

Deterministic List Decoding of Reed Solomon Codes

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Introduction

Introduction to Coding Theory

An Error-Correcting code or simply code, $C \subseteq \Sigma^n$ for some fixed finite set of alphabets Σ . You have a set of messages M and encode them to C .

- Blocklength: n
- Dimension of Code: $k = \log |C|$
- Rate of Code: $R(C) = \frac{k}{n \log |\Sigma|}$

The distance between two codewords $c_1 \neq c_2 \in C$ is the hamming distance between them, $\Delta(c_1, c_2)$.

- Distance of Code: $\Delta(C) = \min_{c_1 \neq c_2 \in C} \Delta(c_1, c_2)$
- Relative Distance: $\delta(C) = \frac{\Delta(C)}{n}$

Introduction to Coding Theory

Goal: Construct codes such that

- Codewords to be “far apart” from each other \implies High Distance
- Redundancy to be low \implies High Rate

Relation between Rate and Distance

For any code C

$$k \leq n - d + 1$$

Asymptotically $R + \delta \leq 1$ as n becomes very large.

Codes achieving this bound are called **Maximum Distance Separable (MDS)** codes.

- Reed Solomon Codes are MDS codes.

Unique Decoding

Let $\Delta(C) = d$. For any $v \in \Sigma^n$ there is at most one codeword $c \in C$ such that $\Delta(v, c) \leq (d - 1)/2$.

Unique Decoding Problem: Given a received word $v \in \Sigma^n$, find the unique codeword $c \in C$ such that $\Delta(v, c) < d/2$ if it exists.

- If we go more than $d/2$ distance, multiple codewords may lie in the radius of hamming ball.

List Decoding

Definition ((ρ, L) -List Decodable)

C is called (ρ, L) -list decodable if for every $v \in \Sigma^n$,

$$|\{c \in C \mid \Delta(c, v) \leq \rho n\}| \leq L$$

We denote the list for v by $L(v)$.

List Decoding Problem: Given a received word $v \in \Sigma^n$

- Combinatorial List Decoding: Prove if $|L(v)| = \text{poly}(n)$
- Algorithmic List Decoding: Find all codewords in $L(v)$ in $\text{poly}(n)$ time.

Theorem (Johnson Bound)

For a code C with rate R the list size remains polynomial in n for $\rho \leq 1 - \sqrt{R}$

We will talk in terms of agreement instead of errors

$$1 - t \text{ fraction of errors} \implies t \text{ fraction of agreement}$$

Reed Solomon Codes

Reed Solomon Codes

Fix the following

- Alphabets: finite field \mathbb{F}_q of size q
- Subset $S \subseteq \mathbb{F}_q$, $|S| = n$. $S = \{\alpha_1, \alpha_2, \dots, \alpha_n\}$

$RS[n, k]_q$ encodes every message polynomial $f(X) \in \mathbb{F}_q[X]$ with $\deg(f) < k$ to

$$(f(\alpha_1), f(\alpha_2), \dots, f(\alpha_n))$$

- Rate $R = \frac{k}{n}$
- Distance $d = n - k + 1$

Reed Solomon Decoding History

Want: unique and list decoding in $\text{poly}(n, \log |\mathbb{F}_q|)$ time.

Deterministic unique decoding upto $(n - k + 1)/2$ errors is possible using **Berlekamp-Welch** algorithm in $\text{poly}(n, \log q)$ time.

Johnson Bound gives polynomial list size for more than $\sqrt{n(k-1)}$ agreement

- **Sudan (1997)** gave randomized list decoding for more than $\sqrt{2n(k-1)}$ agreement in $\text{poly}(n, \log q)$ time.
- **Guruswami-Sudan (1999)** improved it to more than $\sqrt{n(k-1)}$ agreement using randomization in $\text{poly}(n, \log q)$ time.

