcode of it Λ' in it at dimension $\geq k'/2$ and distance d' , such:

1. For every $x \in \Lambda'$ and $y \in C'$ $x \cdot y = 0$
2. For every $x \in \Lambda'$ and $y, z \in C'$ $x \cdot y \cdot z = 0$

Proof. First, we can assume that the generator matrix of C is an upper triangular matrix, such that the first k' rows span Λ . Notice that after applying the algorithm from claim 1.1 starting from the first row and stopping at the k' th row, the first k' rows are kept in Λ . So let's assume that is the form of the generator matrix.

Now, let's consider the following process: going uphill, from right to left, starting at the k' row. Initially, set $j \leftarrow k'$ and in each iteration, advance it to be the index of the next row, namely $j \leftarrow j - 1$. In each iteration, ask how many rows G_m , such that $m < j$, satisfy $G_m G_j = 0$ and how many pairs of rows $G_m, G_{m'}$ such that $m, m' < j$ satisfy $G_m \cdot G_{m'} \cdot G_j = 0$. Denote by p the probability to fall on unsatisfied equation from the above.

- If $p \geq \frac{1}{2}$ then we move on to the next iteration.
- Otherwise, we encode the j th coordinate by C_0 , which maps $1 \rightarrow w$ such that $w \cdot w = 0$. This flips the value of $G_m G_j$ for any pair and $G_m G_{m'} G_j$ for any triple such that $m, m' < j$, so we get that the majority of the equations are satisfied. Also notice that the concatenation doesn't change the value of any multiplication at the form $G_m G_{j'}$ for $j' > j$. Therefore, for any $j < j' \leq k'$ the number of the satisfied equations relative to j' is not changed, meaning it is still the majority.

Set G to be the new matrix after the concatenation by C_0 .

In the end of the process G is going to be the generator matrix of C' . It's left to construct Λ' , we are going to do so by taking from the first k' rows a subset that satisfies the desired property Claim 1.2.

Notice that because we iterate on the upper triangular matrix, we don't change the value of $u_m u_{j'}$ for any $j' > j$ (since its j th coordinate was 0 before the encoding, the encoded bit will also be 0, thus not affecting the multiplication).

Denote the set of the obtained vectors by Γ . Let $S \subset \Gamma$ be the group of vectors for which there exists at least one vector in Γ whose multiplication with them is not zero. Note that the total number of pairs with zero multiplication is greater than:

$$\frac{k' - 1}{2} + \frac{k' - 2}{2} + \dots + \frac{2}{2} = \frac{1}{2} \frac{(k' - 1)(k' - 2)}{2}$$

So

$$|S| \cdot (k' - 1) \leq \binom{k'}{2} - \frac{1}{2} \frac{(k' - 1)(k' - 2)}{2} < \frac{k'(k' - 1)}{2} \Rightarrow |S| < \frac{k'}{2}$$

Set $\Lambda' \leftarrow \Gamma/S$. And we got what we wanted. □

Claim 1.3. *We can repeat Claim 1.2 by considering triple multiplications instead of pair multiplications. Let C_2 and C_3 be the codes obtained from this process. We can then guarantee the existence of $\Lambda_2 \in C_2$ and $\Lambda_3 \in C_3$ such that for any $x, y \in \Lambda_2$, $xy = 0$, and for any triple $x, y, z \in \Lambda_3$, $xyz = 0$. The code $C_2 \otimes C_3$ has a group of codewords Λ_{23} such that for any $x, y, z \in \Lambda_{23}$, $xy = 0$ and $xyz = 0$.*

Claim 1.4. *Suppose that a set of vectors $\Lambda \subset C$ satisfies the relation $xy = 0$ and $xyz = 0$ for any $x, y, z \in \Lambda$. Then, there exists a code C' with a code length roughly equal to C and a subset $\Lambda' \subset C'$ such that for any distinct $x, y, z \in \Lambda'$, $xy = 0$, $xyz = 0$, and $xx =_4 1$.*

Proof. We return to the process in Claim 1.2, but taking the standard upper triangular form of Λ instead the 1-stairs form. Notice that the rows are linear combinations of the original vectors in Λ and therefore also preserve the original relations. So now, for any $j < k$, we have that encoding the M_{jj} bit only affects the multiplication of $u_j u_j$. Thus, we will encode the j th coordinate such that the multiplication of a row by itself is 1 residue 4. □

Claim 1.5. *We can repeat Claim 1.2 by flipping the bit, ensuring that the majority of pairs and triple multiplications are zero. In the end, we will have the following inequality:*

$$|S| \cdot (k + k^2) \leq \frac{1}{2} (k^2 + k^3)$$

And still we will get that $|S| \leq k/2$