A TEMPLATE FOR ARXIV STYLE *

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ABSTRACT

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***K*eywords** First keyword · Second keyword · More

1 Introduction

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2 Background

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2.1 Small Set Flip

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* *Citation*: **Authors. Title. Pages.... DOI:000000/11111.**

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$$\xi_{ij}(t) = P(x_t = i, x_{t+1} = j | y, v, w; \theta) = \frac{\alpha_i(t) a^{w_t}_{ij} \beta_j(t+1) b^{v_{t+1}}_j (y_{t+1})}{\sum^N_{i=1} \sum^N_{j=1} \alpha_i(t) a^{w_t}_{ij} \beta_j(t+1) b^{v_{t+1}}_j (y_{t+1})} \tag{1}$$

2.1.1 Headings: third level

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3 Algorithm: K-Top Probabilistic Flip Method (K-Top PFM)

Algorithm 1: `sort-top-K(T)`

Data: A vector $T \in \mathbb{Z}_2^N$
Result: A set S of the top K indices in T

$S \leftarrow$ `indices of a descending radix sort of` T`'s rows`;
return A set of the top K indices in S;

Algorithm 2: `probabilistic-set-flip`(E)

Data: A syndrome $\sigma_0 \in \mathbb{F}_2^M$
Result: Deduced error $\widehat{E}$ if the algorithm converges and $\perp$ otherwise

$\widehat{E} \leftarrow 0^N$;
$\sigma \leftarrow \sigma_0$;
while $\exists F \in \mathscr{F} : |\sigma| - |\sigma \oplus \sigma_X(\boldsymbol{k})| > 0$ **do**
  $T \leftarrow H_Z H_X^T \sigma$;
  `generators` $\leftarrow$ `sort-top-K`(T);
  `to-check` $\leftarrow \bigcup_{i \in \texttt{generators}} \mathcal{P}(\mathcal{C}_{Z\,i})$;
  $\boldsymbol{k} \leftarrow \arg\max_{\boldsymbol{k} \in \texttt{to-check}} \frac{|\sigma| - |\sigma \oplus \sigma_X(\boldsymbol{k})|}{|\boldsymbol{k}|}$;
  $\widehat{E} \leftarrow \widehat{E} \oplus \boldsymbol{k}$;
  $\sigma \leftarrow \sigma \oplus \sigma_X(\boldsymbol{k})$;
end
return $\widehat{E}$ if $|\sigma| = 0$, $\perp$ otherwise.

3.1 A Moral Reason/ Intuition

The algorithm is essentially the same as Small Set Bit Flip [TODO: CITE] with a minor difference, only a constant number of generators are checked. The idea here is that given a syndrome σ and a parity check matrix, H_X, the ith row of $H_X^T \sigma$ equals the number of error-ed checks that a qubit touches. Then, the kth row of $H_Z H_X^T \sigma$ is roughly correlated to the number of error-ed checks that the qubits in the kth generator touch. This rough correlation comes from the fact that we are working with expander codes. So then, if you get the generators touching the most error-ed stabilizers, it would stand to reason that flipping some subset of qubits from a “highly error-ed generator" would result in decreasing the syndrome.

4 PFM Analysis

The following section assumes that we are working with syndrome $\boldsymbol{\sigma_X}$, a generator matrix H_Z, and parity check matrix H_X. The analysis is the same for a syndrome, $\boldsymbol{\sigma_Z}$, generator matrix H_X, and parity check matrix H_Z.

Notation

Given a vector $\boldsymbol{v}$, define v_i to be the value of the ith row of $\boldsymbol{v}$.

Definitions

Let $\Delta_{\text{stablizer}}$ equal to the degree of a stabilizer vertex. Note that due to the hypergraph's construction, all stabilizers have the same constant degree. Let Δ_{bit} equal to the degree of a qubit vertex. As with the stabilizers, all qubits have the same constant degree. Also, for generator k, let $\aleph$ be the set of stabilizers neighboring the generator. Note that $|\aleph| \leq \Delta_{\text{stablizer}}\Delta_{\text{bit}}$.

