

Counterexamples to Beyond-Johnson Proximity Gaps over Binary Fields

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Abstract

Many hash-based proof systems check that committed words are close to Reed–Solomon codewords by testing one random combination of them. Their soundness analysis uses a *proximity gap*: if the combination agrees with a codeword on many positions, so do the original words, on the same positions, except for a few *exceptional* challenges. Such gaps are known above the Johnson threshold, about $\sqrt{\rho}$ for rate ρ , and extending them below it would shrink proofs. Recent work does so in large characteristic, but not over binary fields, where some of the fastest proof systems run. We show that beyond-Johnson proximity gaps fail over binary fields.

Our first construction applies to any additive domain (a binary linear subspace) filling a constant fraction of a containing binary field. Over a suitable extension challenge field and at rate $1/4$, it gives two words that can simultaneously match codewords on at most 25% of the positions, while their combinations approach the 50% Johnson threshold for superpolynomially many challenges. This rules out any $\text{poly}(N)/|\mathbb{F}|$ bound on the exceptional probability below Johnson. On Binius64’s domain (length 2^{27} , 128-bit challenges), the combination reaches 49.4% agreement with probability above 2^{-30} .

The construction also rules out polynomial-size decoding lists below Johnson: one word agrees with superpolynomially many codewords at agreement approaching 50%, whereas earlier superpolynomial lists needed the rate, or the agreement–rate gap, to vanish.

Our second and third constructions cover every additive domain, including the sparse domains used by LeanVM and Flock. At rate $1/16$, the second gives $(N - 1)(N - 2)/6$ exceptional challenges at the Johnson threshold itself, when the domain lies in a proper subfield of the challenge field. For domains larger than 2^{20} , this rules out even 90 bits of soundness from a single beyond-Johnson proximity-gap check over a 128-bit challenge field.

The third construction trades agreement for larger exception counts: at rate $1/2$ and length 2^{22} , its combinations reach 53.125% agreement from common agreement 50%, with probability at least 2^{-20} over a 192-bit challenge field. Finally, at every fixed rate, some constant agreement above the rate makes every challenge exceptional, over $\text{poly}(N)$ -size challenge fields. All of our results are formally verified in Lean.

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1 Introduction

Many hash-based succinct proof systems (SNARKs) verify large computations by inspecting only a few entries of received words—vectors of field elements—purported to be close to Reed–Solomon codewords. A Reed–Solomon codeword lists the values of a polynomial of degree less than K on a fixed set D of N field elements, the *evaluation domain*; the code has rate $\rho = K/N$. The number of queries directly affects proof size, since each query adds field values and Merkle authentication paths to the proof. Some of the fastest provers for these systems work over binary fields (fields of characteristic two), including Binius [22], Flock [16], BinarySpartan [41], LeanVM [38], and Google’s Longfellow [27].¹

To check many words at once, the verifier combines two received words f, g , fixed before the challenge is drawn, into $f + zg$, for a random element z of a large *challenge field*, and tests only the combination. The standard soundness analysis uses a *proximity gap*: if the combination agrees with a codeword on many positions, the inputs must also agree with codewords on many common positions, except with small probability. The inputs may match different codewords, but the positions must be shared. The largest number of such positions is their *common agreement*. We call a challenge *exceptional* if the combination agrees with a codeword on more positions than this.

The Johnson threshold and beyond. Classical proximity-gap theorems, valid in every characteristic, require the fraction of matching positions to exceed the *Johnson agreement threshold*, approximately $\sqrt{\rho}$ for a code of rate ρ [5]; counted in positions, the threshold is $\sqrt{N(K-1)}$. Capacity corresponds to agreement fraction ρ : interpolation lets any received word match a polynomial of degree less than K on any chosen K positions.

A proximity gap guarantee beyond Johnson, that is, at agreement below the Johnson threshold, lets the soundness analysis of proof systems handle words with more errors. A random query is then more likely to expose an inconsistency. The verifier could thus make fewer queries, reducing proof size without lowering the target security level [3, 18].

How far below Johnson? Ben-Sasson, Carmon, Ishai, Kopparty, and Saraf [6, Conjecture 8.4] conjectured that proximity gaps hold all the way down to capacity: at every agreement fraction exceeding the rate ρ by some $\eta > 0$, the probability that a random challenge is exceptional would be at most a polynomial in N , $1/\rho$, and $1/\eta$, divided by the size of the challenge field. WHIR [3, Conjecture 4.12, item 2] states the corresponding conjecture on *smooth* domains (multiplicative subgroups of power-of-two size and their scalar multiples) for the stronger guarantee of *mutual correlated agreement* (MCA): whenever the combination matches a codeword on a sufficiently large set of positions, the inputs must match codewords on that same set, except with small probability. Thus MCA requires agreement on the particular set explained by the combination, whereas a common-agreement bound only requires some shared set of the requisite size. Conjectured bounds for Reed–Solomon proximity testing have been used to set query counts in implementations, including a binary-field implementation by Ben-Sasson, Bentov, Horesh, and Riabzev [4, Appendix B.8], [6, Section 8.2].

The arbitrary-domain conjecture has now been disproved in every characteristic [17, 21, 37]. The counterexamples of Krachun, Kazanin, and Haböck [37] are on multiplicative subgroups of prime fields, the family of domains that contains the smooth ones. Those counterexamples, however, occur at agreement approaching capacity, or at vanishing rate. They leave open whether proximity gaps hold at fixed rate and agreement bounded away from capacity, including just below Johnson. The smooth-domain conjecture does not literally apply over binary fields: the multiplicative group of a binary field has odd order, so it has no

¹Advantages of binary fields include efficient commitments to small values, fast arithmetic on modern hardware, and efficient representations of bitwise operations; see [11, 22].

nontrivial subgroup of power-of-two size. Over binary fields the corresponding question concerns additive domains, which we study here.

In large characteristic, recent work makes progress toward these weaker guarantees. Following the capacity list-decoding result of Brakensiek, Chen, Putterman, Zhang, and Zheng over prime fields [14]—bounding the number of codewords close to one received word—proximity gaps beyond Johnson are now proved in sufficiently large characteristic [18, 32, 39].

These positive results do not apply to binary fields. For arbitrary evaluation domains, the polynomial bound on exceptional challenges known in every characteristic extends only a constant number of positions below the Johnson threshold [33], and guarantees up to capacity are known when the evaluation points are chosen at random [29]. Binary-field SNARKs, however, evaluate on *additive domains*, $\mathbb{F}_2$ -subspaces of a binary field, because these support fast Fourier transforms (FFTs). For these structured domains, the central question remains:

Over binary fields, on the additive domains that SNARKs use, do proximity gaps hold below the Johnson threshold?

1.1 Our results

We answer this question in the negative.² We give three constructions:

- The *Gold construction* applies to every additive domain that fills a constant fraction of a containing binary field. This includes the Cantor domain used by Binius64 [12]. At agreement thresholds approaching Johnson, the construction gives both superpolynomially many exceptional challenges and decoding lists of superpolynomial size. It also gives a concrete bound on the domains of Google’s Longfellow [26], which are not additive but contain a large affine subspace (Section 5.8).
- The *subspace-locator construction* applies to every additive domain, including the sparse domains used by the LeanVM [38] and Flock [23] SNARK implementations. It gives quadratically many exceptional challenges at every fixed rate, reaching Johnson at rate 1/16 and a fixed agreement below Johnson at other rates. It also makes every challenge exceptional at a fixed gap above the rate, when the challenge field has size polynomial in N .
- The *decision-tree construction* also applies to every additive domain. Its agreement is farther below Johnson, but its exceptional counts are polynomials of arbitrarily high degree.

Several of our constructions violate even the weaker guarantee that each input is individually close to a codeword.

1.1.1 Dense domains: the Gold construction

The dimension of an additive domain is always measured over $\mathbb{F}_2$, and an *affine domain* is a translate of an additive one. We call additive domains of growing length *dense* if each lies in a binary field $\mathbb{B}$ with $|\mathbb{B}|/|D|$ bounded independently of the length. We begin at rate 1/4, where the Johnson agreement threshold is 50%.

²None of the current systems discussed here (Binius64, BinarySpartan, Longfellow, LeanVM, and Flock) relies on beyond-Johnson proximity-gap conjectures. Our counterexamples therefore do not show that these systems are insecure as currently configured; they rule out the proposed proof-size reductions from beyond-Johnson proximity-gap guarantees in the parameter regimes covered by our results. Binius64, BinarySpartan, and Longfellow use guarantees at the unique-decoding radius [12, 26, 41]. LeanVM uses Johnson-bound guarantees, as does Flock’s default configuration, which targets 128 bits of security [23, 38]. Flock’s configuration named Secure targets 120-bit security and uses the smaller unique-decoding radius, requiring more queries and larger proofs.

Theorem (Informal version of Corollary 5.2). On every dense additive domain of sufficiently large size N , over a suitable extension challenge field, the Reed–Solomon code of rate $1/4$ has two fixed received words f, g such that:

1. The inputs can match codewords simultaneously on at most 25% of the positions.
2. For many distinct challenges z , the combination $f + zg$ matches a codeword on nearly 50% of the positions.

As N grows, the agreement in the second item approaches 50% from below, and the number of such challenges grows faster than every fixed polynomial in N .

Two fields appear here. Density is measured in the *containing field* $\mathbb{B}$, which also holds the coefficients of the polynomials we construct. The words f, g and the challenges take values in the challenge field $\mathbb{F} \supseteq \mathbb{B}$, where the exceptional probability is measured.

The number of exceptional challenges is $N^{\Omega(\log N)}$ in a challenge field of size $N^{\Theta(\log N)}$, and in every larger extension of $\mathbb{B}$. Polynomial-size challenge fields are also affected: when D is a hyperplane of a field $\mathbb{B}$ of size a power of four and $\mathbb{F}$ has fixed degree $e \geq 2$ over $\mathbb{B}$, a constant fraction of all challenges is exceptional at agreement $1/2 - O(N^{-1/2})$ (Corollary 5.3).