Their Deterministic variant has polynomial dependence on field characteristic

Framework of Sudan and Guruswami-Sudan

Let $w = \{(\alpha_j, \beta_j)\}_{j \in [n]}$ denote the received word. Both algorithms share the same two-step structure:

- **Interpolation:** Find a nonzero polynomial $Q(X, Y) \in \mathbb{F}_q[X, Y]$ of $(1, k-1)$ -degree at most D that vanishes at each (α_j, β_j) with multiplicity at least m .
- **Factorization:** Factorize $Q(X, Y)$ over \mathbb{F}_q ; for each factor of the form $Y - f(X)$, output f if $\deg f < k$ and f agrees with w on at least t evaluations.

Sudan	Guruswami-Sudan
$m = 1, \quad D, t \approx \sqrt{2n(k-1)}$	$m = \sqrt{n(k-1)}, \quad D \approx m\sqrt{n(k-1)},$ $t = \sqrt{n(k-1)}$

Factorization Barrier

Sudan and Guruswami–Sudan algorithms rely on the factorization of bivariate polynomials over finite fields

- Barlekamp, Cantor-Zassenhaus, LLL, Kaltofen runs in polynomial time but randomized.
- Their deterministic variants have polynomial dependence on field characteristic.

Large field characteristic (super polynomial in n) is a problem.

Want: Do the factorization step deterministically in $\text{poly}(n, \log q)$ time.

Derandomization of Sudan

Newton Iteration

Let $P(X, Y) \in \mathbb{F}_q[X, Y]$ and $f(X) \in \mathbb{F}_q[X]$ such that

- $P(X, f(X)) \equiv 0$
- $\alpha \in \mathbb{F}_q$ such that $\frac{\partial}{\partial Y} P(\alpha, f(\alpha)) \neq 0$.
- $Y_t = f(X) \pmod{X^t}$ for all $t \in \mathbb{N}$

Newton Iteration gives an efficient way to compute Y_{t+1} from Y_t as follows:

$$Y_{t+1} = Y_t - \frac{P(X, Y_t)}{\partial_Y P(X, Y_t)}$$

Sudan Derandomization

Let f is in the list. And let $j \in [n]$ such that $f(\alpha_j) = \beta_j$. Suppose Q is the polynomial from interpolation step.

If $\partial_Y Q(\alpha_j, f(\alpha_j)) \neq 0$: Then Newton Iteration from Y_0 till Y_k gives f .

Else $\partial_Y Q(\alpha_j, f(\alpha_j)) = 0$ for all j in agreement.

Observe: $\partial_Y(Q(X, f(X)))$ has more than $\sqrt{2n(k-1)}$ roots but degree at most $\sqrt{2n(k-1)}$. Implying $\partial_Y(Q(X, f(X))) \equiv 0$

So recurse on $\partial_Y(Q(X, f(X)))$.

Sudan Derandomization

Algorithm:

1. Check for each $j \in [n]$ if $\partial_Y Q(\alpha_j, \beta_j) \neq 0$. If yes, do Newton Iteration from there.
2. Else compute $\partial_Y(Q(X, Y))$ and continue from step 1 with $\partial_Y Q(X, Y)$ instead of Q .

Theorem

There is a deterministic algorithm that, for every finite field \mathbb{F} and parameters $n, k \in \mathbb{N}$ runs in time $\text{poly}(n, \log |\mathbb{F}|)$ list decodes Reed Solomon code $RS[n, k]$ from agreement more than $\sqrt{2n(k-1)}$.

Derandomization of Guruswami-Sudan

Local Splitting

Let $P(X, Y) \in \mathbb{F}_q[X, Y]$ with no-pure X -factors. Let $(\alpha, \beta) \in \mathbb{F}_q^2$ any point.