Given a syndrome, $\boldsymbol{\sigma_X}$, define a “bit-score vector", $\boldsymbol{b} = H_X^T \boldsymbol{\sigma_X}$ where $\boldsymbol{b} \in \mathbb{Z}^N$. Then, define a “generator-score vector" as $\boldsymbol{g} = H_z \boldsymbol{b}$ where $\boldsymbol{g} \in \mathbb{Z}^M$. Moreover, assume that for error $e \in \mathbb{F}_2^N$, $\mathbf{Pr}[e_i = 1] = p$ for all $i \in [N]$ (i.e. the error is modeled as independent). Let $q = 1 - p$. Let $s_1, s_2, ..., s_M$ denote the set of stabilizer vertices. Let $N_i = \sum_{j \in \Gamma(s_i)} \boldsymbol{e}_j$ where $N_i \in \mathbb{Z}$. N_i can be thought of as the number of qubits with an error in the neighborhood of stabilizer i.

Also, let random variable $S_i \in F_2$ correspond to $\boldsymbol{\sigma_X}_i$. Then we know that

$$\mathbf{Pr}[S_i = 1] = \mathbf{Pr}[N_i \texttt{ is odd}] = \tfrac{1}{2} - \tfrac{1}{2}(1-2p)^{\Delta_{\text{stablizer}}}.$$

Next, define indicator random variable, L_j to be 1 if $\boldsymbol{\sigma_X}_i = 0$ and $N_i > 0$. Basically, L_j indicates whether a stabilizer check succeeds, but an error is in its neighborhood. I.e. stabilizer j is “lying."

So then,

$$\begin{aligned}
\mathbf{Pr}[L_j = 1] &= \mathbf{Pr}[\boldsymbol{\sigma_X}_i = 0 \mid S_i > 0] \\
&= \mathbf{Pr}[S_i \texttt{ is even}] - \mathbf{Pr}[S_i = 0] \\
&= \tfrac{1}{2} + \tfrac{1}{2}(1-2p)^{\Delta_{\text{stablizer}}} - (1-p)^{\Delta_{\text{stablizer}}}.
\end{aligned}$$

Then define random variable, E_k to be

$$E_k = \sum_{\texttt{Stabilizer } j \in \aleph_k} L_j.$$

E_k is basically the number of time a generator k, lies for all stabilizers neighboring the generator.

We can then say that

$$E_k \sim \texttt{Binom}(\aleph_k, \tfrac{1}{2} + \tfrac{1}{2}(1-2p)^{\Delta_{\text{stablizer}}} - (1-p)^{\Delta_{\text{stablizer}}}).$$

Then, let random variable $B_i \in \mathbb{Z}$ correspond to $\boldsymbol{b}_i$ and random variable $G'_i \in \mathbb{Z}$ correspond to $\boldsymbol{g}_i$.

So,

$$S_i \sim \texttt{Bernoulli}\Big(\tfrac{1}{2} - \tfrac{1}{2}(1-2p)^{\Delta_{\text{stablizer}}}\Big).$$

Then,

$$B_i = \sum_{\texttt{Stabilizer } j \in \Gamma(\texttt{Bit } i)} S_j$$

So,

$$B_i \sim \texttt{Binom}(\Delta_{\text{bit}}, \tfrac{1}{2} - \tfrac{1}{2}(1-2p)^{\Delta_{\text{stablizer}}}).$$

And then,

$$G'_k = \sum_{\texttt{Bit } i \in \Gamma(\texttt{generator } k)} \sum_{\texttt{Stabilizer } j \in \Gamma(\texttt{Bit } i)} S_j$$

So then,

$$G'_k \sim \texttt{Binom}(\Delta_{\text{bit}}\Delta_{\text{stablizer}}, \tfrac{1}{2} - \tfrac{1}{2}(1-2p)^{\Delta_{\text{stablizer}}}).$$

The pfm algorithm (Algorithm 2) on line 5 gets the K generators, indexed by $g_1, g_2, ..., g_K$, with the top values of $\boldsymbol{g}_i$ for $i \in [M]$. WLOG, assume $\boldsymbol{g}_{g_1} \geq \boldsymbol{g}_{g_2} \geq ... \geq \boldsymbol{g}_{g_K}$. Then, we can think of $\mathbf{E}[G'_{g_i}]$ as the expected value of the ith top sample from M samples of the distribution defining G'_i.