A relaxed guarantee does not help. A proximity gap with *proximity loss* ϵ only requires the inputs to share agreement on a fraction of positions that is ϵ below the combination’s agreement. At a fixed agreement fraction α between 25% and 50%, our pairs defeat every loss below $\alpha - 1/4$; as α approaches 50%, this covers every fixed loss below 25 percentage points. Thus no bound of the form $\text{poly}(N)/|\mathbb{F}|$ on the exceptional probability holds at any fixed agreement fraction between 25% and 50% over all binary challenge fields $\mathbb{F}$ (Theorem 5.4).

List decoding. The same polynomials give superpolynomial *decoding lists*, the sets of codewords agreeing with one received word at a given threshold. On every dense additive domain, the rate-1/4 code over the containing field, of size $O(N)$, has a received word agreeing with $N^{\Omega(\log N)}$ codewords on a $1/2 - o(1)$ fraction of the positions (Corollary 5.2). These codes therefore admit no polynomial list-size bound at any fixed agreement fraction below Johnson. Extensions to other rates and characteristics appear in Corollary 5.23.

Other rates. Superpolynomial exceptional counts also occur at every fixed rate $0 < \rho < 1$, on every sufficiently large dense additive domain and its affine translates. The inputs’ common agreement is ρ , and the combination agreement is a constant strictly between ρ and $\sqrt{\rho}$ (Corollary 5.17).

The Binius64 domain. Binius64 draws its challenges from $\mathbb{F}_{2^{128}}$ and evaluates on a nested family of subspaces V_d of that field [12]. The family is chosen so that V_{32} is the subfield $\mathbb{F}_{2^{32}}$ (Section 5.7). As an example we take the 27-dimensional domain V_{27} . It occupies a $1/32$ fraction of $\mathbb{F}_{2^{32}}$, so the Gold construction applies. At rate $1/4$, a random combination agrees with a codeword on at least 49.417% of positions with probability greater than $2^{-29.889}$, while the inputs’ common agreement is only 25% (Corollary 5.18). The same bound holds for every 27-dimensional binary subspace of $\mathbb{F}_{2^{32}}$.

The Longfellow domains. Google’s Longfellow draws its challenges from $\mathbb{F}_{2^{128}}$ and evaluates on domains that are not additive [26, 27]. Each domain contains a 2048-point affine subspace of $\mathbb{F}_{2^{16}}$, and the Gold construction on that subspace extends to the whole domain. At rate about $1/7$ it gives exceptional probability greater than $2^{-105.522}$ at agreement about 26%, between the inputs’ common agreement of about 14.3% and the Johnson agreement of about 37.8% (Section 5.8).

1.1.2 Every domain: the subspace-locator construction

Other implementations use sparse domains, on which the Gold counting argument does not supply enough polynomials. The domains of LeanVM and Flock are spanned by consecutive powers of a generator of their base field, so no proper subfield contains them [23, 38]. LeanVM’s domain of length 2^{22} occupies only a 2^{-42} fraction of $\mathbb{F}_{2^{64}}$, the smallest field containing it. Our second construction works on every additive domain and at every fixed rate.

Quadratically many exceptional challenges. At rate $1/16$, the Johnson agreement threshold is approximately 25%.

Theorem (Informal version of Theorem 4.1). Let D be a binary additive domain of $N \geq 32$ points, contained in a proper subfield of the challenge field. The rate- $1/16$ Reed–Solomon code on D has two fixed received words f, g such that:

1. The inputs can match codewords simultaneously on fewer than 12.5% of the positions.
2. For exactly $(N - 1)(N - 2)/6$ distinct challenges z , the combination $f + zg$ matches a codeword on $N/4 - 1$ positions.

The exact Johnson threshold is just below $N/4$, and below the combination agreement $N/4 - 1$. Any MCA guarantee for these codes at or below Johnson must therefore have error at least $(N - 1)(N - 2)/(6|\mathbb{F}|)$, even if it gives up nearly $N/8$ positions of agreement.

The proper-subfield condition can be dropped at a cost in the exceptional count. Writing $M = (N - 1)(N - 2)/6$ and $q = |\mathbb{F}|$, Corollary 4.2 gives at least $\lceil qM/(q + M - 1) \rceil$ exceptional challenges on every additive domain in $\mathbb{F}$. In particular, when $q \geq M$, more than half of the quadratic count survives.

Implications for small challenge fields. Many hash-based SNARKs use roughly 128-bit challenge fields while targeting 100–120 bits of security. BinarySpartan [41], for example, uses $\mathbb{F}_{2^{128}}$ and proved proximity-gap guarantees.³ Google’s Longfellow also specifies a $\mathbb{F}_{2^{128}}$ profile targeting at least 115 bits of security [27, Section 5.1], and the bound of Section 5.8 already exceeds 2^{-115} . Our quadratic exceptional count limits the prospect of reducing query counts through beyond-Johnson guarantees over such binary fields. At rate $1/16$, length $N = 2^{20}$ and $q = 2^{128}$, Corollary 4.2 forces exceptional probability greater than $2^{-90.585}$ at Johnson and below, already too large to certify 100–120 bits of soundness from such a guarantee.

Corollary 4.6 applies the same count at rate $1/8$ to the 2018 implementation of Ben-Sasson, Bentov, Horesh, and Riabzev [4, Appendix B.8].

Every challenge, at every rate. We also keep a fixed positive *agreement gap*: the combination’s agreement exceeds the inputs’ common agreement by a constant fraction of the positions. At every fixed rate, we can make every challenge exceptional with such a gap, provided the challenge field has size polynomial in N .

Theorem (Informal version of Theorem 4.5). Fix a rate $0 < \rho < 1$ and an exponent $a \geq 1$. There is a constant $\varepsilon > 0$ with $\rho + \varepsilon < \sqrt{\rho}$ such that, on every binary additive domain of sufficiently large size N , over every challenge field with at most N^a elements, the Reed–Solomon code of message length $\lfloor \rho N \rfloor$ has two fixed received words f, g such that:

1. The inputs can match codewords simultaneously on at most a ρ fraction of the positions.

³The Flock paper specifies $\mathbb{F}_{2^{128}}$ throughout [16, Section 5], whereas the implementation snapshot we analyze uses $\mathbb{F}_{2^{256}}$ for proximity-test challenges [23]. Our Flock case study (Section 6.4) concerns the implementation at rate $1/2$, and its conclusion is weaker: it applies at $17/32$ agreement, close to capacity and well below Johnson.

Domain	N	$\log_2 q$	ρ	Agreement α	Common γ	Probability	Source
Binius64's V_{27}	2^{27}	128	1/4	0.49417	1/4	$> 2^{-29.889}$	Cor. 5.18
Binius64's V_{27}	2^{27}	128	1/2	0.61914	1/2	$> 2^{-29.877}$	Cor. 5.15
Every additive domain in $\mathbb{F}_{2^{64}}$	2^{22}	128	1/16	$1/4 - 1/N$	$1/8 - 1/N$	$> 2^{-87}$	Thm. 4.1
Every additive domain in $\mathbb{F}_{2^{192}}$	2^{22}	192	1/2	17/32	1/2	$\geq 2^{-20}$	Thm. 6.10
Every additive domain in $\mathbb{F}_{2^{256}}$	2^{22}	256	1/2	17/32	1/2	$> 2^{-27}$	Thm. 6.10

Table 1: Concrete lower bounds on the probability that $f + zg$ agrees with a codeword on at least an α fraction of positions, for a uniformly random challenge z in a field of size q . Here γ is the inputs' common agreement fraction. The 128-bit challenge field in the third row is hypothetical.

2. For every challenge z , the combination $f + zg$ matches a codeword on at least a $\rho + \varepsilon$ fraction of the positions.

1.1.3 Every domain, larger counts: the decision-tree construction

Larger challenge fields need more exceptional challenges. In a 192-bit field, such as LeanVM's, exceeding exceptional probability 2^{-128} requires more than 2^{64} distinct exceptional challenges, and at length 2^{22} the quadratic count above is below 2^{42} . Our third construction uses recursive Boolean decision trees to obtain much larger exceptional sets on every binary additive domain, at agreement farther below Johnson.

Theorem (Informal version of Theorem 6.10). On every binary additive domain of length 2^{22} in $\mathbb{F}_{2^{192}}$, the rate-1/2 Reed–Solomon code has two fixed received words such that:

1. The inputs can match codewords simultaneously on at most 50% of the positions.
2. For at least 2^{172} distinct challenges, their combination matches a codeword on at least $17/32 = 53.125\%$ of the positions.

Application to LeanVM and Flock. These bounds apply to the additive domains and rate-1/2 configurations used by LeanVM [38] and Flock [23]. At length 2^{22} and 53.125% agreement, the exceptional probability is at least 2^{-20} over LeanVM's 192-bit challenge field and greater than 2^{-27} over Flock's 256-bit challenge field. A proximity-gap guarantee at this agreement with proximity loss below $1/32$ can therefore certify at most 20 and fewer than 27 bits of soundness, respectively, more than 100 bits short of their 128-bit targets.

The agreement here, $17/32$, is close to capacity ($1/2$) and well below Johnson (about 70.71%). These bounds therefore do not rule out improvements beyond Johnson at rate $1/2$.

Table 1 gives numerical bounds for selected parameters; Tables 2 and 3 summarize the theorem families and their domain and field assumptions.