Suppose we are given the factorization $P = \prod_{i=1}^s P_i$ into irreducibles (with multiplicity)

Eg: $P(X, Y) = (Y^2 + X)(Y^2 + X + 1)^2$ then

$$P_1 = Y^2 + X, \quad P_2 = Y^2 + X + 1, \quad P_3 = Y^2 + X + 1$$

We partition $[s]$ into four sets which defines four types of factors at (α, β) :

$$A(\alpha, \beta), \quad B(\alpha, \beta), \quad C(\alpha, \beta), \quad D(\alpha, \beta)$$

Local Splitting

Let $P(X, Y) = (Y^2 + X + 1)(Y^2 + X)(Y^2 + X^2 + Y)(XY + 1)$ and $(\alpha, \beta) = (0, 0)$

- $A(\alpha, \beta) = \{i \in [s] \mid P_i(\alpha, \beta) \neq 0, \deg(P_i(\alpha, Y)) \geq 1\}$
So $Y^2 + X + 1 \in A(0, 0)$
- $B(\alpha, \beta) = \{i \in [s] \mid P_i(\alpha, Y) = \gamma(Y - \beta)^m, m \geq 1, \gamma \neq 0\}$
So $Y^2 + X \in B(0, 0)$
- $C(\alpha, \beta) = \{i \in [s] \mid P_i(\alpha, Y) = (Y - \beta)^m \hat{P}_i(Y), m \geq 1, \hat{P}_i(\beta) \neq 0, \deg \hat{P}_i \geq 1\}$
So $Y^2 + X^2 + Y \in C(0, 0)$
- $D(\alpha, \beta) = \{i \in [s] \mid P_i(\alpha, \beta) \neq 0, \deg(P_i(\alpha, Y)) = 0\}$
So $XY + 1 \in D(0, 0)$

I will use A, B, C, D to denote these. Define $P_A = \prod_{i \in A} P_i$ and similarly P_B, P_C, P_D .

Observe: If P is monic in Y then D is empty.

A Nice Observation

$w = \{(\alpha_j, \beta_j)\}_{j \in [n]}$ denote the received word.

Q is the polynomial from Interpolation step of Guruswami-Sudan algorithm. Let f is in the list.

For any $j \in [n]$:

If $f(\alpha_j) = \beta_j$: Then $Y - f(X) \mid P_B$

If $f(\alpha_j) \neq \beta_j$: Then $Y - f(X) \mid P_A$

Derandomization

Remark

We will assume Q is monic in Y and has no pure X -factors.

If only we had: An efficient $\text{poly}(n, \log q)$ time algorithm `SPLIT` to find P_A, P_B from $P, (\alpha, \beta)$ then:

Algorithm:

1. $S \leftarrow \{Q\}$
2. Choose $j \in [n]$ and for all $g \in S$ compute $(g_A, g_B) = \text{SPLIT}(g, (\alpha_j, \beta_j))$
3. Remove g from S and put g_A, g_B in S .
4. Continue from step 2 till S stabilizes.
5. Do some interpolations to recover list

Recover List from Stable Set

Observe: If f is in the list there is one factor $g \in S$, $Y - f(X) \mid g$.

Lemma

For all $j \in [n]$,

$$g(\alpha_j, \beta_j) = 0 \iff f(\alpha_j) = \beta_j$$

So go over all $g \in S$, find $j \in [n]$ such that $g(\alpha_j, \beta_j) = 0$, do interpolation to find appropriate f .

But stabilization can take long time !!

Simple potential function:

$$\Phi(S) = \sum_{i=1}^{\deg_Y(Q)} (i-1) \times \#(\text{polynomials with } Y\text{-deg} = i \text{ in } S)$$

You will notice $\Phi(S)$ decreases by at least 1 in each update of S .

Finally

Final Algorithm:

1. $S \leftarrow \{Q\}$
2. Choose $j \in [n]$ and for all $g \in S$ compute $(g_A, g_B) = \text{SPLIT}(g, (\alpha_j, \beta_j))$
3. Remove g from S and put g_A, g_B in S .
4. Continue from step 2 till S stabilizes.
5. Go over all $g \in S$ and do interpolation on the set $\{j \in [n] \mid g(\alpha_j, \beta_j) = 0\}$ and recover list

Theorem

There is a deterministic algorithm that, for every finite field \mathbb{F} and parameters $n, k \in \mathbb{N}$ runs in time $\text{poly}(n, \log |\mathbb{F}|)$ list decodes Reed Solomon code $RS[n, k]$ from agreement more than $\sqrt{n(k-1)}$.

