


Worst-Case to Average Case Reductions for the Distance to a Code

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Abstract

Algebraic proof systems reduce computational problems to problems about estimating the distance of a sequence of functions $\vec{u} = (u_1, \dots, u_k)$, given as oracles, from a linear error correcting code V . The soundness of such systems relies on methods that act “locally” on \vec{u} and map it to a single function u^* that is, roughly, as far from V as are u_1, \dots, u_k .

Motivated by these applications to efficient proof systems, we study a natural worst-case to average-case reduction of distance for linear spaces, and show several general cases in which the following statement holds: If some member of a linear space $U = \text{span}(u_1, \dots, u_k)$ is δ -far from (all elements) of V in relative Hamming distance, then nearly all elements of U are $(1 - \epsilon)\delta$ -far from V ; the value of ϵ depends only on the distance of the code V and approaches 0 as that distance approaches 1. Our results improve on the previous state-of-the-art which showed that nearly all elements of U are $\frac{1}{2}\delta$ -far from V [Rothblum, Vadhan and Wigderson, STOC 2013].

When V is a Reed-Solomon (RS) code, as is often the case for algebraic proof systems, we show how to *boost* distance via a new “local” transformation that may be useful elsewhere. Relying on the affine-invariance of V , we map a vector u to a random linear combination of affine transformations of u , and show this process amplifies distance from V . Assuming V is an RS code with sufficiently large distance, this amplification process converts a function u that is somewhat far from V to one that is $(1 - \epsilon)$ -far from V ; as above, ϵ depends only on the distance of V and approaches 0 as the distance of V approaches 1.

We give two concrete application of these techniques. First, we revisit the axis-parallel low-degree test for bivariate polynomials of [Polischuk-Spielman, STOC 1994] and prove a “list-decoding” type result for it, when the degree of one axis is extremely small. This result is similar to the recent list-decoding-regime result of [Chiesa, Manohar and Shinkar, RANDOM 2017] but is proved using different techniques, and allows the degree in one axis to be arbitrarily large. Second, we improve the soundness analysis of the recent RS proximity testing protocol of [Ben-Sasson et al., ICALP 2018] and extend it to the “list-decoding” regime, bringing it closer to the Johnson bound.

2012 ACM Subject Classification Theory of computation → Error-correcting codes

Keywords and phrases Proximity testing, Reed-Solomon codes, algebraic coding complexity

¹ Supported by the European Research Council under POC grant OMIP – DLV-693423 and Israel Science Foundation grant 1501/14.

² Research supported in part by NSF grants CCF-1253886 and CCF-1540634.

³ Research supported in part by NSF grants CCF-1350572 and CCF-1540634.

Digital Object Identifier 10.4230/LIPIcs.CCC.2018.24

Funding Work supported by the USA–Israel binational science fund, grant # 2014359

1 Introduction

Proof systems that involve *interaction* between a *randomized* verifier and a prover have revolutionized computational complexity and cryptography [7, 14]. A question of paramount importance here is *soundness* – the minimal probability of the verifier rejecting a falsity. Transformations that maintain or increase soundness, while improving other aspects of the proof system (like proof length, or query complexity), are few and hard to obtain. Here, we study certain soundness-preserving techniques for the special case of *linear spaces*, improving on the prior state-of-the-art which was due to Rothblum, Vadhan and Wigderson [19]; see Section 1.2. Then, in Section 1.4, we introduce a soundness-amplifying technique for the special case of Reed-Solomon codes; these codes are used in constructions of efficient proof systems. Before presenting the results we explain their relevance to the general study of proof systems.

1.1 Motivation – improving concrete soundness and communication complexity of interactive protocols

Arithmetization is a technique that was introduced to the construction of interactive proof (IP) systems by [17], and later applied to other systems including multi-prover interactive proof (MIP) [6], probabilistically checkable proof (PCP) [5, 3, 2] and zero knowledge (ZK) systems [14], to name a few notable examples. Arithmetization refers to a family of *reductions* from languages (like 3SAT) to promise problems involving *algebraic codes* like Reed-Solomon (RS), Reed-Muller (RM), or their generalization to algebraic geometry (AG) codes; all are, in particular, *linear* codes.

An arithmetization reduction maps an instance x (like a 3SAT formula) to a sequence of algebraic codes V_1, \dots, V_k , along with a set of “local” constraints, meaning that each constraint depends only on a small number of entries from k purported codewords. The reduction implies that $x \in L$ if and only if there exists a sequence $\vec{u} = (u_1, \dots, u_k) \in V_1 \times \dots \times V_k$ that satisfies all local constraints⁴. The locality of the constraints, along with the distance property of the codes V_1, \dots, V_k also implies that when $x \notin L$, *every* sequence \vec{u} falsifies a large fraction of local constraints, as long as each member u_i of the sequence is *sufficiently close* to the code V_i in relative Hamming distance. Therefore, a major problem in the construction of such proof systems is to build protocols that efficiently ensure each u_i is in close proximity to V_i , and reject with non-negligible probability $s = s(\delta)$ a purported codeword u_i that is δ -far in relative Hamming distance from V_i . This problem is known as *proximity testing*; the study of the reliance of the soundness parameter s on the query complexity q and proximity parameter δ is referred to as *soundness analysis*.

Suffice it to say that protocols that solve the proximity testing problem are often a bottleneck in the construction of efficient proof systems, and the quality of their soundness analysis determines concrete efficiency and applicability (see, e.g., [1, 8] for recent instances). Therefore, it is desirable to construct transformations that minimize the number of proximity

⁴ The exact nature of these constraints is not relevant to our study here. The interested reader is referred, e.g., to [16, Section 3.1] and [11, Section 5] for examples and more information.

testing problems that are needed to be addressed by a proof system, and boost and maintain the distance of \vec{u} from $V_1 \times \dots \times V_k$ when $x \notin L$.

Certain proof systems use several instances of the same proximity problem, i.e., $V_1 = \dots = V_k = V$ for a single linear code V . In this case, a natural optimization arises: instead of having the prover and verifier interact to solve k independent proximity problem, let the verifier sample $r_1, \dots, r_k \in \mathbb{F}$, send them to the prover, and then interact to solve the *single* proximity problem that refers to $\sum_i r_i u_i$. The cost of an extra round of interaction (and extra randomness) are often well-worth the benefit of reducing the number of proximity testing problems. The linearity of C implies that this transformation does not harm (perfect) completeness, because when $\vec{u} \in V$ then $\Pr[(\sum r_i u_i) \in V] = 1$.

The more interesting question, discussed next, is to understand what happens to the “typical” distance of $\sum r_i u_i$ as a function of the maximal distance, defined as $\delta_{\max} = \max_i \Delta(u_i, V)$.

1.2 Soundness transference results for linear spaces and error correcting codes

Our question is a special case of the “worst-case to average-case” problem: Suppose that a member u^* of a linear space $U \subseteq \mathbb{F}^n$ is δ_{\max} -far in relative Hamming distance from all members of another linear space $V \subseteq \mathbb{F}^n$ (this is the “worst-case” assumption), what can be said about the *median*⁵ distance δ_{med} from V , where this median is computed among the members of U ? We address this question first for the case of V be a general space, then for V being an error correcting code.

1.2.1 General spaces

The basic question above was first raised by Rothblum, Vadhan and Wigderson, as part of their construction of efficient interactive proofs of proximity (IPPs) [19]. They also showed that nearly all members of U – all but a $\frac{1}{|\mathbb{F}|-1}$ -fraction of them – are $\delta/2$ -far from V (Lemma 4). Thus, $\delta_{\text{med}} \geq \delta_{\max}/2$. On the other hand, $\delta_{\max} \geq \delta_{\text{med}}$ for certain spaces U (including all 1-dimensional ones). We are interested in closing the gap between these two bounds.

Our first result (Theorem 7) looks at δ_{med} as a function of δ_{\max} and says

$$\delta_{\text{med}}(\delta_{\max}) \geq 1 - \sqrt{1 - \delta_{\max}} - o(1)$$

Here and henceforth, $o(1)$ denotes negligible terms that approach 0 as $|\mathbb{F}| \rightarrow \infty$. In words, the median distance scales roughly like the *Johnson list-decoding function* of δ_{\max} , denoted $J(\delta_{\max})$, where $J(x) \triangleq 1 - \sqrt{1 - x}$. Thus, the median distance δ_{med} is strictly greater than $\delta_{\max}/2$ for all $\delta_{\max} > 0$, and approaches 1 as δ_{\max} approaches 1; the prior state-of-the-art approached $1/2$ in this case. For small values of δ_{\max} , our bound approaches $\delta_{\max}/2$, as in prior works, but for special (and natural) cases we obtain better bounds on δ_{med} , even when it is arbitrarily small, as discussed next.

⁵ All our results hold with high probability, i.e., with respect to the average and 99.9th percentile but we stick to using “median” for simplicity.

1.2.2 Linear error correcting codes

Most of the applications to interactive proof systems use a space V that is an *error correcting code*, i.e., the members of V are pair-wise far. Letting $\Delta(V)$ denote the relative distance of V , our second result (Theorem 9) states

$$\forall \delta_{\max} \leq J(J(\Delta(V)) - o(1), \quad \delta_{\text{med}} \geq \delta_{\max} - o(1).$$

In simple words, $\delta_{\text{med}} \approx \delta_{\max}$ for sufficiently small values of δ_{\max} , where “sufficiently small” depends on $\Delta(V)$ and approaches 1 as $\Delta(V) \rightarrow 1$. Combining Theorems 7 and 9, one sees that for any $\epsilon > 0$ there exists a code-distance parameter δ_ϵ , such that for every V with $\Delta(V) > \delta_\epsilon$ and all spaces U , we have $\delta_{\text{med}} \geq (1 - \epsilon)\delta_{\max}$.

1.3 Applications to low-degree testing

We now present two different applications of our results. First, we extend the soundness analysis of the ubiquitous bivariate low-degree test of Polischuck and Spielman to the high-error regime for polynomials that have constant degree in one variable. Then we improve the soundness bounds on the recently suggested “fast RS interactive oracle proof of proximity” (FRI) protocol to beyond the unique-decoding radius.

1.3.1 High error bivariate testing

The bivariate axis-parallel test theorem of Polischuck and Spielman [18] is a fundamental component in many efficient PCP constructions. Roughly, the theorem says that if a function $f : \mathbb{F} \times \mathbb{F}$ has the property that its restriction to *most* columns is *very close* to a degree d_Y polynomial, and the restriction to *most* rows is a function that is *very close* to a degree d_X polynomial, then f is *very close* to being the evaluation of a bivariate polynomial of degree d_X in X and degree d_Y in Y .