1.2 Comparison with prior results

Earlier binary-field counterexamples. Ben-Sasson, Goldberg, Kopparty, and Saraf [7, Lemma 3.3] use hyperplane locators at rate $1/8$, with agreement above Johnson; Theorem 4.7 adds a pole to the same locators to reach Johnson at rate $1/4$. Ben-Sasson, Carmon, Haböck, Kopparty, and Saraf [5, Corollary 1.7] obtain nearly quadratically many exceptions at Johnson near rate $1/16$. Their construction also gives polynomial counts of arbitrarily large degree, but requires lowering the rate and agreement threshold [5, Theorem 1.6];

Result and rate	Domain and challenge field	Agreement of combination α	Common γ	Exceptional count E
Superpolynomial count $\rho = 1/4$ Corollary 5.2	Every additive $D \subseteq \mathbb{B}$, $ \mathbb{B} = 2^c N$, fixed $c \geq 0$; a suitable extension of size $q = N^{\Theta_c(\log N)}$	$1/2 - o(1)$	$1/4$	$N^{\Omega_c(\log N)}$
Arbitrary additive domains $\rho = 1/16$ Theorem 4.1; Corollary 4.2	Every $D \subseteq \mathbb{F}$. The full quadratic count holds if $D \subseteq \mathbb{B} \subseteq \mathbb{F}$.	$1/4 - 1/N$	$1/8 - 1/N$	Proper subfield: $\geq M$ Any field: $\geq \left\lceil \frac{qM}{q + M - 1} \right\rceil$ $M = (N-1)(N-2)/6$
Exact half agreement $\rho = 1/4$ Theorem 4.7	Every proper affine binary domain $D \subsetneq \mathbb{F}$, $N \geq 8$	$1/2$	$1/4$	$2N - 2$ exactly Equals $q - 2$ if $q = 2N$

Table 2: Counterexamples approaching or reaching the Johnson agreement threshold. Here $N = |D|$, $q = |\mathbb{F}|$, α is the agreement fraction of the combination, γ is the inputs' common agreement fraction, and E counts exceptional challenges for one fixed pair, so the exceptional probability is E/q . Subscripts on asymptotic notation indicate parameters on which the implicit constants may depend. In the second row, $N \geq 32$ is a multiple of 16, and the same challenges are exceptional at every lower threshold down to $N/8 + 1$.

Result and rate	Domain and challenge field	Agreement of combination α	Common γ	Exceptional count E
Superpolynomial count at every rate Any fixed $0 < \rho < 1$ Corollary 5.17	Every affine translate of a dense binary additive domain; suitable $q = N^{O(\log N)}$	$\alpha_0 - o(1)$, $\rho < \alpha_0 < \sqrt{\rho}$	$\lfloor \rho N \rfloor / N$	$N^{\Omega(\log N)}$
Every challenge at every rate Any fixed $0 < \rho < 1$ Theorem 4.5	Every additive domain; $q \leq N^a$ for any fixed $a \geq 1$	A fixed threshold $\rho < \alpha < \sqrt{\rho}$	$\lfloor \rho N \rfloor / N$	q exactly
Cubic count at half agreement $\rho = 3/8$ Corollary 6.7	Every additive domain; $q > N$	$1/2$	$3/8$	$\Omega(\min\{N^3, q/N\})$ Cubic in N when $q \geq N^4$
Higher powers at half rate $\rho = 1/2$ Theorem 6.10	Every additive domain; $q > N$, fixed $h \geq 3$, and $\log_2 N \geq 2^h - 1$	$1/2 + 2^{-h-1}$	$1/2$	$\Omega_h(\min\{N^{e_h}, q/N\})$ $e_h = 2^h - h - 1$

Table 3: Counterexamples at a fixed positive gap above the code rate, with agreement bounded away from Johnson. Notation is as in Table 2, and N is sufficiently large.

raising the rate back to a fixed value shrinks the agreement gap. Our Gold construction gives superpolynomial counts at fixed rate $1/4$, with agreement approaching Johnson and a constant agreement gap (Corollary 5.2).

Their construction selects a suitable additive domain; it does not guarantee a counterexample on the domains chosen by implementations. Our subspace-locator construction covers every prescribed additive

domain, including sparse ones, with a quadratic count at Johnson at rate $1/16$ (Theorem 4.1 and Corollary 4.2).

Near-capacity counterexamples. Crites and Stewart [17, Corollary 1] give examples in which every challenge is exceptional, in any characteristic and on arbitrary evaluation domains. At fixed rate and polynomial field size, their agreement gap tends to zero as the block length grows. On binary additive domains, our Theorem 4.5 keeps the gap constant under the same constraints.

Diamond and Gruen [21, Theorem 4.14] obtain superpolynomial exceptional counts with vanishing rate and agreement. Krachun, Kazanin, and Haböck [37, Theorem 1] obtain arbitrarily large polynomial counts at any fixed limiting rate on multiplicative subgroups of prime fields, but with a vanishing agreement gap; see also Kambiré [35], an earlier write-up of a sketch by Krachun and Kazanin. Our binary-field results keep both the rate and agreement gap constant.

Upper bounds just beyond Johnson. Jo [33] bounds the exceptional count by $O(N^6)$ a fixed number of positions below Johnson, over every field and evaluation set, at each fixed rate $1/r$ for an integer $r \geq 2$. At rate $1/16$, our quadratic exceptional count remains valid at agreement $N/4 - 3$, the first integer below the exact Johnson threshold (Theorem 4.1). Thus our $\Omega(N^2)$ lower bound and Jo’s $O(N^6)$ upper bound leave a gap in the polynomial exponent. Jo’s upper bound rules out superpolynomial exceptional counts within any fixed number of positions below Johnson. Our superpolynomial counts nevertheless occur at agreement fraction $(1 - o(1))\sqrt{\rho}$, with $\rho = 1/4$ (Corollary 5.2). For example, on a full binary field the agreement is below Johnson by $\Theta(N^{3/4})$ positions, or $\Theta(N^{-1/4})$ in agreement fraction.

List-decoding lower bounds. Guruswami and Rudra [31], and Ben-Sasson, Kopparty, and Radhakrishnan [8], construct superpolynomial Reed–Solomon decoding lists with vanishing rate. The latter also give constant-rate lower bounds, but their list-size exponent stays bounded when the rate and agreement fraction are fixed. Justesen and Høholdt [34] obtain linear-size lists at Johnson. In the positive direction, in sufficiently large characteristic, Gabizon [24] and Dao, Kominers, and Thaler [18] prove linear list-size bounds at a constant agreement fraction below Johnson, and the latter give explicit polynomial list-size bounds at every fixed agreement above capacity. Our constructions give superpolynomial lists at fixed rate, with agreement approaching Johnson: at every rate 4^{-k} over a field of size N (Corollary 5.23), and at rate $1/4$ on every dense additive domain (Corollary 5.2). Our results show that, at these rates and on these binary domains, every fixed agreement threshold below Johnson can require superpolynomial-size lists. Thus no polynomial-time algorithm can explicitly output all qualifying codewords in this setting. This contrasts with the polynomial-time list-decoding algorithm approaching capacity over prime fields, which works on every evaluation set at every constant rate [14]. The superpolynomial list sizes also depend on the evaluation domain: randomly chosen evaluation points can achieve list-decoding capacity, including in characteristic two [1, 15, 30].

Our proof techniques in relation to prior work. The shared-coefficient method for constructing decoding lists comes from Ben-Sasson, Kopparty, and Radhakrishnan [8]. The conversion to exceptional challenges by division by a linear factor, and the counting argument for distinct challenges, appear in Ben-Sasson et al. [5, Section 6] and Crites and Stewart [17, Theorem 2]. Gao, Yang, Xu, and Kan [25] give a general reduction from large decoding lists to MCA counterexamples. Our contribution is to construct superpolynomial lists at fixed rate and agreement approaching Johnson on dense additive binary domains, and to exploit their algebraic structure to obtain the exceptional-set bounds of Theorem 5.1.

Our dense-domain families use equations derived from the powers x^{2^e+1} studied by Gold [28]. Earlier work used these equations to identify quadratic functions defining minimum-weight codewords (nonzero codewords with as few ones as possible) of extended BCH codes [9, 10, 36]. The positions where these

codewords equal one become our agreement sets. The same equations let us construct polynomials vanishing on those sets with shared high-degree coefficients. We extend the Gold moment equations from full fields to general additive domains and count the resulting polynomials to obtain large decoding lists and exceptional sets.

Our degree bounds use an identity of Borges and Conceição [13, Lemma 4.1]; our quadratic-function counts use identities of Delsarte and Goethals [20] and a family of Schmidt [40, Theorems 4.9 and 5.6]. Section 2 explains how these ingredients enter the constructions.

1.3 Formal verification and AI assistance

Formal verification in Lean. All of our results are formally verified in Lean, building on the mathematical library ArkLib [2]. This covers every theorem, proposition, corollary, and lemma of this paper, the remarks and numerical bounds derived from them, and the finite arithmetic underlying our concrete Binius64 and Longfellow bounds. The formal statements include the degree and agreement bounds, guarantees for the individual inputs, and distinct-challenge counts of each result. The formalization and its annotated main-theorem statements are publicly available [19]. Its README maps each statement of this paper to the Lean declarations that prove it. Descriptions of deployed systems and results quoted from the literature for comparison are outside the formalization.

AI assistance and author responsibility. GPT-5.6 Sol, GPT-6 Sol, GPT-6.1 Sol, GPT-6 Astra, Claude Fable 5.1, and Claude Opus 5.5 discovered and refined the main results, including the counterexample constructions and their concrete specializations, with our close prompting and guidance. These models also carried out the Lean formalization and assisted with the writing under our direction. We take full responsibility for the results, proofs, and exposition.

2 Technical overview

Our goal is to construct one fixed pair of words f, g for which many challenges z make $f + zg$ agree with a codeword on more positions than f, g can simultaneously agree with codewords. We start with polynomials that have many roots in the evaluation domain and share most of their high-degree coefficients. We turn each polynomial into an identity expressing $f + zg$ minus a codeword; its roots then become agreement positions. Shared coefficients let us use the same f, g throughout the family. The remaining task is to ensure that many family members give different challenges.

