

Algorithmic Coding Theory - Amit Kumar Sinhababu

Scribed: Soham Chatterjee

sohamchatterjee999@gmail.com

Website: sohamch08.github.io

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1.1 Introduction

References for this topic are [Yek12]

Definition 1.1.1 (Locally Decodable Codes). A q -ary code $C : \mathbb{F}_q^k \rightarrow \mathbb{F}_q^N$ is said to be (r, δ, ϵ) -locally decodable if there exists a randomized decoding algorithm \mathcal{A} such that

1. For all $\bar{x} \in \mathbb{F}_q^k$, $i \in [k]$ and all vectors $\bar{y} \in \mathbb{F}_q^N$ such that $\Delta(C(\bar{x}), \bar{y}) \leq \delta$:

$$\Pr[\mathcal{A}^{\bar{y}}(i) = \bar{x}(i)] \geq 1 - \epsilon$$

where the probability is taken over the random coin tosses of the algorithm \mathcal{A}

2. \mathcal{A} makes at most r queries to \bar{y}

We would like to have LDCs that for a given message length k and alphabet size q have small values of r , N and ϵ and a large value of δ . The exact value of r is not very important provided that it is much smaller than k . Similarly the exact value of $\epsilon < \frac{1}{2}$ is not the important since one can easily amplify ϵ to be close to 0 by running the decoding procedure few times and taking a majority vote.

A locally decodable code allows to probabilistically decode any coordinate of a message by probing only few coordinates of its corrupted encoding. A stronger property that is desirable in certain application is that of local correctability allowing to efficiently recover not only coordinates of the message but also arbitrary coordinates of the encoding.

Definition 1.1.2 (Locally Correctable Codes). A q -ary code C in the space \mathbb{F}_q^N is (r, δ, ϵ) -locally decodable if there exists a randomized decoding algorithm \mathcal{A} such that

1. For all $\bar{c} \in C$, $i \in [N]$ and all vectors $\bar{y} \in \mathbb{F}_q^N$ such that $\Delta(\bar{c}, \bar{y}) \leq \delta$:

$$\Pr[\mathcal{A}^{\bar{y}}(i) = \bar{c}(i)] \geq 1 - \epsilon$$

where the probability is taken over the random coin tosses of the algorithm \mathcal{A}

2. \mathcal{A} makes at most r queries to \bar{y}

Lemma 1.1.1. *Let q be a prime power. Suppose $C \subseteq \mathbb{F}_q^N$ is a (r, δ, ϵ) -locally correctable code that is a linear subspace; then there exists a q -ary (r, δ, ϵ) -locally decodable code C' encoding messages of length $\dim C$ to codewords of length N*

Proof: Let $I \subseteq [N]$ be a set of $k := \dim C$ coordinates of C whose values uniquely determine an element of C . For $c \in C$ let $c|_I \in \mathbb{F}_q^k$ denote the restriction of c to coordinates of I . Given a message $x \in \mathbb{F}_q^k$ we define $C'(x)$ to be the unique element $c \in C$ such that $c|_I = x$. Now C' is a (r, δ, ϵ) -locally decodable code ■

1.2 Reed Muller Locally Decodable Codes

The key idea behind early locally decodable codes is that of polynomial interpolation. Local decodability is achieved through reliance on the rich structure of short local dependencies between such evaluations at multiple points. We consider three local corrector for RM codes of increasing level of sophistication.

1.2.1 Basic Decoding on Lines

To recover the value of a degree d polynomial $f \in \mathbb{F}_q[x_1, \dots, x_n]$ at a point $w \in \mathbb{F}_q^n$ it shoots a random affine line through w and then relies on the local dependency between the values of f at some $d + 1$ points along the line.

1.2.2 Improved Decoding on Lines

1.2.3 Decoding On Curves

We require d is substantially smaller than q . The corrector shoots a random parametric degree 2 curve through \bar{w} and then relies on the high redundancy among the values of F along the curve to recover the value of a degree d polynomial $F \in \mathbb{F}_q[x_1, \dots, x_n]$.