As stated there, the result works for degrees d_X, d_Y as large as $\approx |\mathbb{F}|/2$ but requires the columns and rows to have *large agreement* with univariate low-degree polynomials, and this setting is known as the *low error regime*. An intriguing question is whether a similar result holds in the high-error regime, when only a non-trivial fraction of rows/columns exhibit non-trivial agreement with degree d polynomials.

This question has been given a positive answer by Arora and Safra for a richer class of tests that includes the restriction of f to all lines (not just axis-parallel ones), and when $d < |\mathbb{F}|^{1/3}$ [4]. Recently, Chiesa, Manohar and Shinkar have proven the high-error case of the axis parallel test for small degree, i.e., when both d_X and d_Y are less than $\log |\mathbb{F}|$ [13].

As the first application of our results, we improve on [18] and present a high-error analysis of the axis-parallel test. Our result, stated in Theorem 14 works when one of the degrees is a constant ($d_X = O(1)$), but the other can be arbitrarily large $d_Y = \Omega(|\mathbb{F}|)$. Thus, our result is incomparable to that of [13], because of the different requirements on d_X, d_Y ; the proof techniques are also quite different.

1.3.2 Improved soundness analysis of the Fast Reed-Solomon interactive oracle proof of proximity (IOPP)

The *fast RS IOPP* (FRI) protocol [9] is an interactive oracle proof of proximity (IOPP) for the *RS proximity testing* (RPT) problem (cf. [12, 10] for a definition and discussion of the IOPP model). For RS-codes of message length N over a field \mathbb{F} , prover arithmetic

complexity is $O(N)$ and verifier arithmetic complexity for each test⁶ is $O(\log N)$; this also bounds the query complexity of a single test. The efficiency of the FRI protocol is important for proof systems realized in code, like the recent zero knowledge proof system of [8], called a “zk-STARK” there.

The soundness of a proximity testing protocol is described by a *soundness function* $s(\cdot)$ that takes as input a *proximity parameter* δ , and outputs the minimum rejection probability of the verifier, where this minimum is taken over all words that are δ -far from the code. In the case of FRI soundness for a single test, an upper bound $s(\delta) \leq \delta$ is easy to establish. The analysis in [9] showed a nearly matching lower bound for *sufficiently small* values of δ . In particular, the bound obtained there gives

$$s(\delta) \geq \min\{\delta, \delta_0\} - o(1) \tag{1}$$

where δ_0 is a *soundness threshold* constant that depends on the code rate ρ as follows $\delta_0 \approx \frac{1-3\rho}{4}$ (see red line in Figure 1). For codes of rate $\geq 1/3$ this bound is meaningless, and even when $\rho \rightarrow 0$ it holds that $\delta_0 \rightarrow 1/4$; this rather low soundness means that many tests must be applied in order to reach a target soundness error; for soundness error $2^{-\lambda}$ and maximal proximity parameter $1 - \rho$, the number of tests must still be greater than $\frac{\lambda}{-\log_2 \frac{3}{4}} \approx 2.4 \cdot \lambda$.

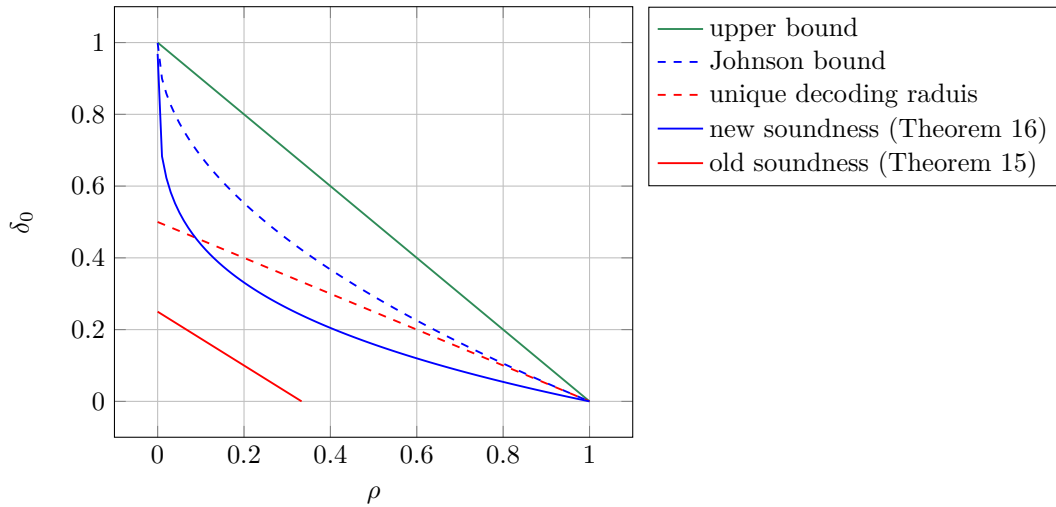
Using the results described in Sections 1.2.1 and 4.2 we improve on this state of affairs, and show that FRI soundness (for a single test) behaves as in Equation (1) but for a larger value of δ_0 , namely, $\delta_0 \approx 1 - \sqrt[4]{\rho}$ (see blue line in Figure 1). Consequently, to reach soundness error $2^{-\lambda}$ as before, the number of tests is reduced to $\approx \frac{4\lambda}{-\log \rho}$ which is always smaller than $2.4 \cdot \lambda$ and approaches 0 as $\rho \rightarrow 0$. We end by pointing out that [9] conjecture that the trivial soundness upper bound (green line in Figure 1) is nearly tight, i.e., that $s(\delta) \approx \delta$ for all values of δ . Reducing further the gap between soundness upper bounds (green line) and lower bounds (blue line) remains an interesting open problem that is relevant to realized proof systems like the zk-STARK of [8].

1.4 Soundness amplification for Reed-Solomon codes

So far we tried to minimize the loss in distance incurred by sampling an element of U . Next, we suggest a way to boost distance via a family of “locally-computable” transformations acting on a *single* purported codeword u . A *q*-*locally computable transformation* is a mapping $M : \mathbb{F}^n \rightarrow \mathbb{F}^n$ for which the *i*th entry of $M(u)$ can be computed by querying at most *q* entries of u . To preserve completeness, we require the mappings M to preserve the space V , and this leads to a natural suggestion. Let $\text{Aut}(V)$ be the *automorphism group* of V . Sample $M_1 \dots, M_{q-1} \in \text{Aut}(V)$ and r_1, \dots, r_{q-1} and let $u^* = M(u) \triangleq u + \sum_{i < q} r_i M_i(u)$. By definition, this mapping is *q*-local and it preserves (perfect) completeness: if u belongs to V then so does each $M_i(u)$, so by linearity $M(u) \in V$. It now stands to reason that if $\text{Aut}(V)$ is sufficiently “pseudo-random”, say, a doubly-transitive group, then the median distance of $M(u)$ should be even greater than $\Delta(u, V)$ (the distance of u from V).

For example, consider the family of Reed-Solomon codes $\text{RS}[\mathbb{F}, \rho]$, which are comprised of all functions $f : \mathbb{F} \rightarrow \mathbb{F}$ such that $\deg(f) < \rho|\mathbb{F}|$ where $\deg(f)$ is the degree of the interpolating polynomial of (the function) f . It is well known that $\text{Aut}(\text{RS}[\mathbb{F}, \rho])$ is the 1-dimensional affine group of \mathbb{F} , denoted $\text{Aff}_1(\mathbb{F})$, whose members are all invertible affine transformations $\text{Aff}_1(\mathbb{F}) = \{M(X) = aX + b \mid a \in \mathbb{F}^*, b \in \mathbb{F}\}$; this group is indeed doubly-transitive.

⁶ In [9], a single test means a single invocation of the QUERY protocol.,



■ **Figure 1** FRI soundness threshold δ_0 as a function of RS code rate ρ , for a single invocation of the FRI QUERY phase (see Equation (1) and explanation in text there for the meaning of the constant δ_0). Higher lines are better. The top line is the trivial upper bound on soundness; the bottom line is the soundness of the original analysis of [9] (cf. Theorem 15). The middle line is the new and improved analysis given by Theorem 16. This analysis presents non-trivial soundness bounds for all code rates, and these bounds are better than the prior state of the art.

Our final set of results studies the effect of taking random linear combinations of random automorphisms for Reed-Solomon codes. Suppose we start with a function u , and then take random linear combinations of a few random affine shifts of u to produce a function u^* . From the discussion above, if u is in a Reed-Solomon code, then so is u^* . We show in Theorem 13 that if u is far from a Reed-Solomon code, then with high probability u^* is very far from that Reed-Solomon code. The main strength of this result is that this process can then amplify the distance to V all the way to $1 - o(1)$ (while more direct analyses, related to the Rothblum-Vadhan-Wigderson [19] lemma, cannot amplify beyond distance $1/2$).

2 Preliminaries

We use Δ to denote normalized Hamming distance, and $\mathbf{0} = 0^n$ denotes the identity element of an n -dimensional vector space, viewed as an additive group.

In what follows Σ is a finite alphabet. For $S \subset \Sigma^n$ let

$$\Delta(S) = \min \{ \Delta(w, w') \mid w, w' \in S, w \neq w' \}$$

denote the relative Hamming distance of S . For $w \in \Sigma^n$ let $B(w, \delta)$ denote the Hamming ball in Σ^n of normalized radius δ centered at w ,

$$B(w, \delta) = \{ r \in \Sigma^n \mid \Delta(w, r) < \delta \}$$

► **Definition 1** (List decodability). For $\rho \in [0, 1]$ and $L \geq 1$, we say a set $S \subseteq \Sigma^n$ is (ρ, L) -list-decodable if for all $w \in \Sigma^n$,

$$|B(w, \rho) \cap S| \leq L.$$

We have the fundamental Johnson bound, which says that sets with large minimum distance have nontrivial list-decodability. See, e.g., [15, Corollary 3.2] for a proof.

► **Theorem 2** (Johnson bound). For every $\epsilon \in (0, 1]$, Let $J_\epsilon : [0, 1] \rightarrow [0, 1]$ be the function

$$J_\epsilon(\delta) = 1 - \sqrt{1 - \delta(1 - \epsilon)}.$$

Let Σ be a finite alphabet, n an integer and $S \subseteq \Sigma^n$. Then S is $(J_\epsilon(\Delta(S)), 1/\epsilon)$ -list-decodable for every $\epsilon \in (0, 1]$.