Section 2.1 introduces this common framework. We then explain the three constructions in the order of the introduction: Gold moments on dense domains (Section 2.2), subspace locators on arbitrary additive domains (Section 2.3), and decision trees for larger counts on sparse domains (Section 2.4). Gold moments and decision trees use the pole reduction of Section 2.1; subspace locators use a variant that divides by X and takes the challenge from a coefficient. The detailed proofs appear in a different order: Section 4 proves the subspace-locator results and develops tools used in Section 5 to prove the Gold results, while Section 6 proves the decision-tree results.

2.1 Common framework: from polynomial families to counterexamples

Choosing the inputs and codewords. Let $\mathbb{F}$ be the challenge field, let $D \subseteq \mathbb{F}$ be the evaluation domain, and put $N = |D|$. Fix a message length $1 \leq K < N$: codewords are evaluations on D of polynomials over $\mathbb{F}$ of degree strictly less than K . Inputs f, g are functions $D \rightarrow \mathbb{F}$, and $f + zg$ means the function $x \mapsto f(x) + zg(x)$.

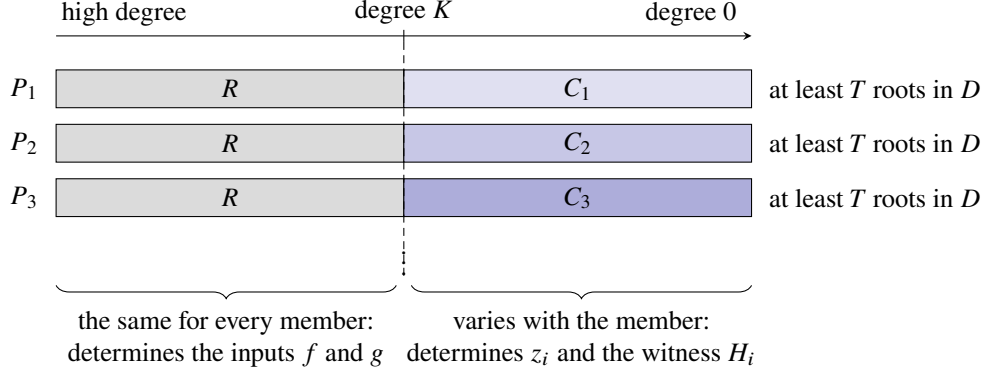


Figure 1: The input to pole reduction, drawn as coefficient vectors. Every member $P_i = R + C_i$ of the family has at least T roots in D , and all members have the same coefficients above degree K . The shared part determines the two input words, which are fixed before the challenge is sampled. The varying part has degree at most K and determines only the challenge and its witness. When $T > K$, each member gives an exceptional challenge. Throughout the figures, gray marks data shared by the whole family and blue marks data that depends on the member.

A polynomial of degree less than K that agrees with a combination $f + zg$ on a specified set of positions is called an *explaining polynomial*, or *witness*, for that agreement. Suppose we can construct a family

$$P_i = R + C_i, \quad \deg C_i \leq K, \quad i = 1, \dots, L,$$

in which every P_i has at least T roots in D for some $T > K$, the polynomial R is fixed, and the C_i are distinct. We call C_i the *correction* to R in P_i . The degree condition says that all family members have the same coefficients above degree K (Figure 1).

Assume $\mathbb{F}$ contains a point outside D . Choose such a point β , called the *pole*, and fix

$$f(x) = \frac{R(x)}{x - \beta}, \quad g(x) = \frac{1}{x - \beta} \quad (x \in D).$$

For the i th family member, take $z_i = C_i(\beta)$ and

$$H_i(X) = -\frac{C_i(X) - C_i(\beta)}{X - \beta}.$$

The numerator vanishes at β , so it is divisible by $X - \beta$. Division reduces its degree by one, making H_i a polynomial of degree strictly less than K . At every $x \in D$,

$$f(x) + z_i g(x) - H_i(x) = \frac{R(x) + C_i(x)}{x - \beta} = \frac{P_i(x)}{x - \beta}.$$

Hence $f + z_i g$ agrees with the codeword of H_i at every root of P_i in D , that is, on at least T positions. Only the challenge and the witness depend on C_i . We call the conversion of the family $P_i = R + C_i$ into the fixed inputs f, g , challenges z_i , and witnesses H_i *pole reduction* (Lemma 3.11).

Common agreement. Write $\text{CA}_K(f, g)$ for the largest number of positions on which f and g simultaneously match two codewords, which may be different. Write $\text{agr}_K(g)$ for the largest number of positions on which g matches one codeword. If g agrees with a polynomial h of degree less than K , each agreement point is a root

of $(X - \beta)h(X) - 1$. This polynomial has value -1 at β , so it is nonzero; its degree is at most K , so it has at most K roots. Thus $\text{CA}_K(f, g) \leq \text{agr}_K(g) \leq K$. Conversely, on any chosen K positions we can interpolate f and g separately by polynomials of degree less than K . Thus

$$\text{agr}_K(g) = \text{CA}_K(f, g) = K.$$

Since $T > K$, every challenge constructed above makes the combination agree with a codeword on more positions than the two inputs can share.

Counting distinct challenges. The construction supplies at least as many exceptional challenges as there are distinct values among $z_1, \dots, z_L$, which can be fewer than L . Two family members give the same challenge exactly when β is a root of $C_i - C_j$, a nonzero polynomial of degree at most K . Each pair therefore collides at at most K poles. Summing over all $\binom{L}{2}$ pairs gives at most $K\binom{L}{2}$ collisions across the $q - N$ possible poles, where q is the challenge-field size. Some pole consequently has at most $K\binom{L}{2}/(q - N)$ colliding pairs. If a pole has c colliding pairs, keeping just one polynomial per challenge discards at most c polynomials and leaves at least $L - c$ distinct challenges. Lemma 3.19 also gives a stronger bound when c is large.

Where the families come from. Here an *additive domain* is a vector space over $\mathbb{F}_2$, and an *affine subspace* is a translate $W + a = \{w + a : w \in W\}$ of a linear subspace W . The *vanishing polynomial*, or *locator*, of any finite set S is $L_S(X) = \prod_{s \in S} (X - s)$: its leading coefficient is one (it is *monic*), and its roots are exactly the points of S , each occurring once. When $S = W$ is an $\mathbb{F}_2$ -subspace, its locator is *linearized* [8], meaning that its exponents are powers of two (Section 3.2 recalls why):

$$L_W = X^{|W|} + a_W X^{|W|/2} + b_W X^{|W|/4} + \dots + c_W X.$$

In characteristic two, $(X + Y)^{2^j} = X^{2^j} + Y^{2^j}$, so a linearized polynomial is additive: $L_W(X + Y) = L_W(X) + L_W(Y)$. Translating W by a therefore changes its locator only by a constant, since $L_{W+a}(X) = L_W(X - a) = L_W(X) - L_W(a)$. All affine subspaces of size $|W|$ thus have locators with leading term $X^{|W|}$ and all remaining terms of degree at most $|W|/2$. This *gap* below the leading term is what gives us shared high-degree coefficients.

The constructions choose different root sets. Gold uses functions with values in $\{0, 1\}$, called *Boolean functions*, that are quadratic in binary coordinates. Their level sets—the points where a function has a specified value—are unions of translates of one common subspace. The subspace-locator construction uses individual subspaces. Decision trees use unions of affine subspaces in different directions.

2.2 Construction 1: Gold moments on dense domains

To obtain superpolynomially many exceptional challenges near Johnson, we need more root sets than subspaces whose dimension is a fixed amount below the domain dimension can supply. We use the sets on which quadratic Boolean functions take the value one. From each such set E we will construct a polynomial P_E vanishing on E . We need these polynomials to have identical coefficients in every degree above K , so that $P_E = R + C_E$ with a fixed R and $\deg C_E \leq K$.

Let $D \subseteq \mathbb{B} = \mathbb{F}_{2^m}$ be a binary additive subspace of dimension d , put $N = 2^d$, and set $K = N/4$. The polynomials are defined over $\mathbb{B}$; challenges may come from a larger field $\mathbb{F} \supseteq \mathbb{B}$. We first describe the form of the vanishing polynomials we need, then how the Gold moment equations produce it, and finally why the resulting family gives many distinct challenges.

Building polynomials with shared coefficients. Let λ be the coefficient of X in L_D . The *formal derivative* uses the usual rule $(X^j)' = jX^{j-1}$, with coefficients computed in the field. In characteristic two, terms with even exponent therefore have derivative zero. Hence $L'_D = \lambda$, and $\lambda \neq 0$ because L_D has no repeated roots. Squaring is a bijection on a finite binary field and produces no cross terms. Since all other exponents in L_D are even, we can halve those exponents and take square roots of their coefficients. Thus

$$R = \sqrt{L_D - \lambda X}$$

is a polynomial of degree $N/2$. The square-root symbol here denotes a polynomial whose square is $L_D - \lambda X$. Suppose a set $E \subseteq D$ has a locator $L_E = U^2 + c_E X$, where U is a polynomial and $c_E \neq 0$ is a scalar. The linear terms cancel in

$$(R + \sqrt{\lambda/c_E} U)^2 = L_D + (\lambda/c_E) L_E.$$

Set $P_E = R + \sqrt{\lambda/c_E} U$. For $x \in E$, both locators on the right vanish, so $P_E(x)^2 = 0$ and hence $P_E(x) = 0$. At the other points of D only L_D vanishes, so the roots of P_E in D are exactly the points of E . Its correction to R has degree $|E|/2$. Sets of size just below $N/2$ therefore give agreement just below Johnson at rate $1/4$. The problem is now to find many sets of that size whose locators are squares plus linear terms.

