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.*

Proof. Consider the following algorithm: Let M be our initial matrix. We iterate over the rows from left to right. In the ith 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 ith row to the jth row. Since M is an upper triangular matrix, adding the ith 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. □

Claim 1.2. *Let Λ be a set of k' independent codewords in a $[n, k, d]$ code. Then there exists a code $C' = [\leq 2n, \geq k - k'/2, d]$ and a set of independent codewords Λ' in it, such that $|\Lambda'| > \frac{1}{2}|\Lambda|$ and for every pair $x, y \in \Lambda'$, we have $x \cdot y = 0$.*

Proof. First, consider the upper triangular matrix obtained by applying Gaussian elimination on Λ that has the 1-stair property. Now, consider the following process: go uphill, from right to left, iterating over the matrix. Let $j = k$ be the first non-zero coordinate in the bottom row of the matrix. In the ith iteration, we ask how many rows u_m, such that $m < j$, satisfy $u_m u_j = 0$.

- If more than half of such u_m satisfy the equality, then we move on to the next iteration.
- Otherwise, we encode the jth coordinate by C_0, which maps $1 \rightarrow w$ such that $w \cdot w = 0$. This flips the value of $u_m u_j$ for any pair, so we get that the majority of pairs satisfy the equality.

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 jth 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:

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

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 jth coordinate such that the multiplication of a row by itself is 1 residue 4. □

Definition 1.2. *Let $\{h_i\}_1^t$ be the checks of Δ-length code C_0. We say that ith bit and the jth bit collide if there a check h such that $h_i = h_j = 1$. We say that a C_0 is a checks-hashed if:*

$$\mathbf{Pr}_{i,j\sim[\Delta]^2}\left[i, j \text{ collide }\right] < \frac{1}{2\Delta}$$

Claim 1.5. *Suppose that $C_0^{\perp}$ is a checks-hashed . Then $\left(C_0^{\otimes m}\right)^{\perp}$ is also a checks-hashed .*

Proof.

$$\begin{aligned}\mathbf{Pr}_{u,v\sim[n]^2}\left[X_{u,v}^{(m)}\right] \leq & \mathbf{Pr}_{u,v\sim[\Delta]^2}\left[X_{u,v}^{(1)}\right] \cdot \mathbf{Pr}_{u,v\sim[n/\Delta]^2}\left[X_{u,v}^{(m-1)}\right] \\ \leq & \frac{1}{2\Delta} \cdot \left(\frac{1}{2\Delta}\right)^{m-1} = \left(\frac{1}{2\Delta}\right)^{m}\end{aligned}$$

□

Consider the following decoder, we flip a bit if flipping it decrease the syndrome. Now observers that if a non faulty bit i has been flip then it means that there is at least one faulty bit j in the error e that i, j collide. Similarly if a faulty bit i hasn't been flip then it means that there is another faulty bit j that collide with him. In overall we conclude that the total number of incorrect flips made by the decoder is at most the number of collisions.

$$\mathbf{E}\left[\sum_{v\in e}\sum_{u\in[n]} X_{v,u}\right] \leq |e| \cdot n \cdot \left(\frac{1}{2\Delta}\right)^m = \frac{|e|}{2^m}$$

Now we are going to add a random error at weight $\frac{|e|}{2^m}$ to ensure that in the next iteration the $\frac{|e|}{2^{m-1}}$ error will distributed uniformly. Repeating for $\log_{2^{m-1}}$ rounds correct the error. (not exactly there is an error in each round that should be handled).

[COMMENT] We flip in over all $|e| \sum \frac{1}{2^i} < 2|e|$ bits, so we would like to have $|e| \leq d/4$.
[COMMENT] Yet we can do better, if $e = z + \tilde{e}$ where z commute with all our generators.
[COMMENT] And if it anticommute with only l of them, then we have only l errors.

$$\Delta^m \leq 1/p_0^2 \to \alpha \cdot 1/p_0^2, \frac{m}{2^m}\log\Delta$$

Claim 1.6. *Let H be a $|V| \times r$ binary parity check matrix of $\tilde{C}$. Also, let G be a Δ-regular graph. A bit assignment over G edges x will be said to be $\tilde{C}$-vertices-respect if the vector $z(x) \in \mathbb{F}_2^{|V|}$ which is defined as:*

$$z(x)_v = \begin{cases} 1 & v \text{ sees at least one } 1 \\ 0 & \text{otherwise} \end{cases}$$

is a codeword of $\tilde{C}$. Let Λ be the set of all $\tilde{C}$-vertices-respect assignments. Then $|\Lambda| > (1-\varepsilon)2^{\rho|V|}$.