An affine space U is an additive coset of a vector space U' , i.e., for some fixed $a \in \mathbb{F}^n$, $U = a + U' \triangleq \{a + u \mid u \in U'\}$. We introduce the following definition.

► **Definition 3** (Divergence). For $U, V \subseteq \Sigma^n$, the *divergence* of U from V is $D(U, V) = \max_{u \in U} \Delta(u, V)$.

Divergence is not a distance measure because it is not symmetric. This is witnessed by $U = \{\mathbf{0}, 10^{n-1}\}$, $V = \{\mathbf{0}, 1^n\} \subset \{0, 1\}^n$, which gives $D(U, V) = \frac{1}{n} \neq \frac{n-1}{n} = D(V, U)$.

The next lemma, due to Rothblum-Vadhan-Wigderson, says that if some vector in a linear space U is δ -far from a space V , then nearly all elements of U are $\delta/2$ -far from V .

► **Lemma 4** ([19, Lemma 1.6]). For any pair of linear spaces U, V over a finite field \mathbb{F} ,

$$\Pr_{u \in U} \left[\Delta(u, V) < \frac{D(U, V)}{2} \right] \leq \frac{1}{|\mathbb{F}| - 1}. \quad (2)$$

3 Preserving distances for general subspaces

In this section, we prove our first strengthening of the Rothblum-Vadhan-Wigderson lemma Lemma 4 from above. The main new qualitative feature is that if $D(U, V) = 1 - o(1)$, then the lemma concludes that most elements of u are at distance $1 - o(1)$ from V .

► **Theorem 5.** For a pair of affine spaces U, V over a finite field \mathbb{F} , and for all $\epsilon \in (0, 1]$,

$$\Pr_{u \in U} [\Delta(u, V) < J_\epsilon(D(U, V))] < \frac{1}{\epsilon(|\mathbb{F}| - 1)}.$$

Theorem 5 is a consequence of the following lemma, which says that if u^* is δ -far from V , then for any line passing through u^* in direction u , most points are $J_\epsilon(\delta)$ from V . We state the Lemma, prove Theorem 5 and then prove the lemma.

► **Lemma 6.** Let $V \subseteq \mathbb{F}^n$ be a linear space over a finite field \mathbb{F} ; suppose $u^* \in \mathbb{F}^n$ satisfies $\Delta(u^*, V) \geq \delta$. For any $u \in \mathbb{F}^n$ and $\epsilon \in (0, 1]$ let

$$A = A_{u, \epsilon} = \{\alpha \in \mathbb{F} \setminus \{0\} \mid \Delta(u^* + \alpha u, V) < J_\epsilon(\delta)\}.$$

Then $|A| \leq 1/\epsilon$.

Proof of Theorem 5. It suffices to prove the Theorem for the case that V is a linear space and U is an affine space (which may be linear as well), because Hamming distance is invariant under shifting both U and V by the same vector v . Let $u^* \in U$ be some element for which $\Delta(u^*, V) = D(U, V)$. We may assume $u^* \neq \mathbf{0}$, otherwise $D(U, V) = 0$ because $\mathbf{0} \in V$ so the claim trivially holds. If $\dim(U) = 0$ the claim also trivially holds because $|U| = 1$. Therefore, we assume $U = u^* + U'$ for some linear space U' of positive dimension d (which may include u^*). There exist $k = |\mathbb{F}|^{d-1}$ vectors u_1, \dots, u_k such that $U \setminus \{u^*\}$ can be partitioned into equi-sized sets, the i th set being the line $\{u^* + \alpha u_i \mid \alpha \in \mathbb{F} \setminus \{0\}\}$. Theorem 5 follows by applying Lemma 6 to each of the sets in this partition. ◀

Proof of Lemma 6. For $\alpha \in A$, let $v^\alpha \in V$ be such that $\Delta(u^* + \alpha u, v^\alpha) < J_\epsilon(\delta)$. Rewriting, we have that for each $\alpha \in A$,

$$\Delta\left(u, \frac{v^\alpha - u^*}{\alpha}\right) < J_\epsilon(\delta).$$

Assume by way of contradiction that $|A| > 1/\epsilon$. Thus, a set (or possibly multi-set) of more than $1/\epsilon$ vectors are all $J(\delta, \epsilon)$ -close to u . By the Johnson bound, two of the vectors must be δ -close to one another. Let α, α' be these distinct members of A for which

$$\Delta\left(\frac{v^\alpha - u^*}{\alpha}, \frac{v^{\alpha'} - u^*}{\alpha'}\right) < \delta.$$

Recalling $\Delta(u, v) = \Pr_{i \in [n]}[u_i \neq v_i]$ where u_i, v_i denote the i th entry of u, v , respectively, we have

$$\begin{aligned} \delta &> \Pr_{i \in [n]} \left[\left(\frac{v^\alpha - u^*}{\alpha} \right)_i \neq \left(\frac{v^{\alpha'} - u^*}{\alpha'} \right)_i \right] = \Pr_{i \in [n]} \left[\left(\frac{v^\alpha - u^*}{\alpha} - \frac{v^{\alpha'} - u^*}{\alpha'} \right)_i \neq 0 \right] \\ &= \Pr_{i \in [n]} \left[\left((\alpha - \alpha')u^* - (\alpha v^{\alpha'} - \alpha' v^\alpha) \right)_i \neq 0 \right] \\ &= \Pr_{i \in [n]} \left[u_i^* \neq \left(\frac{\alpha v^{\alpha'} - \alpha' v^\alpha}{\alpha - \alpha'} \right)_i \right]. \end{aligned}$$

Setting $v' = \frac{\alpha v^{\alpha'} - \alpha' v^\alpha}{\alpha - \alpha'}$ and noticing $v' \in V$ we conclude

$$\Delta(u^*, V) \leq \Delta(u^*, v') < \delta$$

which is false and which contradicts our hypothesis on the size of A . We conclude $|A| \leq 1/\epsilon$, as claimed. \blacktriangleleft

4 Preserving distances for good error correcting code

In this section we prove another strengthening of the Rothblum-Vadhan-Wigderson lemma. This strengthening only works when the subspace V is a code of good distance. Assume for now that V is a code with minimum distance $1 - o(1)$. Then the strengthened theorem gives a stronger guarantee: they show that most elements of U are at distance $\min(D(U, V) - o(1))$ from V . Thus the maximum distance of an element of U from V is also the typical distance of an element of U from V .

We begin with a warm-up: we show a “unique-decoding” version which only works up to $1/3$ of the minimum distance of the code V . The next “list-decoding” version works up to a much larger distance, and in particular for V having distance $1 - o(1)$, it works up to a distance of $1 - o(1)$.

4.1 Unique-Decoding version

► **Theorem 7.** *Let $V \subseteq \mathbb{F}^n$ be a linear space over a finite field \mathbb{F} with $\Delta(V) = \lambda$. Let U be an affine space and suppose $D(U, V) > \delta$. For any $\epsilon > 0$ such that $\delta - \epsilon < \lambda/3$,*

$$\Pr_{u \in U} [\Delta(u, V) < \delta - \epsilon] \leq \frac{1}{\epsilon |\mathbb{F}|}$$

Theorem 7 is a consequence of the following lemma. As in Section 3, we state the lemma, prove Theorem 7 and then prove the lemma.

► **Lemma 8.** *Let $V \subseteq \mathbb{F}^n$ be a linear space over a finite field \mathbb{F} with $\Delta(V) = \lambda$. Suppose $u^* \in \mathbb{F}^n$ satisfies $\Delta(u^*, V) > \delta$ and fix arbitrary $u \in \mathbb{F}^n$. For $\epsilon > 0$ satisfying $\delta - \epsilon < \lambda/3$ let $A = \{\alpha \in \mathbb{F} \mid \Delta(u^* + \alpha u, V) < \delta - \epsilon\}$. If $|A| > 1/\epsilon$ then there exist $v, v^* \in V$ such that:*

$$|\{i \in [n] \mid (u_i = v_i) \wedge (u_i^* = v_i^*)\}| \geq (1 - \delta) \cdot n.$$

Proof of Theorem 7. We prove the contra-positive: If the assumptions on $\epsilon, \delta, \lambda$ hold and

$$\Pr_{u \in U} [\Delta(u, V) < \delta - \epsilon] > \frac{1}{\epsilon |\mathbb{F}|}, \quad (3)$$

then $D(U, V) \leq \delta$.

Let $u^* \in U$ satisfy $\Delta(u^*, V) = D(U, V)$. We may assume V is a linear space and $\dim(U) > 0$, as argued in the proof of Theorem 5. As there, partition $U \setminus \{u^*\}$ into equi-size sets, each of the form $\{u^* + \alpha u_i \mid \alpha \in \mathbb{F} \setminus \{0\}\}$ for some set $u_1, \dots, u_k \in \mathbb{F}^n$ of vectors. By our assumption in Equation (3) there exists u_i such that the set $A = \{\alpha \in \mathbb{F} \mid \Delta(u^* + \alpha u_i, V) < \delta - \epsilon\}$ is of size greater than $1/\epsilon$. Apply Lemma 8 to this set, and conclude $\Delta(u^*, v^*) \leq \delta$, as claimed. ◀

Proof of Lemma 8. For $\alpha \in A$, let $v^\alpha \in V$ be such that $\Delta(u^* + \alpha u, v^\alpha) < \delta - \epsilon$.

We first show that for all $\alpha \in A$, the points (α, v^α) are all collinear. To see this, let $\alpha_1, \alpha_2, \alpha_3 \in A$ be distinct. We have $\Delta(u^* + \alpha_3 u, v^{\alpha_3}) \leq \delta - \epsilon$. On the other hand, if $\beta = \frac{\alpha_3 - \alpha_2}{\alpha_1 - \alpha_2}$, we have:

$$u^* + \alpha_3 u = \beta(u^* + \alpha_1 u) + (1 - \beta)(u^* + \alpha_2 u),$$

and so:

$$\begin{aligned} \Delta(u^* + \alpha_3 u, \beta v^{\alpha_1} + (1 - \beta)v^{\alpha_2}) &\leq \Delta(u^* + \alpha_1 u, v^{\alpha_1}) + \Delta(u^* + \alpha_2 u, v^{\alpha_2}) \\ &\leq (\delta - \epsilon) + (\delta - \epsilon) \\ &= 2(\delta - \epsilon). \end{aligned}$$

Thus $\Delta(\beta v^{\alpha_1} + (1 - \beta)v^{\alpha_2}, v^{\alpha_3}) \leq 3(\delta - \epsilon) < \lambda$. By the minimum distance hypothesis on V , we conclude that

$$\beta v^{\alpha_1} + (1 - \beta)v^{\alpha_2} = v^{\alpha_3},$$

which implies the desired collinearity.