Selecting quadratic functions. Choose a binary basis of D , so each point has coordinates $x_1, \dots, x_d \in \mathbb{F}_2$. A *quadratic Boolean function* is a function $\psi : D \rightarrow \mathbb{F}_2$ given by a polynomial of degree at most two in these coordinates. It has an associated bilinear form

$$B_\psi(x, y) = \psi(x + y) + \psi(x) + \psi(y) + \psi(0),$$

which is linear in each argument separately. Writing x, y as column vectors in binary coordinates, we have $B_\psi(x, y) = x^T A y$, where A is symmetric with zero diagonal. The entries A_{ij} for $i < j$ are the coefficients of the cross terms $x_i x_j$ in ψ ; linear and constant terms disappear from B_ψ . Such a matrix has even rank over $\mathbb{F}_2$, say $2t$. After a change of coordinates and a choice of the linear terms, we can write

$$\psi(x) = x_1 x_2 + x_3 x_4 + \dots + x_{2t-1} x_{2t} + c, \quad c \in \mathbb{F}_2.$$

Each product is zero on three of the four inputs and one on the fourth. Its number of zeros minus its number of ones, $\sum_{u,v \in \mathbb{F}_2} (-1)^{uv}$, is therefore 2. Multiplying these sums over the t independent pairs and counting the $d - 2t$ unused coordinates gives an absolute difference $2^t 2^{d-2t} = N/2^t$ between the numbers of zeros and ones. Choosing c makes the ones the smaller class, of size

$$T = \frac{N}{2} - \frac{N}{2^{t+1}}.$$

In this form ψ does not depend on the last $d - 2t$ coordinates. The points whose first $2t$ coordinates vanish form a subspace V of size $N/2^{2t}$, called the *polar radical* of ψ , and the set of ones is a union of translates of V . Increasing t brings this agreement toward $N/2$. We still need the locator of the set of ones to have the form $U^2 + c_E X$ above; the rank condition alone does not ensure this.

The *Gold moment equations* select matrices for which this additional property holds. To state them, represent the i th coordinate function $x \mapsto x_i$ on D by its unique linearized polynomial ℓ_i of degree at most $N/2$ (Lemma 5.5). Define its *label* by $\omega_i = \sqrt{\ell'_i}$: since ℓ_i is linearized, ℓ'_i is just its coefficient of X , a field element. The lemma shows that $\omega_1, \dots, \omega_d$ are linearly independent. Their binary span, denoted $\widehat{D}$, need not equal D ; it records the coordinate functions rather than the evaluation points. For $2 \leq t \leq d/2$, we impose

$$M_k(A) := \sum_{i < j} A_{ij} (\omega_i \omega_j^{2^k} + \omega_j \omega_i^{2^k}) = 0, \quad k = 1, \dots, t-1. \quad (2.1)$$

Here $M_k(A)$ names the field element on the left, called the k th Gold moment. The name comes from the powers x^{2^k+1} studied by Gold [28]. The equations cancel specific coefficients in the polynomial representing ψ . Lemma 5.12 shows that, when A has rank $2t$, suitable linear and constant terms then give a set of ones of size T whose locator is $U^2 + c_E X$. Lemma 3.16 converts this property into the polynomial $P_E = R + C_E$ needed for pole reduction. The argument works on the prescribed additive domain D , even when D is not a field.

Why the moment equations give this form. The mechanism is a comparison of a degree with a number of roots. Let E be the set of ones of ψ , with the linear and constant terms chosen as above, and let H be the polynomial of degree less than N that agrees with ψ on D . It is one on E and zero on the $N - T$ points of $D \setminus E$. The moment equations cancel the top coefficients of H and leave $\deg H \leq N/2 + N/2^{t+1} = N - T$. A nonzero polynomial of degree at most $N - T$ with $N - T$ roots is a scalar multiple of the locator of those roots, so $L_D = c H L_E$ for a nonzero scalar c . Differentiating gives $\lambda = c (H' L_E + H L'_E)$. At each point of E we have $L_E = 0$ and $H = 1$, so L'_E takes the value λ/c at all T points of E . Its degree is less than T , so it is constant. In characteristic two, a polynomial with constant derivative c_E is a square plus $c_E X$, which is the required form.

Why there are many solutions on dense domains. There are $\binom{d}{2}$ free binary entries A_{ij} with $i < j$. Each moment equation is linear in those entries and takes values in the m -dimensional binary field $\mathbb{B}$, so it imposes at most m binary linear constraints. The $t - 1$ equations leave a solution space of dimension at least $\binom{d}{2} - m(t - 1)$. This supplies many matrices, but we need matrices of rank exactly $2t$, not just many matrices of unspecified rank. The Gold moment equations force every nonzero solution matrix to have rank at least $2t$. An identity of Delsarte and Goethals [20, Eq. (29)] then gives a lower bound on the number of solutions of rank exactly $2t$ (Lemma 5.13).

This is where domain density matters. When $m - d$ is fixed, so D occupies a constant fraction of $\mathbb{B}$, we can take t proportional to d and obtain $N^{\Omega(\log N)}$ distinct polynomials $P_E = R + C_E$, while T/N approaches $1/2$. The argument does not give this count on sparse domains. The density requirement concerns the field $\mathbb{B}$ containing D , not the larger field from which challenges are drawn.

The family already gives a list-decoding counterexample: at a root x of $P_E = R + C_E$, we have $R(x) = -C_E(x)$. Thus the fixed word obtained by evaluating R on D agrees with the codeword obtained from $-C_E$ on at least T positions. These are codewords because $\deg C_E = T/2 < K$. Thus one word has a superpolynomial decoding list at agreement approaching Johnson.

From the family to distinct challenges. Each polynomial $P_E = R + C_E$ produces an exceptional challenge $z_E = C_E(\beta)$ for the same pair of inputs, whose common agreement is $N/4$. Distinct polynomials can give the same challenge: E and E' collide at the pole β when $P_E(\beta) = P_{E'}(\beta)$. The generic bound of Section 2.1 allows up to K colliding poles for each pair. The Gold equations give a much smaller bound: two distinct family members take the same value at at most $N/2^{2t}$ points outside D (Lemma 5.12). Averaging over poles as before then gives a pole at which a constant fraction of the family has distinct challenges, once the challenge field is large enough. The generic bound would already give superpolynomial counts over sufficiently large fields; the sharper one matters for the size of the field and for the concrete bounds. The pair used in the theorems replaces the first input by one that is individually far from the code; this translates every challenge by the same constant (Lemma 3.13).

Section 5.7 specializes these bounds to Binius64's domain and challenge field; Section 5.8 treats Google's Longfellow.

2.3 Construction 2: subspace locators on arbitrary additive domains

Our second construction works directly with subspaces and does not require a dense domain. There are roughly $N^2/6$ subspaces in the family we use. To obtain that many exceptional challenges, we must assign a different challenge to each subspace. We do this by combining two coefficients of its locator into one field element, as described below.

Let D have size $N = 16K$, with $K \geq 2$, and first suppose it lies in a proper subfield $\mathbb{B}$ of the challenge field $\mathbb{F}$. There are $(N - 1)(N - 2)/6$ subspaces $W \leq D$ of codimension two, meaning dimension two less than D . Each has size $N/4 = 4K$, and its locator is

$$L_W = X^{4K} + a_W X^{2K} + b_W X^K + V_W, \quad \deg V_W \leq K/2.$$

The pair (a_W, b_W) determines W . Indeed, two codimension-two subspaces intersect in codimension at most four, so their intersection has at least $N/16 = K$ points. If their locators have the same a_W, b_W , their difference has degree at most $K/2$ and vanishes at all these points. A nonzero polynomial cannot have more roots than its degree, so the locators are equal (Lemma 3.9). But a_W alone need not determine W , and it is the only varying coefficient above degree K . To combine a_W and b_W in one challenge, we square the locator and add a multiple of L_W that makes the coefficient of X^{4K} independent of W . Choose $\theta \in \mathbb{F} \setminus \mathbb{B}$ and set

$$P_W = L_W^2 + (a_W^2 + \theta)L_W = X^{8K} + \theta X^{4K} + z_W X^{2K} + C_W, \quad z_W = a_W^3 + b_W^2 + \theta a_W, \quad \deg C_W \leq K.$$

This polynomial still vanishes on W . Its high-degree coefficients are fixed except for z_W , which will be the challenge. Since all terms are divisible by X , we take

$$f = X^{8K-1} + \theta X^{4K-1}, \quad g = X^{2K-1}, \quad H_W = C_W/X.$$

Here f, g denote the evaluations of these polynomials on D ; division by X is polynomial division before evaluation, so both words are defined even at $x = 0$. Then H_W has degree strictly less than K , and $f + z_W g - H_W = P_W/X$ vanishes on $W \setminus \{0\}$. This gives $N/4 - 1$ agreement positions. We lose the root at zero because removing a factor X can remove that root. The exact Johnson threshold is $\sqrt{N(K-1)}$, which lies just below $N/4 - 1$ when $N = 16K$. The inputs have common agreement $N/8 - 1 = 2K - 1$: subtracting a polynomial of degree less than K from $g = X^{2K-1}$ leaves a nonzero polynomial of degree $2K - 1$, with at most that many roots, and Theorem 4.1 shows that this number of common agreements is attained.

The challenges are distinct because 1 and θ are linearly independent over $\mathbb{B}$. In $z_W = (a_W^3 + b_W^2) + \theta a_W$, the coefficient of θ recovers a_W ; the remaining coefficient then recovers b_W^2 , and squaring is one-to-one in $\mathbb{B}$. Thus z_W determines a_W, b_W and hence W . If no proper subfield contains D , this argument for distinctness is unavailable. But each pair of subspaces gives the same challenge for at most one choice of θ : equality is a linear equation in θ , or is impossible if the a_W coefficients agree. Averaging these collisions over $\theta \in \mathbb{F}$ gives at least $\lceil qM/(q + M - 1) \rceil$ distinct challenges, where $M = (N - 1)(N - 2)/6$ and $q = |\mathbb{F}|$ (Corollary 4.2). When $q \geq M$, more than half the quadratic count survives; smaller fields give a smaller count. Thus the construction also covers arbitrary additive domains in the challenge field.