The advantage upon the decoder of (improved decoding) is that points on a random degree 2 curve constitute a two-dimensional sample from the underlying space.

Theorem 1.2.1. *Let $\sigma < 1$ be a positive real. Let n and d be positive integers. Let q be prime power such that $d \leq \sigma(q - 1) - 1$; then there exists a linear code of dimension $k = \binom{n+d}{d}$ in \mathbb{F}_q^N , $N = q^n$, that for all positive $\delta < \frac{1}{2} - \sigma$ is $(q - 1, \delta, O_{\sigma, \delta}(\frac{1}{q}))$ -locally correctable.*

Proof: Given a δ corrupted evaluation of a degree d polynomial F and a point $\bar{w} \in \mathbb{F}_q^n$ the corrector picks vectors $\bar{v}_1, \bar{v}_2 \in \mathbb{F}_q^n$ uniformly at random and considers a degree two curve

$$C = \{\bar{w} + \lambda \bar{v}_1 + \lambda^2 \bar{v}_2 \mid \lambda \in \mathbb{F}_q\}$$

through \bar{w} . The corrector tries to reconstruct a restriction of F to C which is a polynomial of degree up to $2d$.

The corrector queries coordinates of the evaluation vector corresponding to points $C(\lambda) = \bar{w} + \lambda \bar{v}_1 + \lambda^2 \bar{v}_2$, for all $\lambda \in \mathbb{F}_q^*$ to obtain values $\{e_\lambda\}$. It then recovers the unique univariate polynomial $h = F(\bar{w} + \lambda \bar{v}_1 + \lambda^2 \bar{v}_2)$, $\deg h \leq 2d$ such that $h(\lambda) = e_\lambda$ for all but at most $\left\lfloor \frac{(1-2\sigma)(q-1)}{2} \right\rfloor$ values of $\lambda \in \mathbb{F}_q^*$ and outputs $h(0)$ by Berlekamp-Welch Algorithm since

$$q - 1 - \frac{(1-2\sigma)(q-1)}{2} = (q-1) \left(1 - \frac{1-\sigma}{2}\right) = \sigma(q-1) > d$$

Now we will calculate the probability of number of corrupted queries is at most $\left\lfloor \frac{(1-2\sigma)(q-1)}{2} \right\rfloor$. For $\bar{a} \in \mathbb{F}_q^n$ and $\lambda \in \mathbb{F}_q^*$ consider the random variable x_λ^λ which is the indicator variable of the event $C(\lambda) = \bar{a}$. Let $E \subseteq \mathbb{F}_q^n$

such that $|E| \leq \delta N$ be the set of $\bar{a} \in \mathbb{F}_q^n$ such that the values of F at \bar{a} are corrupted. For every $\lambda \in \mathbb{F}_q^*$ consider a random variable

$$x^\lambda = \sum_{\bar{a} \in E} x_{\bar{a}}^\lambda$$

Note the variables $\{x^\lambda\}$. for all $\lambda \in \mathbb{F}_q^*$ are pairwise independent. For every $\lambda \in \mathbb{F}_q^*$ we have

$$\mathbb{E}[x^\lambda] \leq \delta \text{ and } \text{Var}[x^\lambda] = \mathbb{E}\left[\left(x^\lambda\right)^2\right] - \mathbb{E}[x^\lambda]^2 \leq \delta - \delta^2$$

Now consider the random variable $x = \sum_{\lambda \in \mathbb{F}_q^*} x^\lambda$. Since $\{x^\lambda\}$ are pairwise independent we have

$$\text{Var}[x] = \text{Var}\left[\sum_{\lambda \in \mathbb{F}_q^*} x^\lambda\right] = \sum_{\lambda \in \mathbb{F}_q^*} \text{Var}[x^\lambda]$$

Therefore we have

$$\mathbb{E}[x] = \sum_{\lambda \in \mathbb{F}_q^*} \mathbb{E}[x^\lambda] \leq (q-1)\delta \text{ and } \text{Var}[x] \leq (q-1)(\delta - \delta^2)$$