Thus there exist $v, v^* \in V$ such that for all $\alpha \in A$,

$$v^\alpha = v^* + \alpha v.$$

Taking this information back to the definition of v^α , we have that for all $\alpha \in A$,

$$\Delta(u^* + \alpha u, v^* + \alpha v) < \delta - \epsilon.$$

Rewriting,

$$\Delta(u^* - v^*, \alpha(v - u)) < \delta - \epsilon.$$

for all $\alpha \in A$.

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Now for any coordinate $i \in [n]$ where $u_i \neq v_i$ or $u_i^* \neq v_i^*$, there can be at most one value of $\alpha \in \mathbb{F}$ for which $u_i^* - v_i^* = \alpha(v_i - u_i)$. Let $t = |A|$. Thus there is an $\alpha \in A$ such that:

$$\delta - \epsilon > \Delta(u^* - v^*, \alpha(v - u)) \geq 1 - \frac{|\{i \in [n] \mid (u_i = v_i) \wedge (u_i^* = v_i^*)\}|}{n} - \frac{1}{t}.$$

Putting everything together, we get that:

$$\frac{|\{i \in [n] \mid (u_i = v_i) \wedge (u_i^* = v_i^*)\}|}{n} \geq 1 - \delta + \epsilon - \frac{1}{t}.$$

Thus if $t > \frac{1}{\epsilon}$, we have:

$$\frac{|\{i \in [n] \mid (u_i = v_i) \wedge (u_i^* = v_i^*)\}|}{n} \geq 1 - \delta,$$

as claimed. ◀

4.2 List-Decoding version

► **Theorem 9.** *Let $V \subseteq \mathbb{F}_q^n$ be a subspace with minimum distance λ . Let $\epsilon, \delta > 0$ with $\delta < J_\epsilon(J_\epsilon(\lambda))$.*

Suppose $u^ \in \mathbb{F}_q^m$ is such that $\Delta(u^*, V) > \delta$. Then for all $u \in \mathbb{F}_q^n$, there are at most $2/\epsilon^3$ values of $\alpha \in \mathbb{F}_q$ such that $\Delta(u^* + \alpha u, V) < \delta - \epsilon$.*

This is a consequence of the following theorem.

► **Theorem 10.** *Let $V \subseteq \mathbb{F}^n$ be a linear space over a finite field \mathbb{F} with $\Delta(V) = \lambda$. Let $u^* \in \mathbb{F}^n$ and let $\epsilon > 0$ satisfy $\delta < J_\epsilon(J_\epsilon(\lambda))$. For $u \in \mathbb{F}^n$ let*

$$A = A_{u, \epsilon} = \{\alpha \in \mathbb{F} \setminus \{0\} \mid \Delta(u^* + \alpha u, V) < \delta - \epsilon\}.$$

If $|A| > 2/\epsilon^3$ then there exist $v^, v \in V$ such that*

$$|\{i \in [n] \mid (u_i = v_i) \wedge (u_i^* = v_i^*)\}| \geq (1 - \delta)n.$$

In particular,

$$\Delta(u^*, v^*) \leq \delta.$$

Proof. Let $t = |A|$. For $\alpha \in A$, let $v^\alpha \in V$ be such that $\Delta(u^* + \alpha u, v^\alpha) < \delta - \epsilon$. Thus $\Delta(u^*, v^\alpha - \alpha u) < \delta - \epsilon$.

Now consider the following graph with vertex set A : α and α' are adjacent if $\Delta(v^\alpha - \alpha u, v^{\alpha'} - \alpha' u) < J_\epsilon^{-1}(\delta)$. The Johnson bound implies that this graph has no independent set of size $c' = 1/\epsilon$. Thus by Turan's theorem, there is a vertex α_0 of degree at least $\epsilon|A| - 1$.

Concretely, this means that there is a set $B \subseteq A$, with $|B| \geq \epsilon|A| - 1$, such that for all $\alpha \in B$,

$$\Delta(v^{\alpha_0} - \alpha_0 u, v^\alpha - \alpha u) < J_\epsilon^{-1}(\delta).$$

Rewriting, we have:

$$\Delta(u, \frac{1}{\alpha - \alpha_0} \cdot (v^\alpha - v^{\alpha_0})) < J_\epsilon^{-1}(\delta), \tag{4}$$

for every $\alpha \in B$.

Now we apply the Johnson bound again. Since V has distance λ , and $J_\epsilon(\lambda) > J_\epsilon^{-1}(\delta)$, there can be at most $1/\epsilon$ distinct vectors $v \in V$ such that $\Delta(u, v) < J_\epsilon^{-1}(\delta)$.

The only way this can be consistent with Equation (4) is if many of the $\frac{1}{\alpha - \alpha_0} \cdot (v^\alpha - v^{\alpha_0})$ are identical. Specifically, by the pigeonhole principle we get that there is a $v \in V$ and a set $C \subseteq B$, with $|C| \geq \epsilon|B|$, such that for all $\alpha \in C$,

$$v = \frac{1}{\alpha - \alpha_0} \cdot (v^\alpha - v^{\alpha_0}).$$

So for all $\alpha \in C$,

$$v^\alpha = (v^{\alpha_0} - \alpha_0 v) + \alpha \cdot v.$$

Let us denote this by $v^\alpha = v^* + \alpha v$, where $v, v^* \in V$.

Taking this information back to the definition of v^α , we have that for all $\alpha \in C$,

$$\Delta(u^*, v^* + \alpha(v - u)) < \delta - \epsilon.$$

Rewriting,

$$\Delta(u^* - v^*, \alpha(v - u)) < \delta - \epsilon.$$

for all $\alpha \in C$.

Now for any coordinate $i \in [n]$ where $u_i \neq v_i$ or $u_i^* \neq v_i^*$, there can be at most one value of $\alpha \in \mathbb{F}$ for which $u_i^* - v_i^* = \alpha(v_i - u_i)$. Thus there is an $\alpha \in C$ such that

$$\Delta(u^* - v^*, \alpha(v - u)) \geq 1 - \frac{|\{i \in [n] \mid (u_i = v_i) \wedge (u_i^* = v_i^*)\}|}{n} - \frac{1}{|C|}.$$

Combining this with our upper bound on $\Delta(u^* - v^*, \alpha(v - u))$, we get that:

$$\frac{|\{i \in [n] \mid (u_i = v_i) \wedge (u_i^* = v_i^*)\}|}{n} \geq 1 - \delta + \epsilon - \frac{1}{|C|}. \tag{5}$$

Since $|C| \geq \epsilon|B| \geq \epsilon(\epsilon|A| - 1)$, and since $A \geq 2/\epsilon^3$, we get that

$$|C| > 1/\epsilon,$$

and the desired conclusion follows from Equation (5). ◀

We now state a variation of Theorem 10. The proof of this theorem follows immediately from the proof of Theorem 10 and hence we omit it. The reason we have this variation is that this precise form of the statement will be useful later in the proof of the low degree Polischuk-Spielman theorem.

► **Theorem 11.** *Let $V \subseteq \mathbb{F}^n$ be a linear space over a finite field \mathbb{F} with $\Delta(V) = \lambda$. Let $u^* \in \mathbb{F}^n$ and let $\epsilon > 0$ satisfy $\delta < J_\epsilon(J_\epsilon(\lambda))$. For $u \in \mathbb{F}^n$ let*

$$A = A_{u, \epsilon} = \{\alpha \in \mathbb{F} \setminus \{0\} \mid \Delta(u^* + \alpha u, V) < \delta\}.$$

If $|A| > 2/\epsilon^3$ then the following two statements hold:

1. *There exist $v^*, v \in V$ such that*

$$|\{i \in [n] \mid (u_i = v_i) \wedge (u_i^* = v_i^*)\}| \geq (1 - \delta - \epsilon)n.$$

In particular,

$$\Delta(u^*, v^*) \leq \delta + \epsilon.$$

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2. For $\alpha \in A$, fix $v^\alpha \in V$ such that $\Delta(u^* + \alpha v, v^\alpha) < \delta$. Then there is a large subset $C \subseteq A$ such that $|C| \geq \epsilon^2 |A| - 1$ and such that for all $\alpha \in C$, $v^* + \alpha v = v^\alpha$.

We now state a strengthening of the above theorem from lines to higher degree curves. Define $J_\epsilon^{[k]}(\lambda) = J_\epsilon(J_\epsilon(\dots(J_\epsilon(\lambda))))$, where there are k iterations of the function J_ϵ .

► **Theorem 12.** Let $V \subseteq \mathbb{F}^n$ be a linear space over a finite field \mathbb{F} with $\Delta(V) = \lambda$. Let $u^* \in \mathbb{F}^n$ and let $\epsilon > 0$ satisfy $\delta < J_\epsilon^{[\ell+1]}(\lambda)$. For $u_1, u_2, \dots, u_\ell \in \mathbb{F}^n$ let $A = A_{u_1, u_2, \dots, u_\ell, \epsilon} = \{\alpha \in \mathbb{F} \setminus \{0\} \mid \Delta(u^* + \alpha u_1 + \alpha^2 u_2 + \alpha^3 u_3 + \dots + \alpha^\ell u_\ell, V) < \delta\}$. If $|A| > K_{\epsilon, \ell}$ for some sufficiently large constant $K_{\epsilon, \ell}$ that depends only on ϵ and ℓ , then the following two statements hold:

1. There exist $v^*, v_1, v_2, \dots, v_\ell \in V$ such that

$$|\{i \in [n] \mid (u_i^* = v_i^*) \wedge ((u_1)_i = (v_1)_i) \wedge \dots \wedge ((u_\ell)_i = (v_\ell)_i)\}| \geq (1 - \delta - \epsilon)n.$$

In particular,

$$\Delta(u^*, v) \leq \delta + \epsilon.$$

2. For $\alpha \in A$, fix $v^\alpha \in V$ such that $\Delta(u^* + \alpha u_1 + \alpha^2 u_2 + \alpha^3 u_3 + \dots + \alpha^\ell u_\ell, v^\alpha) < \delta$. Then there is a large subset $C \subseteq A$ such that $|C| \geq c_{\epsilon, \ell} |A|$, where $c_{\epsilon, \ell} > 0$ is a constant only depending on ϵ and ℓ , and such that for all $\alpha \in C$, $v^* + \alpha v_1 + \alpha^2 v_2 + \alpha^3 v_3 + \dots + \alpha^\ell v_\ell = v^\alpha$.