Higher counts and arbitrary rates. For fixed s , subspaces of codimension s provide a number of root sets proportional to N^s , with constants depending on s . A similar cancellation using powers of their locators encodes their first s coefficients into one challenge. The encoding is one-to-one when the challenge field has degree at least $s + 1$ over a field containing D ; otherwise the averaging argument above bounds the collisions. Increasing s gives larger counts at lower agreement fractions (Lemma 4.3). To reach other rates, we build such a pair on a smaller subspace and multiply its inputs and witnesses by a vanishing polynomial, adding a fixed set of agreement points. This preserves a positive agreement gap while setting the desired rate.

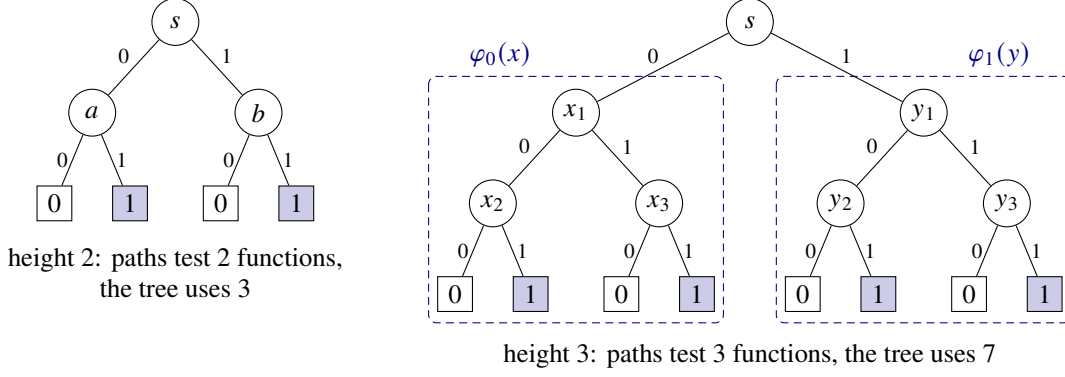


Figure 2: Decision trees of heights two and three. Each circle tests one binary linear function on D , and all functions appearing in a tree are linearly independent. A point of D follows one path from the root, and the support A consists of the points that reach a shaded leaf. Every leaf is an affine subspace cut out by the tests on its path: at height h it has $N/2^h$ points, and the 2^{h-1} shaded leaves together contain $N/2$ points. The whole tree uses $2^h - 1$ independent functions. The dashed boxes mark the two children in the recursion $\varphi = (1 + s)\varphi_0(x) + s\varphi_1(y)$.

Here M denotes the number of root sets in this higher-codimension family. If the challenge field has size $q \leq N^a$ for a fixed exponent a , choosing $s > 2a$ makes $M > (q - 1)^2$ for all sufficiently large N . The same collision-counting argument gives more than $q - 1$ distinct challenges: $qM/(q + M - 1) > q - 1$, so there must be all q possible challenges. Combining this choice with the preceding multiplication step gives, at every fixed rate, a pair for which every challenge is exceptional by a fixed positive agreement gap (Theorem 4.5). The gap depends on the rate and a ; it need not be close to Johnson.

2.4 Construction 3: decision trees for sparse domains

Decision trees give much larger families on sparse domains by allowing different branches to test different linear functions $D \rightarrow \mathbb{F}_2$. A point $x \in D$ follows a branch according to whether each tested function is zero or one at x ; the final output is also zero or one. A leaf represents all points following one path. Its tests are linear equations, so that set is an affine subspace. We use the points with output one as the root set.

Branching creates more choices. For example, choose three independent binary linear functions s, a, b on D . Test s first; if it is zero, output a , and otherwise output b . The set on which this rule outputs one is

$$A = \{x \in D : s(x) = 0, a(x) = 1\} \cup \{x \in D : s(x) = 1, b(x) = 1\}.$$

Each part is an affine subspace of size $N/4$, and the parts are disjoint, so $|A| = N/2$. Each path uses two tests, although the tree uses three independent functions (Figure 2).

For $h \geq 2$, a full tree of height h makes h tests on each path and uses $2^h - 1$ linear functions altogether. As in the example, its output is the value of the last tested function; more generally, each branch may output that value or its complement. We require all these functions to be linearly independent, which is possible when $\dim_{\mathbb{F}_2} D \geq 2^h - 1$. Every path fixes h independent bits, leaving $N/2^h$ points. Half of the 2^h leaves output one, so the root set A is a union of 2^{h-1} disjoint affine subspaces and has size $N/2$. The count of distinct sets, rather than just distinct choices of tests, is $\Theta_h(N^{2^{h-1}})$; the subscript allows the constants to depend on fixed h (Lemma 6.6). Different trees can give the same set, but only in a bounded number of ways: the set determines the span of the tested functions, and for $h \geq 3$ it determines the root test and the two subtrees, while for $h = 2$

of order N^h for fixed h . The resulting number of distinct sets is $\Theta_h(N^{2^h-h-1})$. After accounting for challenge collisions, Theorem 6.10 gives

$$\Omega_h(\min\{N^{2^h-h-1}, q/N\})$$

exceptional challenges at agreement fraction $1/2 + 2^{-h-1}$, where q is the challenge-field size. This is a guaranteed count: a family much smaller than q/N loses few challenges to collisions, and a larger one still guarantees on the order of q/N . The finite bounds improve the collision estimate by using the roots that two locators already share inside D : those roots leave fewer possible collisions outside D .

After these restrictions, height three gives a family of order N^4 at agreement 9/16; height four gives order N^{11} at agreement 17/32. Thus taller trees give larger families while bringing the combination agreement closer to the common agreement 1/2. For LeanVM's length 2^{22} and 192-bit challenge field, height four already supplies enough sets that the finite bound guarantees at least 2^{172} distinct exceptional challenges. Dividing by the 2^{192} possible challenges gives exceptional probability at least 2^{-20} . Section 6 proves the counts and the finite bounds used for LeanVM and Flock.

3 Notation and common tools

Every construction uses the notation below, the locators and pole reduction of Section 3.2, and the collision averaging of Section 3.5. Section 3.3 serves only to make both inputs individually far from the code, Section 3.4 only the Gold construction, and padding only the moves to other rates.

3.1 Notation and agreement

All fields in this paper are finite. Throughout this section, let $\mathbb{F}$ be a field, let $D \subseteq \mathbb{F}$ have size $N \geq 2$, and fix a message length $1 \leq K < N$. Most constructions use characteristic two; Section 5.9 also treats other characteristics.

Definition 3.1 (Reed–Solomon code and received words). The *Reed–Solomon code* on D with message length K is

$$C_K(D; \mathbb{F}) = \{(P(x))_{x \in D} : P \in \mathbb{F}[X], \deg P < K\}.$$

Its length is N , its message length (dimension) is K , and its *rate* is $\rho = K/N$. A *received word* is any function $f : D \rightarrow \mathbb{F}$, without a promise that it belongs to $C_K(D; \mathbb{F})$.

We measure agreement in numbers of coordinates.

Definition 3.2 (Individual and common agreement). For received words $f, g : D \rightarrow \mathbb{F}$, their *individual agreement* and *common agreement* with the code are

$$\begin{aligned} \text{agr}_K(f) &= \max_{\substack{F \in \mathbb{F}[X] \\ \deg F < K}} |\{x \in D : f(x) = F(x)\}|, \\ \text{CA}_K(f, g) &= \max_{\substack{F, G \in \mathbb{F}[X] \\ \deg F, \deg G < K}} |\{x \in D : f(x) = F(x), g(x) = G(x)\}|. \end{aligned}$$

The corresponding *agreement fractions* are $\text{agr}_K(f)/N$ and $\text{CA}_K(f, g)/N$. The relative Hamming distance of f to the code is $1 - \text{agr}_K(f)/N$. The *two-word interleaved code* consists of the words $x \mapsto (c_1(x), c_2(x))$ with $c_1, c_2 \in C_K(D; \mathbb{F})$, viewed over alphabet $\mathbb{F}^2$.

The two input words are chosen before the challenge is sampled.

Definition 3.3 (Received line and exceptional challenges). For fixed inputs $f, g : D \rightarrow \mathbb{F}$, the *received line* is $\{f + zg : z \in \mathbb{F}\}$. The scalar z is called a *challenge*. At an integer agreement threshold T , define

$$\text{Bad}_T(f, g) = \{z \in \mathbb{F} : \text{agr}_K(f + zg) \geq T\}.$$

Its elements are the *exceptional challenges* at threshold T . Their *exceptional probability* under uniform sampling is $|\text{Bad}_T(f, g)|/|\mathbb{F}|$.

We use this set as a counterexample when $T > \text{CA}_K(f, g)$. Its size counts distinct challenges for one fixed received pair, even if several polynomials explain the same combination. Mutual correlated agreement at threshold T requires that, outside a small set of challenges, f and g agree with codewords on the very set where $f + zg$ does. In particular it requires $\text{CA}_K(f, g) \geq T$ as soon as one such challenge exists. So when $T > \text{CA}_K(f, g)$, every challenge in $\text{Bad}_T(f, g)$ violates this conclusion, and it also violates the weaker conclusion that f and g agree with codewords on some common set of size T . List decoding counts a different object: distinct codewords close to one fixed word.