Splitting Algorithm

Hensel Lifting

Let $P(X, Y) \in \mathbb{F}_q[X, Y]$ and P is monic in Y . Let $g, h, a, b \in \mathbb{F}_q[X, Y]$ such that

$$P \equiv gh \bmod (X - \alpha)^m \quad ag + bh \equiv 1 \bmod (X - \alpha)^m$$

Then there exists unique $g', h', a', b' \in \mathbb{F}_q[X, Y]$ such that

1. $P \equiv g' h' \bmod (X - \alpha)^{2m}$
2. $g' \equiv g \bmod (X - \alpha)^m, h' \equiv h \bmod (X - \alpha)^m$, called lifts
3. $a' g' + b' h' \equiv 1 \bmod (X - \alpha)^{2m}$

You can compute g', h', a', b' in $\text{poly}(\deg P, m, \log q)$ field operations

Remark

General version: Non-monic [Sinhbabu-Thierauf, 2021], Sudan's notes.

We gave degree bounds for multiple iteration of general Hensel Lifting

Algorithm: Lifting

$P(X, Y) \in \mathbb{F}_q[X, Y]$, monic in Y with no pure X -factors and point (α, β) .

We factorize:

$$P(\alpha, Y) = \underbrace{(Y - \beta)^m}_{g_0} \cdot \underbrace{\hat{P}(Y)}_{h_0}, \quad \hat{P}(\beta) \neq 0$$

If $(Y - \beta)^m = P(\alpha, Y)$ then $P = P_A$

If $\hat{P}(Y) = P(\alpha, Y)$ then $P = P_B$

Otherwise:

Use Hensel Lifting $t = 2 \log(\deg_Y P)$ times to get g_t, h_t such that

$$P \equiv g_t h_t \bmod (X - \alpha)^{2^t}, \quad g_t \equiv g_0 \bmod (X - \alpha), \quad h_t \equiv h_0 \bmod (X - \alpha)$$

Algorithm: Recursive Step

g_t, h_t may not be actual factors of P as we are viewing modulo $(X - \alpha)^{2^t}$.

Observe: Actual factor of g', h' such that $g_t = g' \cdot h'', h' = h'' \cdot h_t$.

Need to solve linear systems of the form:

$$F \equiv E \cdot h_t \bmod (X - \alpha)^{2^t}, \quad V \equiv U \cdot g_t \bmod (X - \alpha)^{2^t}$$

$$\deg_Y(F, V) \leq \deg_Y(P) - 1, \deg_X(F, V) \leq \deg_X(P).$$

Observe: Both F, V have factors of P but not exactly factor of P .

So we take $\gcd P_1 = \gcd(P, F), P_2 = \gcd(P, V)$

Recurse on $P_1, P/P_1$ (or $P_2, P/P_2$). Then combine them to get P_A, P_B .

Final Theorem

Lemma

*If the algorithm passes initial checks and has no solution of linear systems.
Then $P = P_C$.*

Here we mention the full version of the theorem we proved:

Theorem

*For every bivariate polynomial $P(X, Y) \in \mathbb{F}_q[X, Y]$ and point $(\alpha, \beta) \in \mathbb{F}_q^2$
the above algorithm outputs (P_1, P_2) such that $P_1 = P_A \cdot R_1$ and $P_2 = P_B \cdot R_2$
where $R_1 R_2 \mid P_D$.*

Open Problems

- Derandomize Sudan and Guruswami-Sudan in near linear time.
- What about beyond Johnson bound list decoding of Reed Solomon Codes?

Ben-Sasson, Kopparty, Radhakrishnan (2006) showed us we have no hope for low rate regime. But high/constant rate we have hope

- For beyond Johnson Bound even finding one element of the list is open.
- List decode Folded Reed Solomon Codes and Univariate Multiplicity Codes deterministically upto list decoding capacity in $\text{poly}(1/\epsilon)\tilde{O}(n)$ time.

Thank You