Proof. The proof of the above theorem follows from the proof of Theorem 11 and an induction on ℓ . When $\ell = 1$, the result follows from Theorem 11. Let us assume the result is true for $\ell \leq k - 1$, and now consider $\ell = k$.

Let $t = |A|$. For $\alpha \in A$, let $v^\alpha \in V$ be such that $\Delta(u^* + \alpha u_1 + \alpha^2 u_2 + \alpha^3 u_3 + \dots + \alpha^k u_k, v^\alpha) < \delta$. Thus $\Delta(u^*, v^\alpha - (\alpha u_1 + \alpha^2 u_2 + \alpha^3 u_3 + \dots + \alpha^k u_k)) < \delta$.

Now consider the following graph with vertex set A : α and α' are adjacent if $\Delta(v^\alpha - (\alpha u_1 + \alpha^2 u_2 + \alpha^3 u_3 + \dots + \alpha^k u_k), v^{\alpha'} - (\alpha' u_1 + \alpha'^2 u_2 + \alpha'^3 u_3 + \dots + \alpha'^k u_k)) < J_\epsilon^{-1}(\delta)$. The Johnson bound implies that this graph has no independent set of size $c' = 1/\epsilon$. Thus by Turan's theorem, there is a vertex α_0 of degree at least $\epsilon |A| - 1$.

Concretely, this means that there is a set $B \subseteq A$, with $|B| \geq \epsilon |A| - 1$, such that for all $\alpha \in B$,

$$\Delta(v^{\alpha_0} - (\alpha_0 u_1 + \alpha_0^2 u_2 + \alpha_0^3 u_3 + \dots + \alpha_0^k u_k), v^\alpha - (\alpha u_1 + \alpha^2 u_2 + \alpha^3 u_3 + \dots + \alpha^k u_k)) < J_\epsilon^{-1}(\delta).$$

Rewriting, we have:

$$\Delta\left(\frac{v^{\alpha_0} - v^\alpha}{\alpha_0 - \alpha}, \frac{1}{\alpha_0 - \alpha} \cdot \sum_{i=1}^k (\alpha_0^i - \alpha^i) u_i\right) < J_\epsilon^{-1}(\delta), \quad (6)$$

for every $\alpha \in B$.

Now, let $W^\alpha \in V$ be the vector

$$\frac{v^{\alpha_0} - v^\alpha}{\alpha_0 - \alpha},$$

and let $u'_1, u'_2, \dots, u'_k \in \mathbb{F}^n$ be such that u'_i is the coefficient of α^{i-1} in

$$\frac{1}{\alpha_0 - \alpha} \cdot \sum_{i=1}^k (\alpha_0^i - \alpha^i) u_i.$$

Thus,

$$\frac{1}{\alpha_0 - \alpha} \cdot \sum_{i=1}^k (\alpha_0^i - \alpha^i) u_i = \sum_{i=1}^k u'_i \cdot \alpha^{i-1},$$

and for all $\alpha \in B$,

$$\Delta(W^\alpha, u'_1 + \alpha u'_2 + \dots + \alpha^{k-1} u'_k) < J_\epsilon^{-1}(\delta).$$

Notice that since we are given that $\delta < J_\epsilon^{[k+1]}(\lambda)$, where the function J_ϵ is iterated $k+1$ times, thus for $\delta' = J_\epsilon^{-1}(\delta)$, $\delta' < J_\epsilon^{[k]}(\lambda)$, where the function J_ϵ is iterated k times.

Now, $|B| \geq \epsilon|A| - 1$. Thus, if $|A|$ is large enough, then by induction hypothesis, there is a large subset $C \subseteq B$ such that $|C| \geq c_{\epsilon,k}|B|$, where $c_{\epsilon,k} > 0$ is a constant only depending on ϵ and k , and there exist $v'_1, v'_2, \dots, v'_k \in V$ such that for all $\alpha \in C$, $v'_1 + \alpha v'_2 + \alpha^2 v'_3 + \dots + \alpha^k v'_k = W^\alpha$.

Thus

$$\frac{v^{\alpha_0} - v^\alpha}{\alpha_0 - \alpha} = v'_1 + \alpha v'_2 + \alpha^2 v'_3 + \dots + \alpha^k v'_k,$$

where $v'_1, v'_2, \dots, v'_k \in V$.

Rearranging, this shows that for all $\alpha \in C$, we can express v^α as $v^* + \alpha v_1 + \alpha^2 v_2 + \alpha^3 v_3 + \dots + \alpha^k v_k$, where $v^*, v_1, v_2, \dots, v_k \in V$.

Taking this back to the definition of v^α , we have that for all $\alpha \in C$,

$$\Delta(u^*, v^* + (\alpha(v_1 - u_1) + \alpha^2(v_2 - u_2) + \alpha^3(v_3 - u_3) + \dots + \alpha^k(v_k - u_k))) < \delta.$$

Rewriting, we have that for all $\alpha \in C$,

$$\Delta(u^* - v^* + \alpha(u_1 - v_1) + \alpha^2(u_2 - v_2) + \alpha^3(u_3 - v_3) + \dots + \alpha^k(u_k - v_k), 0) < \delta.$$

Now for any coordinate $i \in [n]$ where $u_i^* \neq v_i^*$ or $(u_j)_i \neq (v_j)_i$ for any $j \in [k]$, the restriction to the i th coordinate gives us a nonzero degree k polynomial in α , and so there are at most k values of $\alpha \in \mathbb{F}$ for which $(u^* - v^*)_i + \alpha \cdot (u_1 - v_1)_i + \alpha^2 \cdot (u_2 - v_2)_i + \alpha^3 \cdot (u_3 - v_3)_i + \dots + \alpha^k \cdot (u_k - v_k)_i = 0$.

Thus there is an $\alpha \in C$ such that

$$\Delta(u^* - v^* + \alpha(u_1 - v_1) + \alpha^2(u_2 - v_2) + \alpha^3(u_3 - v_3) + \dots + \alpha^k(u_k - v_k), 0) \geq 1 - \frac{|\{i \in [n] \mid (u_i^* = v_i^*) \wedge ((u_1)_i = (v_1)_i) \wedge \dots \wedge ((u_k)_i = (v_k)_i)\}|}{n} - \frac{k}{|C|}.$$

Combining this with our upper bound on

$$\Delta(u^* - v^* + \alpha(u_1 - v_1) + \alpha^2(u_2 - v_2) + \alpha^3(u_3 - v_3) + \dots + \alpha^k(u_k - v_k), 0),$$

we get that:

$$\frac{|\{i \in [n] \mid (u_i^* = v_i^*) \wedge ((u_1)_i = (v_1)_i) \wedge \dots \wedge ((u_k)_i = (v_k)_i)\}|}{n} \geq 1 - \delta - \frac{k}{|C|}. \quad (7)$$

Since Now is $|A|$ is a large enough constant depending on ϵ and k , then the bounds on $|C|$ imply that

$$|C| > k/\epsilon,$$

and the desired conclusion follows from Equation (7). ◀

5 Distance Amplification for Reed-Solomon codes

In this section, we show how to use the results of the previous section to show that some simple transformations *amplify* the distance of a function from the space of low-degree polynomials (i.e., Reed-Solomon codes). In the previous section, we saw results with the flavor: if u^* is δ -far from the subspace V , then there are many other functions (related to u^*) that are also almost δ -far from the subspace V . Now we will get more: we will find many functions related to u^* that are δ' -far from V for some δ' bigger than δ . The main strength of this result is that this process can then amplify the distance to V all the way to $1 - o(1)$ (while more direct analyses, related to the Rothblum-Vadhan-Wigderson [19] lemma, cannot amplify beyond distance $1/2$).

For a function u^* we consider taking random linear combinations of a few random affine shifts of u^* . Notice that if u^* was actually a low-degree polynomial, then the resulting function would also be a low-degree polynomial (since low-degree polynomials are closed under taking affine shifts and taking linear combinations). We show that if u^* is far from low-degree polynomials, this operation amplifies distance to low-degree polynomials noticeably. More precisely, suppose V is the space of polynomials of degree at most ρq , let $\delta > 0$, and suppose $\rho > 0$ is small enough as a function of δ . We show that if u^* is δ -far from V , then the function $u(x) = u^*(x) + c \cdot u^*(ax + b)$ (where a, b, c are picked uniformly at random from \mathbb{F}_q) is with high probability $\approx (2\delta - \delta^2)$ far from V . This final distance matches what one would expect if we took the sum of two random functions that were δ -far from V - thus the random affine shift of u^* behaves nearly independently of u^* (subject to the trivial constraint that the random affine shift is also δ -far from V).

To state the theorem, we begin with some notation. For a function $f : \mathbb{F}_q \rightarrow \mathbb{F}_q$, we denote by $T_{a,b}(f)$ the function $g : \mathbb{F}_q \rightarrow \mathbb{F}_q$ given by:

$$g(\beta) = f(a\beta + b),$$

for each $\beta \in \mathbb{F}_q$.

► **Theorem 13.** *Let $V = \text{RS}(\mathbb{F}_q, (1 - \lambda)q) \subseteq \mathbb{F}_q^q$ be the Reed-Solomon code over \mathbb{F}_q with minimum distance λ .*

Let $u', u'' : \mathbb{F}_q \rightarrow \mathbb{F}_q$ be functions with $\Delta(u', V) \geq \delta'$ and $\Delta(u'', V) \geq \delta''$. Let $\epsilon > 0$, and let

$$\delta = \min(J_\epsilon(J_\epsilon(\lambda)) - \epsilon, \delta' + \delta'' - \delta'\delta'' - 2\epsilon).$$

Then:

$$\Pr_{a,b,c \in \mathbb{F}_q} [\Delta(u' + c \cdot T_{a,b}(u''), V) < \delta] \leq \frac{K}{q}, \quad (8)$$

where $K = 8/\epsilon^4$.