Let random variable G_k then equal

$$G_k = \sum_{\texttt{Stabilizer } j \in \aleph_k} S_j.$$

Note that $|\aleph| \geq (1-\delta)\Delta_{\text{stablizer}}\Delta_{\text{bit}}$ because we are working with expander codes. So then,

$$\begin{aligned}\mathbf{E}[G_k] &= \sum_{\texttt{Stabilizer } j \in \aleph_k} \mathbf{E}[S_j] \\ &\geq (1-\delta)\Delta_{\text{stablizer}}\Delta_{\text{bit}} \mathop{\mathbf{E}}_{j\in[M]}[S_j] \\ &\geq (1-\delta)\,\mathbf{E}[G'_k].\end{aligned}$$

Lemma 4.1. *For a generator, given E_k and G, we can find some correction vector $\boldsymbol{k} \in \mathbb{F}_2^N$ such that $|\sigma| - |\sigma \oplus \sigma_X(\boldsymbol{k})| \geq G_k - E_k$ and $|k| \leq \frac{1-\delta}{\Delta_{bit}}(G_k + E_k)$ for $G > E_k$.*

Proof. TODO: part 1 is that there are 3 types of stabilizers in neighbourhood. Those from G', those from E, and those in neither. If those in neither, there is no neighbourhood in their error, so you can leave those bits alone. Then, by flipping bits connected to G' you decrease syndrome by G', but you add in at most E'

part 2: each flipping bit effects at least (1-delta) Δ_{bit}stables ☐

So then for any $\boldsymbol{e}$ where $|\boldsymbol{e}| < \min(\gamma_A n_A, \gamma_B n_B)$ by TODO: cite hypergraph prod paper, we know that we can always successfully correct errors if we can find a $\boldsymbol{k}$ such that $\boldsymbol{k}$ is a subset of a generator and

$$\frac{|\sigma| - |\sigma \oplus \sigma_X(\boldsymbol{k})|}{|\boldsymbol{k}|} \geq \frac{1}{3}.$$

Lemma 4.2. *We claim the following holds for an $i \in [K]$ and for $p_S = \mathbf{Pr}[S_j = 1]$ for any stabilizer j*

$$\begin{aligned}&\mathbf{Pr}\left[\frac{\Delta_{bit}(Gg_i - E_{g_i})}{(1-\delta)(Gg_i + E_{g_k})} < \frac{1}{3}\right] \\ &\leq \sum_{e=0}^{\Delta_{bit}-1} \text{orderprob}\left(\Delta_{bit}\Delta_{stablizer} - \Delta_{stablizer}e, p_S, i, \frac{(3\Delta_{bit}+1-\delta)e}{3\Delta_{bit}-1+\delta}\right) \cdot \mathbf{Pr}[E_{g_i} = e] + \sum_{e=\Delta_{bit}}^{\Delta_{bit}\Delta_{stablizer}} \mathbf{Pr}[E_{g_i} = e]\end{aligned}$$

where

$$\text{orderprob}(n, p, i, v) = \mathbf{Pr}[W_i \leq v]$$

and W_i is the ith largest order statistic from M samples of $\texttt{Binomial}(n, p)$.

See appendix TODO: cite for details

So then,

$$\mathbf{Pr}[\texttt{loop cannot find a correcting error}] \leq \prod_{i\in[K]} \mathbf{Pr}\left[\frac{\Delta_{\text{bit}}(Gg_i - E_{g_i})}{(1-\delta)(Gg_i + E_{g_k})} < \frac{1}{3}\right]$$

lemma 4.1,

5 PFM Numerical Simulations

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6 PFM Future Outlook

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7 Conclusion

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8 Acknowledgments

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9 Examples of citations, figures, tables, references

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The documentation for `natbib` may be found at

`http://mirrors.ctan.org/macros/latex/contrib/natbib/natnotes.pdf`

Of note is the command `\citet`, which produces citations appropriate for use in inline text. For example,

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\citet{hasselmo} investigated\dots
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> Hasselmo, et al. (1995) investigated…

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9.1 Figures

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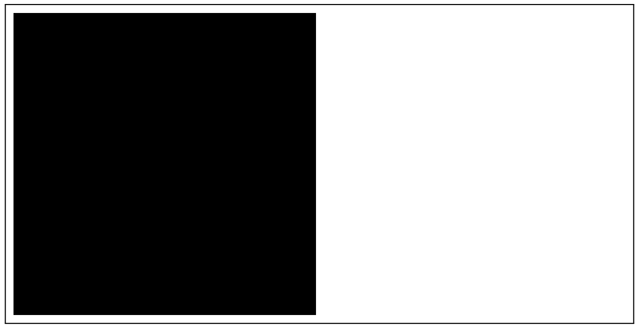

Figure 1: Sample figure caption.