Proof. Any $x \in \Lambda$ is a solution for the following system of equations:

$$z_v = 1 + \prod_{e \in v} (1 - x_e)$$
$$Hz = 0$$

□

Claim 1.7. *Assume that C_0 is a Δ-length code such that for any two non-trival codewords $c, c' \in C_0$ we have that $c \cdot c' = 1$, and denote by $C = \mathcal{T}(G, C_0)$. And let Λ be a the set of all $\tilde{C}$-vertices-respect assignments where $\tilde{C}$ satisfies relation R. Then also $C \cap \Lambda$ satisfies R.*

Let $|f\rangle$ be a codeword in C_X, and let X_g be the indicator that equals 1 if f has support on X_g, and 0 otherwise. Observes that applying $T^{\otimes}$ on $|f\rangle$ yilds the state:

$$\begin{aligned}
T^{\otimes n}|f\rangle = T^{\otimes n}|\sum_g X_g g\rangle &= \exp\Big(i\pi/4 \sum_g X_g|g| - 2 \cdot i\pi/4 \sum_{g,h} X_g X_h |g \cdot h| \\
&+ 4 \cdot i\pi/4 \sum_{g,h} X_g X_h X_l |g \cdot h \cdot l| - 8 \cdot i\pi/4 \cdot \text{ integers }\Big)|f\rangle \\
&= \exp\Big(i\pi/4 \sum_g X_g|g| - 2 \cdot \pi/4 \sum_{g,h} X_g X_h |g \cdot h| + 4 \cdot i\pi/4 \sum_{g,h} X_g X_h X_l |g \cdot h \cdot l|\Big)|f\rangle
\end{aligned}$$

2 Many to One.

Assume that f is supported on exactly one generator. Then we have that $T^{\otimes n}|f\rangle = e^{i\pi|g|/4}|f\rangle$ Therefore, if $|g| = 4k + 1$ then we are done.

3 Using Quntum Error Correction Codes.

Now assume that the code C_X is the quantum Tanner code, denote by G, A, B the group and the two generator sets that are used for constructing the square complex.

Claim 3.1. *Consider g, h that are supported on the same $v \in V$. We will call such a pair a source-sharing pair. Suppose that for any we have that $|g \cdot h|$ is even. Then there is a Clifford gate that computes $|f\rangle \mapsto \exp\Big(-i\pi \sum_{g,h \text{ source-sharing}} X_g X_h |g \cdot h|\Big)|f\rangle$.*

Claim 3.2. *Let C_A and $C_{A'}$ such that $C_{A'} \subset C_A$. Then $\left(C_A^\perp \otimes C_B^\perp\right)^\perp$, $C_{A'} \otimes C_{B'}$ form a **CSS** code C such there exists a subspace $V \subset C$ with effictive distance d.*

Proof. Idea. consider generators of the form $e_0 \otimes g$. Any codeword in their span is just a first row asssitmentd to a code word of C_A. If we assume less than linear number on that row then we will secucess to decode it, + some other generators that we don't care about. □

$$C_X = \left((C_A \otimes C_0)^\perp \otimes C_0^\perp\right)^\perp$$
$$C_Z = ((C_A \otimes C_0) \otimes C_0)^\perp$$

Claim 3.3. *Let C be a code at rate $\rho(C) > 7/8$ has at least one codeword $x \in C$, such that $|x| =_8 1$.*

Definition 3.1. *We will say that a code C is (l, m)-genorthogonal if there exists a generator set G for C such that for any $I \subset G$ such that $1 < |I| < l$ we have that:*

$$\sum_{i \in [n]} \prod_{g_j \in I \subset G} g_j^i =_m 0$$

Claim 3.4. *If there exists a single (l,m)-genorthogonal code for a finite length Δ, then there is a family of (l,m)-genorthogonal good codes. Moreover, if there exists a generator in C_0 of weight $|\cdot|_m = 1$, then there exists a family that also has at least one generator of weight $|\cdot|_m = 1$.*

Proof. Denote by $C_0 = \Delta[1, \rho_0, \delta_0]$ an (l,m)-genorthogonal code and observes that for any $C = [n, \rho n, \delta n]$ the tensor code $C_0 \otimes C = [\Delta n, \rho_0 \rho \Delta n, \delta_0 \delta \Delta n]$ is also (l,m)-genorthogonal code.

For the seconed part of the claim, Choose C to be a good code with rate $> (2^m - 1)/2^m$ by Claim 3.3 there is at least on codeword c in C such that $|c| =_m 1$.

So pick the base for $C_0 \otimes C$ such the first generator is $g_0 \otimes c$ where g_0 denote a generator of C_0 satisfies $|g_0| =_m 1$. Then $|g_0 \otimes c| = |g_0| \cdot |c| =_m 1$. □

Claim 3.5. *Suppose that there exists $(m+1,m)$-genorthogonal code, such that any generator of it has weight $|\cdot| =_m 1$ then there exists also a family of good $(m+1,m)$-genorthogonal codes such that a liner portion of his generators g have weight $|g| =_m 1$.*

Proof. Denote by C_0 a finte $(m+1,m)$-genorthogonal code, such that any generator of it has weight $|\cdot| =_m 1$. Let C be a good $(m+1,m)$-genorthogonal code with generator c such that $|c| =_m 1$, the existence of which is given by Claim 3.4. Denote its rate by ρ. If C has more than $\rho/m \cdot n$ generators at weight $|\cdot| =_m 1$ then we are done. Otherwise, by the pigeonhole principle, there is an i such that more than ρ/m portion of the generators are at weight $|\cdot| =_m i$. Denote them by $g_1, g_2, g_3, \ldots, g_m$.