Proof. Set $\bar{\delta} = \delta + \epsilon$. Note that

$$\bar{\delta} = \delta + \epsilon < J_\epsilon(J_\epsilon(\lambda)) < J_\epsilon(\lambda).$$

Suppose Equation (8) did not hold. Thus:

$$\Pr_{a,b,c \in \mathbb{F}_q} [\Delta(u' + c \cdot T_{a,b}(u''), V) < \bar{\delta} - \epsilon] > \frac{K}{q}.$$

Then with probability at least $\frac{K}{2q}$ over the choice of (a, b) , we have that:

$$\Pr_{c \in \mathbb{F}_q} [\Delta(u' + c \cdot T_{a,b}(u''), V) < \bar{\delta} - \epsilon] > \frac{K}{2q}.$$

Fix such an $(a, b) \in \mathbb{F}_q^2$. Since $K > 4/\epsilon^3$ and $\bar{\delta} < J_\epsilon(J_\epsilon(\lambda))$, we may apply Theorem 10 to u' and $T_{a,b}(u'')$. It tells us that there exist $y, y^* \in V$ such that:

$$|\{\beta \in \mathbb{F}_q \mid u'(\beta) = y(\beta) \wedge u''(a\beta + b) = y^*(\beta)\}| \geq (1 - \bar{\delta})q, \quad (9)$$

which, after letting $y^{**}(T) = y^*((\beta - b)/a)$, can be rewritten as:

$$|\{\beta \in \mathbb{F}_q \mid u'(\beta) = y(\beta) \wedge u''(a\beta + b) = y^{**}(a\beta + b)\}| \geq (1 - \bar{\delta})q. \quad (10)$$

It is thus natural to consider the collection of polynomials close to u', u'' :

$$\mathcal{L}' = \{f \in V \mid \Delta(u', f) \leq \bar{\delta}\},$$

$$\mathcal{L}'' = \{f \in V \mid \Delta(u'', f) \leq \bar{\delta}\},$$

as well as the collection of agreement sets:

$$\mathcal{F}' = \{A \subseteq \mathbb{F}_q \mid \text{for some } f \in \mathcal{L}' \text{ we have } A = \{\beta \in \mathbb{F}_q \mid f(\beta) = u'(\beta)\}\}.$$

$$\mathcal{F}'' = \{A \subseteq \mathbb{F}_q \mid \text{for some } f \in \mathcal{L}'' \text{ we have } A = \{\beta \in \mathbb{F}_q \mid f(\beta) = u''(\beta)\}\}.$$

By the Johnson bound, Theorem 2, (and since $\bar{\delta} < J_\epsilon(\lambda)$), we have that

$$|\mathcal{L}'|, |\mathcal{L}''|, |\mathcal{F}'|, |\mathcal{F}''| < 1/\epsilon.$$

Equation (10) and the discussion before it tells us that with probability at least $\frac{K}{2q}$ over the choice of $(a, b) \in \mathbb{F}_q^2$, there exists some $A' \in \mathcal{F}'$ and some $A'' \in \mathcal{F}''$ such that

$$|A' \cap \frac{1}{a}(A'' - b)| \geq (1 - \bar{\delta})q.$$

By averaging, this means that there must exist some $A' \in \mathcal{F}'$ and $A'' \in \mathcal{F}''$ such that with probability at least $\frac{\epsilon^2 K}{2q}$ over the choice of $(a, b) \in \mathbb{F}_q^2$,

$$|A' \cap \frac{1}{a}(A'' - b)| \geq (1 - \bar{\delta})q. \quad (11)$$

We will use this to deduce that either A' or A'' must be big. For each $r \in A''$, let X_r denote the indicator random variable for the event that $(r - b)/a \in A'$. Let $X = \sum_{r \in A''} X_r$. Note that

$$X = |A' \cap \frac{1}{a}(A'' - b)|.$$

It is easy to see that $\mathbf{E}[X_r] = |A'|/q$, and so:

$$\mathbf{E}[X] = \frac{|A'| \cdot |A''|}{q} = \mu.$$

Furthermore, the X_r are pairwise independent, and thus the variance of X is bounded by:

$$\mathbf{Var}[X] \leq 4 \frac{|A''||A'|}{q} \leq 4q.$$

Thus:

$$\Pr[X \geq \mu + 2t\sqrt{q}] \leq \frac{1}{t^2}.$$

If $|A'|, |A''|$ are such that $|A'| \cdot |A''| \leq (1 - \bar{\delta} - \epsilon) \cdot q^2$, then $\mu \leq (1 - \bar{\delta} - \epsilon)q$, and the above equation with $t = \frac{\epsilon}{2}\sqrt{q}$ gives us that:

$$\Pr[X \geq (1 - \bar{\delta})q] \leq \frac{4}{\epsilon^2 q}.$$

This is a contradiction to Equation (11), since by the choice of K ,

$$\frac{\epsilon^2 K}{2q} < \frac{4}{\epsilon^2 q}.$$

Thus we must have that:

$$|A'| \cdot |A''| > (1 - \bar{\delta} - \epsilon)q^2.$$

Recalling that $A' \in \mathcal{F}'$ and $A'' \in \mathcal{F}''$, we conclude that

$$(1 - \delta')(1 - \delta'') > (1 - \delta - 2\epsilon),$$

a contradiction to our assumption on δ', δ'' . ◀

6 A low-agreement analysis of the Polischuk–Spielman axis-parallel test

In this section, we use the tools we developed above to give improved versions of the Polischuk-Spielman robust low-degree test [18] in certain settings. Their result gives a way to robustly test proximity of a 2-dimensional function $f : \mathbb{F}_q^2 \rightarrow \mathbb{F}_q$ to bivariate polynomials with individual degrees (d, ℓ) . Our result shows that for $\ell = O(1)$, and for $d = O(q)$, the Polischuk-Spielman low-degree test works even in the presence of high noise: even if the test passes with some tiny probability η , it means that the underlying bivariate function has nontrivial agreement with some low degree bivariate polynomial.

The original Polischuk-Spielman analysis (improving on Arora-Safra [3]) allows d, ℓ to both be $\Omega(q)$, but could only conclude something if the passing probability η was at least $1/2$. The very recent analysis of the Polischuk-Spielman test due to Chiesa et al. [13] allows η to be small, as in the result we obtain below, but the two results are incomparable (neither implies the other). The result of [13] works for d, ℓ as large as $O(\log q)$ whereas ours requires $\ell = O(1)$ but allows d to be as large as $\Omega(q)$.

► **Theorem 14** (High-error soundness analysis of the Polischuk–Spielman test). *There exists a function $f : \mathbb{N}^+ \times (0, 1) \times (0, 1)$ that, for each fixed $\ell \in \mathbb{N}^+$, satisfies $f(\ell, \rho, \epsilon) \rightarrow 0$ as $\rho \rightarrow 0$ and $\epsilon \rightarrow 0$, and for which the following holds.*

Let $d = \rho q$. Suppose for each $x \in \mathbb{F}_q$, we have a degree ℓ polynomial $Q_x(Y)$, and for each $y \in \mathbb{F}_q$ we have a degree d polynomial $P_y(X)$. Suppose that for some non-trivial agreement parameter $\eta > f(\ell, \rho, \epsilon)$ all these polynomials meet the following nontrivial agreement condition:

$$\Pr_{x, y \in \mathbb{F}_q} [Q_x(y) = P_y(x)] \geq \eta. \tag{12}$$

Then there exists a bivariate polynomial $R(X, Y)$ of individual degree (d, ℓ) such that

$$\Pr_{x, y \in \mathbb{F}_q} [Q_x(y) = R(x, y)] \geq \eta - 2\epsilon,$$

$$\Pr_{x, y \in \mathbb{F}_q} [Q_x(y) = P_y(x) = R(x, y)] \geq C_{\epsilon, \ell} \cdot \eta,$$

where $C_{\epsilon, \ell} > 0$ is a constant only depending on ϵ and ℓ .

Proof. Our plan is to use Theorem 12 to deduce some information about Q_x and P_y . Let $V \subseteq \mathbb{F}_q^d$ be the Reed-Solomon code of polynomials of degree at most d . Let $\lambda = \Delta(V) = 1 - \rho$.

Let u^*, u_1, \dots, u_ℓ be functions from \mathbb{F}_q to \mathbb{F}_q such that:

$$Q_x(Y) = u^*(x) + u_1(x)Y + u_2(x)Y^2 + \dots + u_\ell(x)Y^\ell.$$

For each $\alpha \in \mathbb{F}_q$, define $v^\alpha(X) = P_\alpha(X)$.

The non-trivial agreement hypothesis of Equation (12) tells us that:

$$\Pr_{\alpha, x \in \mathbb{F}_q} [u^*(x) + u_1(x)\alpha + \dots + u_\ell(x)\alpha^\ell = v^\alpha(x)] \geq \eta.$$

Equivalently:

$$\mathbb{E}_{\alpha \in \mathbb{F}_q} [\Delta(u^* + \alpha u_1 + \alpha^2 u_2 + \dots + \alpha^\ell u_\ell, v^\alpha)] \leq 1 - \eta.$$

Set $\delta = 1 - \eta + \epsilon$. By an averaging argument, we get:

$$\Pr_{\alpha \in \mathbb{F}_q} [\Delta(u^* + \alpha u_1 + \alpha^2 u_2 + \dots + \alpha^\ell u_\ell, v^\alpha) < \delta] \geq \epsilon.$$

Let A be the set of α for which the above event happens: thus $|A| \geq \epsilon \cdot q$.

We now apply Theorem 12. We need $\delta < J_\epsilon^{[\ell]}(\lambda)$, which we may assume by suitably setting $f(\ell, \rho, \epsilon)$. We get that there exist $v^*, v_1, \dots, v_\ell \in V$ and a subset $G \subseteq \mathbb{F}_q$ with $|G| \geq (1 - \delta - \epsilon)q$ for all $x \in G$,

$$v^*(x) = u^*(x), v_1(x) = u_1(x), \dots, v_\ell(x) = u_\ell(x).$$

Since v^* and the v_i are all in V , they are polynomials of degree at most d . Define

$$R(X, Y) = v^*(X) + v_1(X)Y + \dots + v_\ell(X)Y^\ell.$$

Rephrasing what we just concluded in terms of R , we get that for all $x \in G$:

$$R(x, Y) = Q_x(Y),$$

and thus:

$$\Pr_{x \in \mathbb{F}_q, y \in \mathbb{F}_q} [R(x, y) = Q_x(y)] \geq 1 - \delta - \epsilon = \eta - 2\epsilon.$$

Moreover, we conclude from Item 2 of Theorem 12 that for some $c_{\epsilon, \ell}$ fraction of the $\alpha \in A$, we have:

$$v^\alpha = v^* + \alpha v_1 + \dots + \alpha^\ell v_\ell.$$

For any such α where this identity holds, we get that:

$$R(x, \alpha) = v^\alpha(x) = P_\alpha(x),$$

and thus

$$\Pr_{x \in \mathbb{F}_q} [R(x, \alpha) = P_\alpha(x) = Q_x(\alpha)] \geq 1 - \delta = \eta - \epsilon > \eta/2.$$

This completes the proof of the theorem. ◀

7 Improved soundness for the Fast RS IOPP (FRI) protocol

In this section we describe how our prior results lead to a better analysis of the soundness of the FRI protocol of [9]. We start by recalling the notation needed to state our results, referring the reader to [9] for a detailed description of the protocol with its two phases, the COMMIT and QUERY sub-protocols.