Therefore

$$\begin{aligned} \Pr\left[x \geq \left\lfloor \frac{(1-2\sigma)(q-1)}{2} \right\rfloor\right] &= \Pr\left[x - \mathbb{E}[x] \geq \left\lfloor \frac{(1-2\sigma)(q-1)}{2} \right\rfloor - \mathbb{E}[x]\right] \\ &\leq \Pr\left[|x - \mathbb{E}[x]| \geq \left\lfloor \frac{(1-2\sigma)(q-1)}{2} \right\rfloor - \delta(q-1)\right] \\ &\leq \Pr\left[|x - \mathbb{E}[x]| \geq \frac{(q-1)(1-2(\sigma+\delta))}{2}\right] \\ &\leq \frac{(q-1)(\delta - \delta^2)}{\left[\frac{(q-1)(1-2(\sigma+\delta))}{2}\right]^2} \quad [\text{By Theorem 3.1.2}] \\ &= \frac{4(\delta - \delta^2)}{(q-1)(1-2(\sigma+\delta))^2} = O_{\sigma,\delta}\left(\frac{1}{q}\right) \end{aligned}$$

Hence we probability $1 - O_{\sigma,\delta}\left(\frac{1}{q}\right)$ we can obtain the correct h and decode the value of F at \bar{w} . Therefore it is $\left(q-1, \delta, O_{\sigma,\delta}\left(\frac{1}{q}\right)\right)$ -locally correctable. ■

References for this topic are [KS^Y11], [Kop15]

Notation:

- For a vector $\vec{i} = \langle i_1, i_2, \dots, i_m \rangle$ of non-negative integers its **weight** denoted $wt(\vec{i}) := \sum_{j=1}^m i_j$
- $\mathbb{F}[\overline{X}] = \mathbb{F}[X_1, \dots, X_m]$
- For a vector of non-negative integers \vec{i} , $\overline{X}^{\vec{i}} := \prod_{j=1}^m X_j^{i_j}$

2.1 Hasse Derivative

Definition 2.1.1 ((Hasse) Derivative). For $P(\overline{X}) \in \mathbb{F}[\overline{X}]$ and non-negative vector \vec{i} , the \vec{i} th (Hasse) derivative of P denoted $P^{(\vec{i})}(\overline{X})$ is the coefficient of $\overline{Z}^{\vec{i}}$ in the polynomial $\tilde{P}(\overline{X}, \overline{Z}) \triangleq P(\overline{X} + \overline{Z}) \in \mathbb{F}[\overline{X}, \overline{Z}]$. Thus

$$P(\overline{X} + \overline{Z}) = \sum_{\vec{i}} P^{(\vec{i})}(\overline{X}) \overline{Z}^{\vec{i}}$$

2.1.1 Basic Properties of Hasse Derivatives

Proposition 2.1.1 ([HKT08], [Dvi+09]). Let $P(\overline{X}), Q(\overline{X}) \in \mathbb{F}[\overline{X}]$ and let \vec{i}, \vec{j} be vectors of nonnegative integers. Then:

1. $P^{(\vec{i})}(\overline{X}) + Q^{(\vec{i})}(\overline{X}) = (P + Q)^{(\vec{i})}(\overline{X})$
2. $(P \cdot Q)^{(\vec{i})}(\overline{X}) = \sum_{0 \leq \vec{e} \leq \vec{i}} P^{(\vec{e})}(\overline{X}) \cdot Q^{(\vec{i} - \vec{e})}(\overline{X})$
3. $\left(P^{(\vec{i})} \right)^{(\vec{j})}(\overline{X}) = \binom{\vec{i} + \vec{j}}{\vec{i}} P^{(\vec{i} + \vec{j})}(\overline{X})$

Proof:

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- We will expand $P(\bar{X} + \bar{Z} + \bar{W})$ in two ways.