Table 1: Sample table title

Part		
Name	Description	Size (μm)
Dendrite	Input terminal	$\sim$100
Axon	Output terminal	$\sim$10
Soma	Cell body	up to 10^6

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9.2 Tables

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9.3 Lists

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10 Conclusion

Your conclusion here

Acknowledgments

This was was supported in part by......

[2] Sample of the first footnote.

References

[1] George Kour and Raid Saabne. Real-time segmentation of on-line handwritten arabic script. In *Frontiers in Handwriting Recognition (ICFHR), 2014 14th International Conference on*, pages 417–422. IEEE, 2014. 9

[2] George Kour and Raid Saabne. Fast classification of handwritten on-line arabic characters. In *Soft Computing and Pattern Recognition (SoCPaR), 2014 6th International Conference of*, pages 312–318. IEEE, 2014. 9

[3] Guy Hadash, Einat Kermany, Boaz Carmeli, Ofer Lavi, George Kour, and Alon Jacovi. Estimate and replace: A novel approach to integrating deep neural networks with existing applications. *arXiv preprint arXiv:1804.09028*, 2018. 9

A Proof of Lemma 4.1

First, to just restate the lemma. We claim the following holds for an $i \in [K]$ and for $p_S = \mathbf{Pr}[S_j = 1]$ for any stabilizer j

$$\mathbf{Pr}\left[\frac{\Delta_{\text{bit}}(Gg_i - E_{g_i})}{(1-\delta)(Gg_i + E_{g_k})} < \frac{1}{3}\right]$$
$$\leq \sum_{e=0}^{\Delta_{\text{bit}}-1} \text{orderprob}\left(\Delta_{\text{bit}}\Delta_{\text{stablizer}} - \Delta_{\text{stablizer}}e, p_S, i, \frac{(3\Delta_{\text{bit}}+1-\delta)e}{3\Delta_{\text{bit}}-1+\delta}\right) \cdot \mathbf{Pr}[E_{g_i} = e] + \sum_{e=\Delta_{\text{bit}}}^{\Delta_{\text{bit}}\Delta_{\text{stablizer}}} \mathbf{Pr}[E_{g_i} = e]$$

where

$$\text{orderprob}(n, p, i, v) = \mathbf{Pr}[v < (1-\delta)W_i]$$

and W_i is the ith largest order statistic from M samples of $\texttt{Binomial}(n, p)$.

First, because $0 \leq E_{g_i} \leq \Gamma(\texttt{generator i}) \leq \Delta_{\text{bit}}\Delta_{\text{stablizer}}$,

$$\begin{aligned}
\mathbf{Pr}\left[\frac{\Delta_{\text{bit}}(Gg_i - E_{g_i})}{(1-\delta)(Gg_i + E_{g_k})} < \frac{1}{3}\right] &= \sum_{e=0}^{\Delta_{\text{bit}}\Delta_{\text{stablizer}}} \mathbf{Pr}\left[\frac{\Delta_{\text{bit}}(G_{g_i} - e)}{(1-\delta)(G_{g_i} + e)} < \frac{1}{3}\right] \mathbf{Pr}[E_{g_i} = e] \\
&\leq \sum_{e=0}^{\Delta_{\text{bit}}-1} \mathbf{Pr}\left[\frac{\Delta_{\text{bit}}(G_{g_i} - e)}{(1-\delta)(G_{g_i} + e)} < \frac{1}{3}\right] \mathbf{Pr}[E_{g_i} = e] + \sum_{e=\Delta_{\text{bit}}}^{\Delta_{\text{bit}}\Delta_{\text{stablizer}}} 1 \cdot \mathbf{Pr}[E_{g_i} = e] \\
&= \sum_{e=0}^{\Delta_{\text{bit}}-1} \mathbf{Pr}\left[G_{g_i} < \frac{(3\Delta_{\text{bit}}+1-\delta)e}{3\Delta_{\text{bit}}-1+\delta}\right] \mathbf{Pr}[E_{g_i} = e] + \sum_{e=\Delta_{\text{bit}}}^{\Delta_{\text{bit}}\Delta_{\text{stablizer}}} 1 \cdot \mathbf{Pr}[E_{g_i} = e].
\end{aligned}$$

