

# Memory.

August 31, 2025

## 1 Relaxation to The Fault Tolerance Model.

We are interested in the following extension to the fault tolerance circuit model. We are equipped with additional type, in each turn a strong entity, on which we trust, set an hint  $I_t$  on the type. We would like to minimize  $|I| := \min_t |I_t|$ . In particular, A fault tolerance construction in the standard model exhibits a fault tolerance construction in the relaxed model with  $|I| = 0$ .

Another example, is using the hints given by the strong entity for either deciding what correction should be applied or what 'gate-teleportation correction' should be applied. It easy to check that previews constructions gives relaxed fault tolerance such:

1. They output an encoded states with non-trivial distance.
2. The exhibit only a constant overhead in depth.
3. At each turn  $|I_t|/\text{logical qubits}$  depends on the code length.

That brings us to ask the following:

**Open-Problem 1.** Is there a relaxed fault tolerance scheme that enjoys form the first and the second bullets above, yet requires hint at length which is constant per logical qubit? Namely:

$$\frac{|I|}{\text{logical qubits}} = O(1)?$$

## 2 Notations and Definitions.

Consider a code with a left  $k$ -colorized Tanner graph  $\mathcal{T}$ , such that any two left bits of the same color share no check. For a subset of bits  $S$ , we denote by  $S_{c_1}$  its restriction to color  $c_1$ . We use the integer  $\Delta$  to denote the right degree of  $\mathcal{T}$ . Our computation is subjected to  $p$ -depolarized noise. We denote by  $m$  the block length of the code. The decoder works as follows:

1. On the hint-type Pick a random color.  
[COMMENT] In the relaxed version: the 'right/best' color is given by the strong entity.
2. For any (q)bit at that color, check if flipping it decreases the syndrome. If so, then flip it.

We say that a density matrix  $\rho$ , induced on the  $m$ -length block, is a **good noisy distribution** if:

1.  $\rho$  is subjected to  $q$  - local stochastic noise.
2. Denote by  $S$  the support of an error occurring on  $\rho$  ( $S$  is a random variable). Then, with high probability<sup>1</sup>,  $|S_{c_1}| > \frac{1}{4}|S|$ .

**Claim 2.1.** Given density  $\rho$ , which is a **good noisy distribution**, then with high probability, after correction and noise accumulation, it will remain a **good noisy distribution**.

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<sup>1</sup>I'm leaving specifying what it is to later.

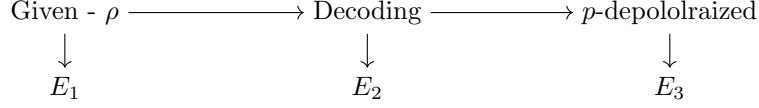


Figure 1: Illustration of the cycle.

## 2.1 Proof.

First, let's bound the probability that the error after the decoding round ( $E_2$ ) is supported on  $S$ . (We use here the fact that views of the bits through their stabilizer don't overlap since we took only bits of the same color for the decoding):

$$\Pr[\text{Sup}(E_2) = S] \leq \Pr[\text{any bit } v \in S_{c_1} \text{ sees majority of satisfied stabilizers}] \leq q^{\Delta|S|_{c_1}}$$

Now, for roughly analyzing the error after observing a round of  $p$ -depolarized noise, we consider a model in which new errors due to the depolarized channel don't correct previous errors. So we get:

$$\begin{aligned}
 \Pr[\text{Sup}(E_3) = S] &\leq \sum_{S' \subset S} \Pr\left[\text{Sup}(E_2) = S' \cap \text{Sup}(E_3/E_2) = S/S' \mid |S'_{c_1}| \geq \frac{1}{4}|S'|\right] \\
 &\quad + \Pr\left[|\text{Sup}(E_2)_{c_1}| < \frac{1}{4}|\text{Sup}(E_2)|\right] \\
 &= \sum_{S' \subset S \text{ and } |S'_{c_1}| \geq \frac{1}{4}|S'|} q^{\Delta|S'_{c_1}|} p^{|S/S'|} + \Pr\left[|\text{Sup}(E_2)_{c_1}| < \frac{1}{4}|\text{Sup}(E_2)|\right] \\
 &\leq \sum_{S' \subset S} q^{\Delta \frac{1}{4}|S'|} p^{|S/S'|} + \Pr\left[|\text{Sup}(E_2)_{c_1}| < \frac{1}{4}|\text{Sup}(E_2)|\right] \\
 &\leq \left(q^{\frac{1}{4}\Delta} + p\right)^{|S|} + \Pr\left[|\text{Sup}(E_2)_{c_1}| < \frac{1}{4}|\text{Sup}(E_2)|\right]
 \end{aligned}$$

So, it remains to show that property (2) still holds with high probability. The following is incorrect, yet almost correct. I want to say that a new error observed by the depolarized channel has to spread evenly on bits at color  $c_1$ , and by concentration get that they are far away from  $\frac{1}{4}$  with probability less than  $\exp(-\varepsilon m)$ .

Then, let  $S^t = \text{Sup}(E)$  at time  $t$  and denote by  $\mathcal{P}_t$  the probability that  $|S^t_{c_1}| > \frac{1}{4}|S^t|$ . Then:

$$\begin{aligned}
 \mathcal{P}_{t+1} &\geq \Pr\left[|S^t_{c_1}| > \frac{1}{4}|S^t| \text{ and } |(S_{t+1}/S^t)_{c_1}| \geq \frac{1}{4}|S_{t+1}/S^t|\right] \\
 &\geq \mathcal{P}_t \cdot (1 - e^{-\varepsilon m}) \geq \mathcal{P}_0 (1 - e^{-\varepsilon m})^{t+1} \\
 &\geq \mathcal{P}_0 (1 - (t+1)e^{-\varepsilon m})
 \end{aligned}$$

There is a problem with the assumption that the new error spreads uniformly across the colors. In particular,  $m$  should be taken as the untapped qubits, so it changes over time and might not contain qubits of color  $c_1$  at all.

( [COMMENT] See the comment in blue below, it gets complicated. )

**Question.** Consider the  $n$ -dimensional toric code, where qubits are placed on  $k$ -cells of the  $n$ -dimensional hypercubic lattice. For an  $i$ -cell, denote by  $\Delta_i^+$  the number of  $(i+1)$ -cells adjacent to it, and by  $\Delta_i^-$  the number of  $(i-1)$ -cells adjacent to it. For which values of  $k$  do both of the following strict inequalities hold?

$$\Delta_k^+ > \Delta_{k+1}^-, \quad \Delta_k^- > \Delta_{k-1}^+.$$

**Answer.** In an  $n$ -dimensional hypercubic lattice one has

$$\Delta_i^+ = 2(n-i), \quad \Delta_i^- = 2i.$$

Therefore, the two inequalities become

$$2(n - k) > 2(k + 1) \iff k < \frac{n-1}{2},$$

$$2k > 2(n - (k - 1)) \iff k > \frac{n+1}{2}.$$

These conditions are mutually exclusive, since they require simultaneously

$$k < \frac{n-1}{2} \quad \text{and} \quad k > \frac{n+1}{2}.$$

Thus, there is no value of  $k$  (for any dimension  $n$ ) for which both inequalities hold at once.

Yet, if one is willing to satisfy only the first inequality. Then:

$$1 < \frac{\Delta_k^-}{\Delta_{k-1}^+} = \frac{2k}{2(n - (k - 1))} \rightarrow k > \frac{2}{3}n$$

**Should be verified:**

1. In addition the dimension of the code should be  $\binom{n}{k}$ . (Also known as the Betti numbers).
2. Numebr of  $k$ -cells shared by a  $j$  - cell and a  $i$  -cell.  $\binom{j-i}{k-i}$ .
3. The partiy of  $\binom{2l}{l}$ .
4. should understand: [Math stachexchange](#).