$$P(\bar{X} + (\bar{Z} + \bar{W})) = \sum_{\bar{k}} P^{(\bar{k})}(\bar{X})(\bar{Z} + \bar{W})^{\bar{k}} = \sum_{\bar{k}} P^{(\bar{k})}(\bar{X}) \sum_{\bar{i} + \bar{j} = \bar{k}} \binom{\bar{k}}{\bar{i}} \bar{Z}^{\bar{j}} \bar{W}^{\bar{i}} = \sum_{\bar{i}, \bar{j}} P^{(\bar{i} + \bar{j})}(\bar{X}) \binom{\bar{i} + \bar{j}}{\bar{i}} \bar{Z}^{\bar{j}} \bar{W}^{\bar{i}}$$

$$P((\bar{X} + \bar{Z}) + \bar{W}) = \sum_{\bar{i}} P^{(\bar{i})}(\bar{X} + \bar{Z}) \bar{W}^{\bar{i}} = \sum_{\bar{i}} \sum_{\bar{j}} \left(P^{(\bar{i})} \right)^{(\bar{j})}(\bar{X}) \bar{Z}^{\bar{j}} \bar{W}^{\bar{i}}$$

Hence comparing the coefficients of $\bar{Z}^{\bar{j}} \bar{W}^{\bar{i}}$ we obtain $\left(P^{(\bar{i})} \right)^{(\bar{j})}(\bar{X}) = \binom{\bar{i} + \bar{j}}{\bar{i}} P^{(\bar{i} + \bar{j})}(\bar{X})$

■

2.2 Multiplicity

Now we will define the notion of the multiplicity of a polynomial.

Definition 2.2.1 (Multiplicity). For $P(\bar{X}) \in \mathbb{F}[\bar{X}]$ and $\bar{a} \in \mathbb{F}^m$ the multiplicity of P at $\bar{a} \in \mathbb{F}^m$ denoted $\text{mult}(P, \bar{a})$ is the largest integer M such that for every non-negative vector \bar{i} with $\text{wt}(\bar{i}) < M$ we have $P^{(\bar{i})}(\bar{a}) = 0$ (If M may be taken arbitrarily large we set $\text{mult}(P, \bar{a}) = \infty$)

Note that $\text{mult}(P, \bar{a}) \geq 0$ for all $\bar{a} \in \mathbb{F}^m$.

2.2.1 Basic Properties of Multiplicity

We now translate some of the properties of the Hasse derivative into properties of the multiplicities. We will discuss the properties of multiplicities from [Dvi+09]

Proposition 2.2.1. If $P(\bar{X}) \in \mathbb{F}[\bar{X}]$ and $\bar{a} \in \mathbb{F}^m$ are such that $\text{mult}(O, \bar{a}) = n$ then $\text{mult}(P^{(\bar{i})}, \bar{a}) \geq n - \text{wt}(\bar{i})$

Proof: By assumption, for any \bar{k} with $\text{wt}(\bar{k}) < n$, we have $P^{(\bar{k})}(\bar{a}) = 0$. Now take any \bar{j} such that $\text{wt}(\bar{j}) < n - \text{wt}(\bar{i})$. Using Theorem 2.1.1 (3) we have

$$\left(P^{(\bar{i})} \right)^{(\bar{j})}(\bar{a}) = \binom{\bar{i} + \bar{j}}{\bar{i}} P^{(\bar{i} + \bar{j})}(\bar{a})$$

Since $\text{wt}(\bar{i} + \bar{j}) = \text{wt}(\bar{i}) + \text{wt}(\bar{j}) < n$, hence $\left(P^{(\bar{i})} \right)^{(\bar{j})}(\bar{a}) = 0$. Thus $\text{mult}(P^{(\bar{i})}, \bar{a}) \geq n - \text{wt}(\bar{i})$ ■