Define the set $g_1^{'}, g_2'..g_m'$ as

$$g_t' = c + \sum_{j=t}^{t+m} g_j$$

$$\Rightarrow |g_{t+1}'| = |c| + \sum_t |g_j| + \sum_{|I|<l+1} \left| \prod_{g \in I} \alpha_\star g \right|$$

$$=_m c + m \cdot i =_m c =_m 1$$

Now take $C_0 \otimes C$, and set the new generator set to be $g_i^0 \otimes g_j'$. And it's easy to verify that we got the code we wanted. □

Claim 3.6. *There exists, a good LDPC code (classic) C such that $C^\perp$ is also a good code and a generator set G, for exists $G' \subset G$ and $|G'| = \Theta(|G|)$ such:*

1. *For any pair $x \neq y \in G' \to x \cdot y =_8 0$*
2. *For any triple $x \neq y, z \in G' \to \sum_i x_i y_i z_i =_8 0$*
3. *For any $x \in G' \to |x| =_8 1$*

Claim 3.7. *There is $n \to \Theta(n)$ magic states distillation into a binary qldpc code with $\Theta(\sqrt{n})$ distance, and therefore with asymptotic overhead approaching* 1

Proof. For the encoding we are going to use the hyperproduct code defined in [TZ14]. Let C be the code given by Claim 3.6 and consider the hyperproduct of C with itself $Q = Q(C \times_H C)$. In addition, denote by C_X, C_Z the CSS representation of Q.

By the fact that $C^\perp$ is also a good code, then Q is a positive rate, square root distance code. Let ρ be the rate of C and $1-\rho$ be the rate of $C^\perp$. As $\rho > 0$, then one can find $I \subset [n]$ coordinates such that for any $i \in I$ the indicator $e_i \notin C^\perp$. Hence, it holds from [TZ14] that any vector of the form $e_i \otimes x$ is a codeword of $C_X / C_Z^\perp$.

Denote by ρ' the portion of G' as defined in Claim 3.6, and define S to be:

$$S = \left\{ e_i \otimes x | e_i \notin C^\perp, x \in G' \right\}$$

Observes that $|S| = \rho'\rho n^2$ and in addition S satisfies the properties in Claim 3.6. Denote by f a codeword supported only on S and denote by X_s the indecator that indicate that s supports f. Thus:

$$\begin{aligned} T^{\otimes n}|f\rangle = \exp\Big(i\pi/4\sum_g X_g \overbrace{|g|}^{8k+1} \\ -2\cdot i\pi/4 \overbrace{\sum_{g,h} X_g X_h |g\cdot h|}^{8k} \\ +4\cdot i\pi/4 \overbrace{\sum_{g,h} X_g X_h X_l |g\cdot h\cdot l|}^{8k}\Big)|f\rangle \end{aligned}$$

$$= \exp\Big(i\pi/4\sum_{g\in S} X_g\Big)|f\rangle$$

Therefore we can, generate the enocded (**[COMMENT]** For now without spanning on on $C_Z^\perp$) product of $T^{\otimes|S|}|+\rangle^{|S|}$:

$$\prod_{s\in S}\Big(|0\rangle + \exp(i\pi/4)|s\rangle\Big)$$

[COMMENT] What is left:

1. Show that one can generate $\prod_{s\in S}\Big(|C_Z^\perp\rangle + \exp(i\pi/4)|C_Z^\perp + s\rangle\Big)$ without propagate the errors. I think I know how to do it.
2. Compute a threshold p_0 for using Baravi construction.

Thus we have that $\gamma = \log(n/k)/\log(d) = \log(n/|S|)/\log(\Theta(\sqrt{n})) \to 0$ and the overhead growes as $\log^\gamma(n) \to 1$ [BH12], [MEK12]. □

References

[BH12] Sergey Bravyi and Jeongwan Haah. "Magic-state distillation with low overhead". In: *Physical Review A* 86.5 (2012), p. 052329.

[MEK12] Adam M. Meier, Bryan Eastin, and Emanuel Knill. *Magic-state distillation with the four-qubit code*. 2012. arXiv: 1204.4221 [quant-ph].

[TZ14] Jean-Pierre Tillich and Gilles Zemor. "Quantum LDPC Codes With Positive Rate and Minimum Distance Proportional to the Square Root of the Blocklength". In: *IEEE Transactions on Information Theory* 60.2 (Feb. 2014), pp. 1193–1202. DOI: 10.1109/tit.2013.2292061. URL: https://doi.org/10.1109%2Ftit.2013.2292061.