Definition 3.4 (Explaining polynomials, witnesses, and decoding lists). An *explaining polynomial* for a word f on a set $A \subseteq D$ is a polynomial $H \in \mathbb{F}[X]$ with $\deg H < K$ and $H(x) = f(x)$ for all $x \in A$. A *witness* for $z \in \text{Bad}_T(f, g)$ is an explaining polynomial for $f + zg$ on at least T coordinates. The *decoding list* of f at threshold T is

$$\mathcal{L}_T(f) = \{c \in C_K(D; \mathbb{F}) : |\{x \in D : f(x) = c(x)\}| \geq T\}.$$

Its *list size* is $|\mathcal{L}_T(f)|$.

Since $K < N$, distinct polynomials of degree less than K give distinct codewords. Thus counting polynomials in a decoding list is equivalent to counting its codewords.

Definition 3.5 (Agreement thresholds and gaps). At rate $\rho = K/N$, the *Johnson agreement threshold* is $\sqrt{N(K-1)}$ coordinates, with limiting agreement fraction $\sqrt{\rho}$. We call ρ the *capacity threshold* in agreement fraction. For an agreement target T , its *Johnson deficit* is $\sqrt{\rho} - T/N$. It is measured against the limiting fraction $\sqrt{\rho}$, not against the exact finite threshold. For inputs f, g , the *common-agreement gap* at this target is

$$\frac{T - \text{CA}_K(f, g)}{N}.$$

An input f is *individually far* at threshold T if $\text{agr}_K(f) < T$.

Going beyond Johnson means allowing more errors, or equivalently requiring agreement on fewer coordinates. The lower reference value ρ corresponds to the message length K : interpolation always explains any word on any chosen K coordinates.

The common-agreement gap. Put $C = \text{CA}_K(f, g)$. The distance of (f, g) to the interleaved code is $1 - C/N$, whereas a combination agreeing on T coordinates has distance at most $1 - T/N$. Such a combination exceeds the proximity loss ϵ^* permitted in the formulation of Ben-Sasson et al. [5, Definition 1.1] whenever

$$\epsilon^* < \frac{T - C}{N}.$$

This is a different quantity from the Johnson deficit $\sqrt{\rho} - T/N$. A large exceptional set with only one coordinate between T and C does not exclude a fixed positive fractional loss.

Field and polynomial notation. We write $\mathbb{B}$ for a field containing the domain before extending the challenge field to $\mathbb{F}$. For $\mathbb{B} = \mathbb{F}_{b^m}$, the field trace to $\mathbb{F}_b$ is $\text{Tr}_{\mathbb{B}/\mathbb{F}_b}(x) = \sum_{i=0}^{m-1} x^{b^i}$. We write $\text{lc}(P)$ for the leading coefficient of a nonzero polynomial P .

Definition 3.6 (Canonical polynomial representative). For a function $u : \mathbb{B} \rightarrow \mathbb{B}$ on a finite field $\mathbb{B}$, its *canonical representative* is the unique polynomial $H \in \mathbb{B}[X]$ of degree less than $|\mathbb{B}|$ with $H(x) = u(x)$ for all $x \in \mathbb{B}$. If P is any polynomial representing u on $\mathbb{B}$, then H is its remainder modulo $X^{|\mathbb{B}|} - X$. More generally, for a function $u : D \rightarrow \mathbb{B}$ on a subset $D \subseteq \mathbb{B}$, its canonical representative is the unique polynomial of degree less than $|D|$ that agrees with u on D ; it is the remainder modulo the vanishing polynomial $\prod_{x \in D} (X - x)$ of any polynomial representing u on D .

This reduction preserves values on $\mathbb{B}$, but can change values in an extension field. When evaluating outside $\mathbb{B}$, we always use the specified polynomial representative. Subscripts on asymptotic notation indicate parameters on which the implicit constants may depend; the variable tending to infinity is the code length. Table 4 collects the symbols that keep one meaning throughout the paper.

Gaussian binomial coefficients. For a prime power q and integers $a \geq 0$ and b , the *Gaussian binomial coefficient* $\begin{bmatrix} a \\ b \end{bmatrix}_q$ is the number of b -dimensional subspaces of $\mathbb{F}_q^a$. It is zero when $b < 0$ or $b > a$, and otherwise

$$\begin{bmatrix} a \\ b \end{bmatrix}_q = \prod_{i=0}^{b-1} \frac{q^{a-i} - 1}{q^{b-i} - 1}.$$

The subscript is the size of the field over which dimensions are counted, so $\begin{bmatrix} a \\ b \end{bmatrix}_4$ counts subspaces over $\mathbb{F}_4$. We use four consequences of the product formula.

- *Size.* Let $0 \leq b \leq a$. Each factor is at least q^{a-b} , and $\prod_{j \geq 1} (1 - q^{-j})^{-1} < 4$, so

$$q^{b(a-b)} \leq \begin{bmatrix} a \\ b \end{bmatrix}_q < 4q^{b(a-b)}.$$

Thus $\log_q \begin{bmatrix} a \\ b \end{bmatrix}_q = b(a-b) + O(1)$, with an absolute constant.

- *Symmetry.* $\begin{bmatrix} a \\ b \end{bmatrix}_q = \begin{bmatrix} a \\ a-b \end{bmatrix}_q$.
- *Removing one dimension.* For $0 \leq b < a$,

$$\frac{q^{a-b} - 1}{q^a - 1} \begin{bmatrix} a \\ b \end{bmatrix}_q = \begin{bmatrix} a-1 \\ b \end{bmatrix}_q.$$

- *Small cases over $\mathbb{F}_2$.* With $N = 2^d$,

$$\begin{bmatrix} d \\ 1 \end{bmatrix}_2 = N - 1, \quad \begin{bmatrix} d \\ 2 \end{bmatrix}_2 = \frac{(N-1)(N-2)}{6}, \quad \begin{bmatrix} d \\ 3 \end{bmatrix}_2 = \frac{(N-1)(N-2)(N-4)}{168}.$$

3.2 Additive locators and pole reduction

The following properties of subspace locators supply the shared high-degree coefficients used in our constructions.

Symbol	Meaning
$\mathbb{F}, q$	Challenge field and its size; all words take values in $\mathbb{F}$
$\mathbb{B}$	Field containing the domain, before any extension to $\mathbb{F}$
D, N, d	Evaluation domain, its size, and its dimension when D is additive
K, ρ	Message length (degrees are less than K) and rate K/N
T, α	Agreement threshold for the combination, in coordinates and as a fraction
$\text{agr}_K, \text{CA}_K, \gamma$	Individual agreement, common agreement, and (in the summary tables) the common-agreement fraction $\text{CA}_K(f, g)/N$
$\text{Bad}_T(f, g), z$	Exceptional challenges at threshold T ; a challenge
$\begin{bmatrix} a \\ b \end{bmatrix}_q$	Number of b -dimensional subspaces of $\mathbb{F}_q^a$ (Gaussian binomial coefficient)
L_S	Locator of a finite set S
λ, λ_0	The constant derivative L'_D of the locator of an additive domain
β	Pole outside the domain in a received pair $R(x)/(x - \beta), 1/(x - \beta)$
R, C_i	Common part and distinct low-degree parts of the polynomials $R + C_i$
w	Number of padded coordinates; for decision trees, also the degree gap $N/2^{h+1}$ of the same size

Table 4: Notation used throughout. Other letters are local to the statement or proof that introduces them.

Definition 3.7 (Additive domains and affine flats). In characteristic two, a *binary additive domain* is a vector subspace of $\mathbb{F}$ over $\mathbb{F}_2$. Its dimension is measured over $\mathbb{F}_2$. An *affine flat* is a translate of a linear subspace; an *affine domain* is such a flat used as the evaluation domain. More generally, when $\mathbb{F}_b \subseteq \mathbb{F}$, an affine $\mathbb{F}_b$ -space is a translate of an $\mathbb{F}_b$ -linear subspace of $\mathbb{F}$.

Definition 3.8 (Locators and linearized polynomials). For a finite set $S \subseteq \mathbb{F}$, its *locator*, or vanishing polynomial, is

$$L_S(X) = \prod_{x \in S} (X - x).$$

In characteristic two, a *binary linearized polynomial* is a polynomial of the form $L(X) = \sum_i a_i X^{2^i}$ with $a_i \in \mathbb{F}$. We call a polynomial *additive* if it satisfies the polynomial identity $L(X + Y) = L(X) + L(Y)$.

The locator is monic and has exactly the points of S as its roots, each with multiplicity one. As discussed in the technical overview (Section 2.1), the locator L_W of a binary linear space W is linearized [8]. To see this, build W one basis vector at a time. The locator of $\{0\}$ is X . If L_W is linearized and $v \notin W$, then the locator of $W \cup (W + v)$ is

$$L_W(X) L_W(X + v) = L_W(X)^2 + L_W(v) L_W(X),$$

and squares and scalar multiples of linearized polynomials are linearized. Every binary linearized polynomial is additive, since taking a power of two commutes with addition in characteristic two. Translating W changes only the constant term of its locator. An affine flat of size 2^r with $r \geq 1$ therefore has locator X^{2^r} plus terms of degree at most 2^{r-1} . Its roots are simple, so its derivative is a nonzero constant c ; every exponent other than one is even, so adding cX gives the square of a polynomial of degree 2^{r-1} .

Two further facts about locators are used in Section 4. The first lets a few coefficients of a subspace locator stand for the subspace. The second recognizes a subspace locator from a polynomial identity.

Lemma 3.9 (Leading coefficients determine the subspace). Let D be a binary additive domain of dimension d , and let $s \geq 1$ with $d \geq 2s$. For a subspace $W \leq D$ of codimension s , write

$$L_W = X^{2^{d-s}} + \sum_{i=1}^{d-s} a_i(W) X^{2^{d-s-i}}.$$

Then W is determined by $a_1(W), \dots, a_s(W)$.