We will now discuss the behavior of multiplicities under composition of polynomial tuples. Let $\bar{X} = (X_1, X_2, \dots, X_m)$ and $\bar{Y} = (Y_1, Y_2, \dots, Y_n)$ be formal variables. Let $P(\bar{X}) = (P_1(\bar{X}), \dots, P_k(\bar{X})) \in \mathbb{F}[\bar{X}]^k$ and also $Q(\bar{Y}) = (Q_1(\bar{Y}), \dots, Q_m(\bar{Y})) \in \mathbb{F}[\bar{Y}]^m$. We define the composition polynomial $P \circ Q(\bar{Y}) \in \mathbb{F}[\bar{Y}]^k$ to be the polynomial $P(Q_1(\bar{Y}), \dots, Q_m(\bar{Y}))$. In this situation we have the following proposition:

Proposition 2.2.2. Let $P(\bar{X}), Q(\bar{Y})$ be defined as above. Then for any $\bar{a} \in \mathbb{F}^n$

$$\text{mult}(P \circ Q, \bar{a}) \geq \text{mult}(P, Q(\bar{a})) \cdot \text{mult}(Q - Q(\bar{a}), \bar{a})$$

In particular, since $\text{mult}(Q - Q(\bar{a}), \bar{a}) \geq 1$, we have $\text{mult}(P \circ Q, \bar{a}) \geq \text{mult}(P, Q(\bar{a}))$

Proof: Let $m_1 = \text{mult}(P, Q(\bar{a}))$ and $m_2 = (Q - Q(\bar{a}), \bar{a})$. Clearly $m_2 > 0$. If $m_1 = 0$ the result is obvious. Now assume $m_1 > 0$ (so that $P(Q(\bar{a})) = 0$). Now

$$\begin{aligned}
P(Q(\bar{a} + \bar{Z})) &= P\left(Q(\bar{a}) + \sum_{\bar{i} \neq 0} Q^{(\bar{i})}(\bar{a}) \bar{Z}^{\bar{i}}\right) \\
&= P\left(Q(\bar{a}) + \sum_{\text{wt}(\bar{i}) \geq m_2} Q^{(\bar{i})}(\bar{a}) \bar{Z}^{\bar{i}}\right) && [\text{Since } \text{mult}(Q - Q(\bar{a}), \bar{a}) = m_2 > 0] \\
&= P(Q(\bar{a}) + h(\bar{Z})) && \left[\text{where } h(\bar{Z}) = \sum_{\text{wt}(\bar{i}) \geq m_2} Q^{(\bar{i})}(\bar{a}) \bar{Z}^{\bar{i}} \right] \\
&= P(Q(\bar{a})) + \sum_{\bar{j} \neq 0} P^{(\bar{j})}(Q(\bar{a})) h(\bar{Z})^{\bar{j}} \\
&= \sum_{\text{wt}(\bar{j}) \geq m_1} P^{(\bar{j})}(Q(\bar{a})) h(\bar{Z})^{\bar{j}} && [\text{since } \text{mult}(P, Q(\bar{a})) = m_1 > 0]
\end{aligned}$$

Since each monomial $\bar{Z}^{\bar{i}}$ appearing in h has $\text{wt}(\bar{i}) \geq m_2$ and each occurrence of $h(\bar{Z})$ in $P(Q(\bar{a} + \bar{Z}))$ is raised to the power \bar{j} with $\text{wt}(\bar{j}) \geq m_1$ we conclude that $P(Q(\bar{a} + \bar{Z}))$ is of the form $\sum_{\text{wt}(\bar{k}) \geq m_1 \cdot m_2} c_{\bar{k}} \bar{Z}^{\bar{k}}$. This shows that $(P \circ Q)^{(\bar{k})}(\bar{a}) = 0$ for each \bar{k} with $\text{wt}(\bar{k}) < m_1 \cdot m_2$. And hence we get the result. ■

Corollary 2.2.3. Let $P(\bar{X}) \in \mathbb{F}[\bar{X}]$. Let $\bar{a}, \bar{b} \in \mathbb{F}^m$. Let $P_{\bar{a}, \bar{b}}(T)$ be the polynomial $P(\bar{a} + T \cdot \bar{b}) \in \mathbb{F}[T]$. Then for any $t \in \mathbb{F}$,

$$\text{mult}(P_{\bar{a}, \bar{b}}, t) \geq \text{mult}(P, \bar{a} + t \cdot \bar{b})$$