So then, for a given e, we just need to find an upper bound for

$$\mathbf{Pr}\left[G_{g_i} < \frac{(3\Delta_{\text{bit}}+1-\delta)e}{3\Delta_{\text{bit}}-1+\delta}\right].$$

We can then use Chebyshev inequality to get an upper bound of

$$\min\left(\frac{\mathbf{Var}[G_{g_i} \mid E_{g_i} = e]}{\left[\mathbf{E}[G_{g_i} \mid E_{g_i} = e] - \frac{1}{3}\right]^2}, 1\right)$$

if $\mathbf{E}[G_{g_i}] > \frac{1}{3}$ and an upper bound of 1 otherwise.

Then, we need to related G_{g_i} to G'_{g_i} as our algorithm only know G'_{g_i}.

Lemma A.1. $\mathbf{E}[G_{g_i} \mid E_{g_i} = e] \geq \mathbf{E}[G'_{g_i} \mid E_{g_i} = e] \cdot \left(1 - \frac{\Delta_{\textit{stablizer}}-1}{N}\right)$

Proof. Fix $E_{g_i} = e$. Then, let $\alpha = G'_{g_i}$ and $\aleph = \{\, j \in [M] : S = 1 \,\}$. Note that $G_{g_i} = |\aleph|$ by definition of G_{g_i}. We then know that $\alpha \geq |\aleph|$ because α counts each stabilizer in $s \in \Gamma(\texttt{generator i})$ where $S_s = 1$ at least once. For $s \in \aleph$, let

$$O_s = |\, \{\, k : k \in \texttt{generator } i \wedge s \in \Gamma(\texttt{bit k}) \,\} \,| - 1.$$

In other words, O_s is the number of times a stabilizer in the neighborhood of a generator is “over-counted" in α. Then, $|\aleph| = \alpha - \sum_{s \in \aleph} O_s$ because we are subtracting the total number of “over-counted" stabilizers. Then, note that

$$\begin{aligned}
\mathbf{E}[O_s] &= \sum_{b \in \Gamma(s)} \mathbf{Pr}[b \in \texttt{generator i}] - 1 \\
&= 1 + \sum_{b \in \Gamma(s) \setminus t} \mathbf{Pr}[b \in \texttt{generator i}] - 1 && \text{(at least 1 } t \in \Gamma(s) \text{ must be in } \texttt{generator i}\text{)} \\
&= (\Delta_{\text{stablizer}} - 1)\frac{1}{N}
\end{aligned}$$

for some $s \in \aleph$ and $t \in \Gamma(s)$. So then,

$$\begin{aligned}
\mathbf{E}[|\aleph|] &= \mathbf{E}[\alpha] - \sum_{s \in \aleph} \mathbf{E}[O_s] \\
&\geq \mathbf{E}[\alpha] - \mathbf{E}[|\aleph|] \mathop{\mathbf{E}}_{s \in \aleph}[O_s] \\
&\geq \mathbf{E}[\alpha] - \mathbf{E}[\alpha] \mathop{\mathbf{E}}_{s \in \aleph}[O_s] \\
&\geq \mathbf{E}[\alpha]\left(1 - \frac{\Delta_{\text{stablizer}} - 1}{N}\right).
\end{aligned}$$

□

Lemma A.2. $\mathbf{E}[G'_{g_i}] \geq \mathbf{E}[G''_{g_i} \mid E = e]$

Proof. □

Lemma A.3. $\mathbf{E}[G'_{g_i} \mid E = e] \geq \mathbf{E}[G''_{g_i}]$

Proof. □

Lemma A.4. $\mathbf{Var}[G'_{g_i}] \geq \mathbf{Var}$

Proof. □