7.1 Notation

We use the notation introduced in [9, Sections 3.4, 4.2.1]; let us briefly recall it. Our starting point is a function $f^{(0)} : L^{(0)} \rightarrow \mathbb{F}$ where \mathbb{F} is a finite field of characteristic 2 and size 2^n , the evaluation domain $L^{(0)} \subset \mathbb{F}$ is an affine space over the two element field \mathbb{F}_2 , i.e., $L^{(0)}$ is a coset of an additive subgroup of \mathbb{F} , and $|L^{(0)}| = 2^{k^{(0)}}$ which means that $k^{(0)} = \dim(L^{(0)})$. We assume the target rate is $\rho = 2^{-\mathcal{R}}$ for some positive integer \mathcal{R} . The COMMIT phase of the FRI protocol involves $r = k^{(0)} - \mathcal{R}$ rounds. For $i > 0$, during the i th round the verifier sends a uniformly random $x^{(i)} \in \mathbb{F}$ and the prover responds with a function $f^{(i+1)} : L^{(i+1)} \rightarrow \mathbb{F}$ where $L^{(i+1)}$ is an affine space of dimension $k^{(i+1)} = k^{(i)} - 1$ (and size $2^{k^{(i+1)}}$) defined by $L^{(i+1)} = q^{(i)}(L^{(i)})$ where $q^{(i)}$ is a linearized polynomial of degree 2 that is a subspace polynomial of a space $L_0^{(i)}$ such that $L^{(i)}$ can be partitioned into additive cosets of $L_0^{(i)}$. Let $\mathcal{S}^{(i)}$ denote the set of cosets of $L_0^{(i)}$ contained in $L^{(i)}$.

For $f, g : L^{(i)} \rightarrow \mathbb{F}$ let $\Delta^{(i)}(f, g)$ be the block-wise distance between f, g (cf. [9, Definition 3.2]), defined as the fraction of cosets of $L_0^{(i)}$ on which f and g differ,

$$\Delta^{(i)}(f, g) \triangleq \Pr_{S \in \mathcal{S}^{(i)}} [f|_S \neq g|_S]$$

where $f|_S$ is the restriction of f to S (and $g|_S$ is similarly defined) and equality above is in the space \mathbb{F}^S . Notice $\Delta^{(i)}(f, g) \geq \Delta(f, g)$. For a set of functions $V \subset \mathbb{F}^{L^{(i)}}$ let $\Delta^{(i)}(f, V) = \min \{ \Delta^{(i)}(f, v) \mid v \in V \}$.

7.2 Statement of results

The following is the main theorem from [9], and we improve its soundness in Theorem 16, stated after it.

► **Theorem 15 (FRI – main properties).** *The following properties hold when the FRI protocol is invoked on oracle $f^{(0)} : L^{(0)} \rightarrow \mathbb{F}$ with rate $\rho = 2^{-\mathcal{R}}$ for $\mathcal{R} \in \mathbb{N}^+$ such that $\rho|L^{(0)}| > 16$:*

1. **Completeness** *If $f^{(0)} \in \text{RS}^{(0)} \triangleq \text{RS}[\mathbb{F}, L^{(0)}, \rho = 2^{-\mathcal{R}}]$ and $f^{(1)}, \dots, f^{(r)}$ are computed by the prover specified in the COMMIT phase, then the FRI verifier outputs accept with probability 1.*
2. **Soundness** *Suppose $\delta^{(0)} \triangleq \Delta^{(0)}(f^{(0)}, \text{RS}^{(0)}) > 0$. Then with probability at least*

$$1 - \frac{3|L^{(0)}|}{|\mathbb{F}|} \tag{13}$$

over the randomness of the verifier during the COMMIT phase, and for any (adaptively chosen) prover oracles $f^{(1)}, \dots, f^{(r)}$, the QUERY protocol with repetition parameter ℓ outputs accept with probability at most

$$\left(1 - \min \left\{ \delta^{(0)}, \frac{1 - 3\rho - 2/\sqrt{|L^{(0)}|}}{4} \right\} \right)^\ell \tag{14}$$

Consequently, the soundness of FRI is at least

$$s^-(\delta^{(0)}) \triangleq 1 - \left(\frac{3|L^{(0)}|}{|\mathbb{F}|} + \left(1 - \min \left\{ \delta^{(0)}, \frac{1 - 3\rho - 2/\sqrt{|L^{(0)}|}}{4} \right\} \right)^\ell \right). \quad (15)$$

3. **Prover complexity** is $O(|L^{(0)}|)$ arithmetic operations over \mathbb{F}
4. **Verifier complexity** is $O(\log |L^{(0)}|)$ arithmetic operations over \mathbb{F} for a single invocation of the QUERY phase; this also bounds communication and query complexity (measured in field elements).

We improve FRI soundness as follows:

► **Theorem 16** (FRI with improved soundness). *The following properties hold when the FRI protocol is invoked on oracle $f^{(0)} : L^{(0)} \rightarrow \mathbb{F}$, $|L^{(0)}| = k^{(0)}$, with rate $\rho = 2^{-\mathcal{R}}$, $\mathcal{R} \in \mathbb{N}^+$ such that $\rho|L^{(0)}| > 16$:*

1. **Soundness** Suppose $\delta^{(0)} \triangleq \Delta^{(0)}(f^{(0)}, \text{RS}^{(0)}) > 0$. Then for any $\epsilon > 0$, with probability at least

$$1 - \frac{2k^{(0)}}{\epsilon^3 |\mathbb{F}|} \quad (16)$$

over the randomness of the verifier during the COMMIT phase, and for any (adaptively chosen) prover oracles $f^{(1)}, \dots, f^{(r)}$, the QUERY protocol with repetition parameter ℓ outputs accept with probability at most

$$\left(1 - \min \left\{ \delta^{(0)}, J_\epsilon(J_\epsilon(1 - \rho)) \right\} + \epsilon k^{(0)} \right)^\ell \quad (17)$$

Consequently, the soundness of FRI is at least

$$s^-(\delta^{(0)}) \triangleq 1 - \left(\frac{2k^{(0)}}{\epsilon^3 |\mathbb{F}|} + \left(1 - \min \left\{ \delta^{(0)}, J_\epsilon(J_\epsilon(1 - \rho)) \right\} + \epsilon k^{(0)} \right)^\ell \right). \quad (18)$$

7.3 Proof of Theorem 16

Before presenting the proof of our main theorem for this section, we require a corollary of our prior results, which we state first. To state the corollary, we need more notation from [9]

7.3.1 More notation

Given $x^{(i)} \in \mathbb{F}$, the function $f_{f^{(i)}, x^{(i)}}^{(i+1)} : L^{(i+1)} \rightarrow \mathbb{F}$ is that which is provided by the honest FRI prover upon input $f^{(i)}$ and verifier randomness $x^{(i)}$. For $s^{(i+1)} \in L^{(i+1)}$ and $s_0^{(i)}, s_1^{(i)}$ the two roots of $q^{(i)}(X) - s^{(i+1)}$, we have

$$f_{f^{(i)}, x^{(i)}}^{(i+1)}(s^{(i+1)}) \triangleq P_{f^{(i)}, s_0^{(i)}, s_1^{(i)}}(s^{(i+1)}) \quad (19)$$

where $P_{f^{(i)}, s_0^{(i)}, s_1^{(i)}}(X)$ is the polynomial that interpolates the two points $\left(s_0^{(i)}, f^{(i)}\left(s_0^{(i)}\right) \right)$ and $\left(s_1^{(i)}, f^{(i)}\left(s_1^{(i)}\right) \right)$; notice $\deg\left(P_{f^{(i)}, s_0^{(i)}, s_1^{(i)}}\right) \leq 1$ and $\left\{ s_0^{(i)}, s_1^{(i)} \right\}$ is a coset of $L_0^{(i)}$, denoted $S_{s^{(i+1)}}^{(i)}$.

7.3.2 A corollary of Theorem 10

The following statement is a corollary of Theorem 10, as applied to a single round of the FRI protocol involving an honest prover.

► **Corollary 17.** *Suppose $\delta^{(i)} \triangleq \Delta^{(i)}(f^{(i)}, \text{RS}^{(i)})$ satisfies $\delta^{(i)} < J_\epsilon(J_\epsilon(1 - \rho))$. Then*

$$\Pr_{x^{(i)} \in \mathbb{F}} \left[\Delta \left(f_{f^{(i)}, x^{(i)}}^{(i+1)}, \text{RS}^{(i+1)} \right) \geq \delta^{(i)} - \epsilon \right] \leq \frac{2}{\epsilon^3 |\mathbb{F}|}. \quad (20)$$

Proof. Consider the space of functions $U = U^{(i+1)} = \{f_{f^{(i)}, x^{(i)}}^{(i+1)} \mid x^{(i)} \in \mathbb{F}\} \subset \mathbb{F}^{L^{(i+1)}}$ that are supplied by the honest prover in response to the various verifier messages $x^{(i)}$. Let

$$u^* = f_{f^{(i)}, 0}^{(i+1)}, \quad u = f_{f^{(i)}, 1}^{(i+1)} - f_{f^{(i)}, 0}^{(i+1)}.$$

Since $\deg(P_{f^{(i)}, s_0^{(i)}, s_1^{(i)}}) \leq 1$ for every pair $\{s_0^{(i)}, s_1^{(i)}\} \in \mathcal{S}^{(i)}$ it follows that every $u' = f_{f^{(i)}, x^{(i)}}^{(i+1)} \in U$ can be written as a linear combination of u^*, u ; specifically, $f_{f^{(i)}, x^{(i)}}^{(i+1)} = u^* + x^{(i)} \cdot u$. Let $\bar{U}^{(i+1)} \subseteq U$ be the set of elements in U that have distance less than $\delta^{(i)} - \epsilon$ to $\text{RS}^{(i+1)}$.