Proof: Let $Q(T) = \bar{a} + T \cdot \bar{b} \in \mathbb{F}[T]^m$. Applying Proposition 2.2.2 and $Q(T)$ we get the desired claim. ■

2.2.2 Strengthening of the Schwartz-Zippel Lemma

Theorem 2.2.4 (Schwartz-Zippel Lemma). Let $P(\bar{X}) \in \mathbb{F}[\bar{X}]$ be a non-zero polynomial with degree d . Let S be a finite subset of \mathbb{F} with at least d elements in it. If we take $\bar{a} \in S^m$ independently and uniformly at random then

$$\Pr_{\bar{a} \in S^m} [P(\bar{a}) = 0] \leq \frac{d}{|S|}$$

We will prove the strengthening of this lemma using *mult*.

Theorem 2.2.5 ([Dvi+09]). Let $P(\bar{X}) \in \mathbb{F}[\bar{X}]$ be a

Now we need a bound on the number of points that a low-degree polynomial can vanish on with high multiplicity. We state a basic bound on the total number of zeroes (counting multiplicity) that a polynomial can have on a product set S^m .

Theorem 2.2.6 ([Dvi+09]). Let $P(\bar{X}) \in \mathbb{F}[\bar{X}]$ be a nonzero polynomial of total degree at most d . Then for any finite $S \subseteq \mathbb{F}$,

$$\sum_{\bar{a} \in S^m} \text{mult}(P, \bar{a}) \leq d \cdot |S|^{m-1}$$

In particular, for any integer $s > 0$

$$\Pr_{\bar{a} \in S^m} [\text{mult}(P, \bar{a}) \geq s] \leq \frac{d}{s|S|}$$

Proof: We will prove this by induction on m . For the base case when $m = 1$ we will first show that if $\text{mult}(P, a) = k$ then $(X - a)^k$ divides $P(X)$. To see this, note that by definition of multiplicity, we have that $P(a + Z) = \sum_i P^{(i)}(a)Z^i$ and $P^{(i)}(a) = 0$ for all $i < k$ we conclude that Z^k divides $P(a + Z)$. And thus $(X - a)^k$ divides $P(X)$. It follows that $\sum_{a \in S} \text{mult}(P, a)$ is at most the degree of P .

Now suppose $m > 1$. Let

$$P(\overline{X}) = \sum_{j=0}^t P_j(X_1, \dots, X_{m-1})X_m^j$$

where $0 \leq t \leq d$, $P_t(X_1, \dots, X_{m-1}) \neq 0$ and $\deg(P_j) \leq d - j$. For any $a_1, \dots, a_{n-1} \in S$ let $m_{a_1, \dots, a_{n-1}} = \text{mult}(P_t, (a_1, \dots, a_{n-1}))$. We will show that

$$\sum_{a_n \in S} \text{mult}(P, \overline{a}) \leq m_{a_1, \dots, a_{n-1}} \cdot |S| + t$$

■

Corollary 2.2.7. Let $P(\overline{X}) \in \mathbb{F}_q[\overline{X}]$ be a polynomial of total degree at most d . If

$$\sum_{\overline{a} \in \mathbb{F}_q^m} \text{mult}(P, \overline{a}) > d \cdot q^{m-1}$$

then $P(\overline{X}) = 0$

3.1 Probabilistic Inequalities

Theorem 3.1.1 (Markov's Inequality). *For any random variable X and $a > 0$*

$$\Pr[X \geq a] \leq \frac{\mathbb{E}[X]}{a}$$

Theorem 3.1.2 (Chebyshev's Inequality). *For a random variable with variance σ , and expected value μ with $a \geq 0$*

$$\Pr[|X - \mu| \geq a] \leq \frac{\text{Var}[X]}{a^2}$$

CHAPTER 4

References

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