Assume by way of contradiction that $|\bar{U}^{(i+1)}| > \frac{2}{\epsilon^3}$. Then Theorem 10 implies the existence of $v^*, v \in \text{RS}^{(i+1)}$ and a subset $T \subset L^{(i+1)}$, $\frac{|T|}{|L^{(i+1)}|} \geq 1 - \delta^{(i)}$, such that $v^*|_T = u^*|_T$ and $v|_T = u|_T$. Let $Q^*(Y), Q(Y)$ be the polynomials interpolating v^* and v respectively. We have $\deg(Q^*), \deg(Q) < \rho |L^{(i+1)}|$ because $v^*, v \in \text{RS}^{(i+1)}$. Let

$$\hat{Q}(X, Y) \triangleq Q^*(Y) + X \cdot Q(Y)$$

and notice that (i) $\deg_X(\hat{Q}) < 2$, $\deg_Y(\hat{Q}) < \rho |L^{(i+1)}|$ (ii) $\hat{Q}(0, Y) = Q^*(Y)$, (iii) $\hat{Q}(1, Y) = Q(Y)$.

Consider the polynomial $R(X) \triangleq \hat{Q}(X, q^{(i)}(X))$. We have

$$\deg(R) \leq 2 \cdot \deg_Y(\hat{Q}) - 1 < 2|L^{(i+1)}| = \rho |L^{(i)}|.$$

We claim that R agrees with $f^{(i)}$ on $\{S_{s^{(i+1)}}^{(i)} \mid s^{(i+1)} \in T\}$. Indeed, for each $s^{(i+1)} \in T$ let $S_{s^{(i+1)}}^{(i)} = \{s_0^{(i)}, s_1^{(i)}\} \in \mathcal{S}^{(i)}$ be the pair of roots of the polynomial $q^{(i)}(X) - s^{(i+1)}$. By our assumption on T ,

$$\hat{Q}(0, s^{(i+1)}) = f_{f^{(i)}, 0}^{(i+1)}(s^{(i+1)}) \quad \text{and} \quad \hat{Q}(1, s^{(i+1)}) = f_{f^{(i)}, 1}^{(i+1)}(s^{(i+1)}).$$

The polynomials $\hat{Q}(X, s^{(i+1)})$ and $P_{f^{(i)}, s_0^{(i)}, s_1^{(i)}}(X)$ are both of degree less than 2 and they agree on the two points $\{0, 1\}$, hence they agree everywhere. It follows that

$$f^{(i)}(s_0^{(i)}) = \hat{Q}(s_0^{(i)}, s^{(i+1)}) = \hat{Q}(s_0^{(i)}, q^{(i)}(s_0^{(i)})) = R(s_0^{(i)})$$

and similarly $f^{(i)}(s_1^{(i)}) = R(s_1^{(i)})$. Therefore, R and $f^{(i)}$ agree on T , as claimed.

We have established $\Delta^{(i)}(f^{(i)}, \text{RS}^{(i)}) \leq 1 - \frac{|T|}{|L^{(i+1)}|} \leq \delta^{(i)}$ and this contradicts our assumption. Therefore $|U^{(i+1)}| \leq \frac{2}{\epsilon^3 |\mathbb{F}|}$, as claimed. ◀

7.3.3 Proof of improved soundness

Armed with Corollary 17 we move on to the proof of the main theorem of this section.

Proof of Theorem 16. Let $E^{(i)}$ be the “bad” event that $f_{f^{(i)},x^{(i)}}^{(i+1)} \in \bar{U}^{(i+1)}$; in words, $E^{(i)}$ is the event that $\Delta\left(f_{f^{(i)},x^{(i)}}^{(i+1)}, \text{RS}^{(i+1)}\right) \leq \delta^{(i)} - \epsilon$. Corollary 17 implies that $\Pr[E^{(i)}] \leq \frac{2}{\epsilon^3|\mathbb{F}|}$. (When $\delta^{(i)} < \frac{1-\rho}{2}$ the stronger bound $\Pr[E^{(i)}] \leq \frac{1}{\epsilon|\mathbb{F}|}$ holds.) By the union bound

$$\Pr\left[\bigvee_{i=0}^{r-1} E^{(i)}\right] \leq \frac{2r}{\epsilon^3|\mathbb{F}|} \leq \frac{2k^{(0)}}{\epsilon^3|\mathbb{F}|} \quad (21)$$

We continue our analysis assuming no such event holds. Let $f^{(0)}, \dots, f^{(r)}$ be the sequence of functions sent by the prover, which is not necessarily honest. Recall that during the QUERY phase of the FRI protocol, the verifier selects a random $s^{(0)} \in L^{(0)}$ and this defines a sequence $s^{(0)}, \dots, s^{(r)}$ inductively by using the rule $s^{(i+1)} = q^{(i)}(s^{(i)})$ for $i \in \{1, \dots, r\}$; Recall $S_{s^{(i+1)}}^{(i)} \in \mathcal{S}^{(i)}$ is the coset containing the two roots of the polynomial $q^{(i)}(X) - s^{(i+1)}$, and one of them is $s^{(i)}$. The test associated with $s^{(0)}$ accepts iff Equation (19) holds for all $i \in \{0, \dots, r-1\}$ and additionally $f^{(r)}$ is a constant function; we assume it by associating the constant function with the first entry of $f^{(r)}$.

For the sake of analysis, consider the directed graph in which an edge appears from $s^{(i)}$ to $s^{(i+1)}$ if and only if $s^{(i)} \in S_{s^{(i+1)}}^{(i)}$. This graph has $r+1$ layers, and the vertices in the i th layer are the elements of $L^{(i)}$. For all nodes but for the root and leaves, the in-degree is 2; all non-root nodes have out-degree is 1, making the graph a directed tree (we direct edges from leaves to root). A single invocation of the QUERY phase involves selecting a leaf $s^{(0)}$ and performing the sequence of tests along the path from $s^{(0)}$ to the top layer of the graph (which corresponds to $L^{(r)}$).

Call a vertex $s^{(i)}$ *bad* if Equation (19) fails to hold for $s^{(i)}$ and $S_{s^{(i)}}^{(i-1)}$; all other vertices are called *good*. A QUERY test rejects if and only if the path examined by it contains a bad vertex. To analyze the rejection probability of the test, it will be simpler to consider only the last such bad vertex along a path. To this end, we shall modify the sequence of functions $f^{(1)}, \dots, f^{(r-1)}$ (but not $f^{(0)}$ and $f^{(r)}$) in a way that may change some bad vertices into good ones, but will not make a good vertex bad. We will then analyze the rejection probability of a QUERY test applied to the modified set of functions.

Working top down with $i = r, \dots, 2$ in decreasing order, for each bad vertex $s^{(i)} \in L^{(i)}$, we modify the entries in the sub-tree whose root is $s^{(i)}$, as follows. Let $L_{s^{(i)}}^{(j)}$ be the set of vertices in layer j that have a path to $s^{(i)}$. For $j \in \{0, \dots, i-2\}$, in increasing order, set

$$f^{(j+1)}|_{L_{s^{(i)}}^{(j+1)}} \triangleq f_{f^{(j)},x^{(j)}}^{(j+1)}.$$

This modification process may change the entries of $f^{(1)}, \dots, f^{(r-1)}$ but does not change neither $f^{(0)}$, nor $f^{(r)}$ because $0 \leq j < r-1$ and we only modify entries in layer $j+1$. Crucially, the probability of rejecting during the QUERY phase does not increase as a result of this modification, because the modification does not turn a good vertex into a bad one and hence the set of post-modification bad vertices is a subset of the pre-modification bad vertices.

Consider the sequence of modified functions $f^{(0)}, \dots, f^{(r)}$. Let $\beta^{(i)}$ denote the fraction of bad vertices in $L^{(i)}$. As said earlier, the probability of rejection during a single QUERY invocation is precisely the probability that a path originating in a random leaf passes through a bad vertex. After our modification process, the set of leaves that lead to distinct bad vertices, are distinct, and along a path there is at most one bad vertex. Hence, the probability

that the FRI verifier rejects on a single invocation of the QUERY protocol is precisely $\sum_{i=1}^r \beta^{(i)}$. All that remains is to bound this sum from below, as done next.

► **Claim 18.** *If $E^{(i)}$ does not hold, then*

$$\beta^{(i+1)} \geq \delta^{(i)} - \delta^{(i+1)} - \epsilon$$

Proof. Assuming $E^{(i)}$ does not hold, Corollary 17 implies

$$\Delta\left(f_{f^{(i)}, x^{(i)}}^{(i+1)}, \text{RS}^{(i+1)}\right) \geq \delta^{(i)} - \epsilon$$

By the properties of the modification process, $f^{(i+1)}(s^{(i+1)}) = f_{f^{(i)}, x^{(i)}}^{(i+1)}$ for every $s^{(i+1)}$ that is not bad. So

$$\Delta\left(f^{(i+1)}, \text{RS}^{(i+1)}\right) \geq \delta^{(i)} - \epsilon - \beta^{(i+1)}$$

or, rearranging,

$$\beta^{(i+1)} \geq \delta^{(i)} - \Delta\left(f_{f^{(i)}, x^{(i)}}^{(i+1)}, \text{RS}^{(i+1)}\right) - \epsilon$$

The claim follows because $\delta^{(i+1)} \triangleq \Delta\left(f^{(i+1)}, \text{RS}^{(i+1)}\right) \geq \Delta\left(f_{f^{(i)}, x^{(i)}}^{(i+1)}, \text{RS}^{(i+1)}\right)$. ◀

We continue with the proof. By assumption $\delta^{(r)} = 0$ and $f^{(0)}$ is unchanged by the modification process, so

$$\delta^{(0)} = \delta^{(0)} - \delta^{(r)} = \sum_{i=0}^{r-1} \delta^{(i)} - \delta^{(i+1)}$$

Applying Claim 18 to the rightmost term above we conclude that whenever no event $E^{(i)}$ holds (cf. Equation (21)), then the probability of the verifier rejecting during a single invocation of the QUERY phase is at least $\sum_{i=1}^r \beta^{(i)} \geq \delta^{(0)} - r\epsilon$. This completes the proof. ◀

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