Proof. Let W, W' have the same first s coefficients. If $d = 2s$, these are all the coefficients, so $L_W = L_{W'}$. If $d > 2s$, the difference $L_W - L_{W'}$ has degree at most 2^{d-2s-1} and vanishes on $W \cap W'$, which has codimension at most $2s$ in D and hence at least 2^{d-2s} points. The difference is therefore zero. In both cases $W = W'$. $\square$

Lemma 3.10 (Inner polynomials of additive compositions). Let $L, A, P \in \mathbb{F}[X]$ satisfy $L = A \circ P$, that is, $L(X) = A(P(X))$. If L and A are additive, $A \neq 0$, and $P(0) = 0$, then P is additive. In particular, the roots of P in $\mathbb{F}$ form an additive subgroup.

Proof. Put $\Phi(X, Y) = P(X+Y) - P(X) - P(Y)$. Since L and A are additive, $A(\Phi) = 0$. If Φ were nonconstant, the highest-degree term of $A(\Phi)$ could not cancel. Thus Φ is constant, and $\Phi(X, 0) = -P(0) = 0$ makes it zero. $\square$

We also apply Lemma 3.10 to the locator of an affine flat, after subtracting the constant terms of L and P .

The next lemma performs *pole reduction*: the shared part R determines the first input, and each correction C_i determines a challenge and its explaining polynomial. Choosing the pole β outside the domain makes all denominators nonzero at evaluation points.

Lemma 3.11 (From common high coefficients to a received line). Let $1 \leq K < N$, and suppose $R + C_i \in \mathbb{F}[X]$, for i in a nonempty index set, have at least T roots on D , where the C_i are distinct and $\deg C_i \leq K$. For any $\beta \in \mathbb{F} \setminus D$, put

$$f(x) = \frac{R(x)}{x - \beta}, \quad g(x) = \frac{1}{x - \beta}, \quad z_i = C_i(\beta), \quad H_i(X) = -\frac{C_i(X) - C_i(\beta)}{X - \beta}.$$

Then $\deg H_i < K$ and $f + z_i g$ agrees with H_i on at least T coordinates. Moreover $\text{agr}_K(g) = \text{CA}_K(f, g) = K$. If each $R + C_i$ has degree $T > K$ and all its roots lie in D , one may instead take

$$\tilde{f}(X) = \frac{R(X) - R(\beta)}{X - \beta}, \quad \tilde{z}_i = (R + C_i)(\beta).$$

The same witnesses and common-agreement bound apply, every $\tilde{z}_i$ is nonzero, and $\text{agr}_K(\tilde{f}) \leq T - 1$.

More generally, for $1 \leq J < N$ and a polynomial A with $\deg A \leq J$ and $A(\beta) \neq 0$, the word $g_A(x) = A(x)/(x - \beta)$ satisfies $\text{agr}_J(g_A) = \text{CA}_J(u, g_A) = J$ for every received word u .

Proof. The numerator defining H_i vanishes at β , and at every $x \in D$,

$$f(x) + z_i g(x) - H_i(x) = \frac{R(x) + C_i(\beta) + C_i(x) - C_i(\beta)}{x - \beta} = \frac{R(x) + C_i(x)}{x - \beta}.$$

If g agrees with a polynomial G of degree less than K , the agreement points are roots of $(X - \beta)G - 1$. This polynomial is nonzero, has degree at most K , and takes value -1 at β . It has at most K roots. Interpolating both words on any K points gives equality for common agreement as well as individual agreement. For the second pair, $\tilde{f} + \tilde{z}_i g = f + z_i g$. The challenges $\tilde{z}_i$ are nonzero since $\beta \notin D$, and $\tilde{f}$ is a polynomial of degree $T - 1 \geq K$. Its difference from any codeword polynomial therefore has at most $T - 1$ roots. Finally, if g_A agrees with a polynomial h of degree less than J , the agreement points are roots of $(X - \beta)h - A$. This polynomial has degree at most J and takes the nonzero value $-A(\beta)$ at β , so it has at most J roots. Interpolating u and g_A on any J points gives both equalities. $\square$

Different corrections can have the same value at the pole, so their count alone does not yet give a count of distinct challenges.

3.3 Individual agreement bounds

A bound on common agreement limits the positions where both inputs can be explained at once. It need not limit either input on its own. We give two ways to obtain individual bounds: change the pair after extending the field, or bound the inputs directly in the existing field. The latter avoids a loss in exceptional probability from enlarging the challenge space.

Lemma 3.12 (Equal individual and common agreement). Let $f, g : D \rightarrow \mathbb{F}_0$, where $D \subseteq \mathbb{F}_0$, put $C = \text{CA}_K(f, g)$, and choose $s \in \mathbb{F} \setminus \mathbb{F}_0$ in a proper finite extension. The pair

$$F = f + sg, \quad G = f + (s + 1)g$$

satisfies $\text{agr}_K(F) = \text{agr}_K(G) = \text{CA}_K(F, G) = C$. For $T > C$, every old exceptional challenge $y \in \mathbb{F}_0$ gives the distinct nonzero exceptional challenge

$$z = \frac{y - s}{s + 1 - y}.$$

These are all the exceptional challenges except possibly $z = -1$, which is exceptional exactly when $\text{agr}_K(g) \geq T$.

Proof. Since f and g take values in $\mathbb{F}_0$, we can expand an explaining polynomial over $\mathbb{F}$ in a basis over $\mathbb{F}_0$ beginning with $1, z$, for $z \notin \mathbb{F}_0$. Taking the coefficients of these two basis elements gives

$$\text{agr}_{K, \mathbb{F}}(f + zg) = \text{CA}_{K, \mathbb{F}_0}(f, g). \quad (3.1)$$

An explaining polynomial for $f + zg$ projects to explaining polynomials for f and g on the same set; conversely, two such polynomials combine. Apply (3.1) with challenges s and $s + 1$ to obtain $\text{agr}_K(F) = \text{agr}_K(G) = C$. Explaining polynomials over $\mathbb{F}_0$ for f and g on a common set of C positions combine into explaining polynomials for F and G on that set, so $\text{CA}_K(F, G) \geq C$, and $\text{CA}_K(F, G) \leq \text{agr}_K(F) = C$. The challenge map is injective and nonzero, and

$$F + zG = \frac{f + yg}{s + 1 - y}.$$

For any $z \neq -1$, write $F + zG = (1 + z)(f + yg)$ with $y = s + z/(1 + z)$. If $y \in \mathbb{F}_0$, projection preserves the old agreement; otherwise (3.1) gives agreement exactly C . The remaining case is $F - G = -g$. $\square$

A quadratic extension suffices, but the exceptional probability is at most $(|\mathbb{F}_0| + 1)/|\mathbb{F}|$. For pole constructions on additive domains, the next lemma avoids this cost: it changes the first input within the same field and translates the exceptional set, preserving its size. Its binary case supplies the individual bound in the Binius64 example, including after multiplication by a polynomial to add agreement points. This multiplication is called *padding* (Section 3.5).

A prime denotes the formal derivative. In the lemma, b is a power of the characteristic, so taking a b th power is a bijection on the finite field; $c^{1/b}$ denotes its unique b th root. The locator of an affine $\mathbb{F}_b$ -space is a constant plus terms with exponents $1, b, b^2, \dots$, so its derivative is a nonzero constant λ . Removing λX leaves only exponents divisible by b ; taking roots of the coefficients then defines the polynomial $(L_D - \lambda X)^{1/b}$.

At a point $x \in D$ this polynomial takes the value $(-\lambda x)^{1/b}$. A polynomial C of degree $m \geq 1$ therefore agrees with it on at most bm points of D : the polynomial $C^b + \lambda X$ vanishes at every such point, has degree bm , and is nonzero because every exponent of C^b is divisible by b . At rate $1/b^2$, agreement equal to b times the message length is N/b , the asymptotic Johnson value; the exact threshold is $\sqrt{N(N/b^2 - 1)}$. This explains the rates $1/b^2$: the constructions below approach agreement fraction $1/b = \sqrt{\rho}$ from below.

Lemma 3.13 (Two individually far inputs). Let b be a prime power, let $\mathbb{F} \supseteq \mathbb{F}_b$ be finite, and let $D \subseteq \mathbb{F}$ be an affine $\mathbb{F}_b$ -space of size $N = b^d$, with $d \geq 3$. Put $K = N/b^2$, $\lambda = L'_D$, and $R = (L_D - \lambda X)^{1/b}$. For any $\beta \in \mathbb{F} \setminus D$, the pair

$$f(x) = \frac{(-\lambda(x - \beta))^{1/b}}{x - \beta}, \quad g(x) = \frac{1}{x - \beta}$$

satisfies

$$\text{agr}_K(f) \leq \frac{(b+1)K}{2} - 1, \quad \text{agr}_K(g) = \text{CA}_K(f, g) = K.$$

Replacing the first word of Lemma 3.11, with this R , by f translates its challenge set by $-(\lambda\beta)^{1/b}$. The number of exceptional challenges is unchanged, and zero is not exceptional when $T \geq (b+1)K/2$. For $b = 2$, the first input is $f(x) = \sqrt{\lambda/(x - \beta)}$ and its bound is $3N/8 - 1$. In this binary case, let A be any polynomial of degree w with $A(\beta) \neq 0$ and $3w \leq K - 1$. At the same message length K , the padded pair also satisfies

$$\text{agr}_K(Af) \leq \lfloor (3K + w - 1)/2 \rfloor, \quad \text{agr}_K(Ag) = \text{CA}_K(Af, Ag) = K.$$

Proof. Lemma 3.11 already bounds the agreement of g and the common agreement. For f , we construct a nonzero polynomial in which every agreement point is a double root. Its degree then bounds twice the number of agreements. Put $S = R + (\lambda\beta)^{1/b}$. On D , we have $S(x)^b = -\lambda(x - \beta)$, so $f(x) = S(x)/(x - \beta)$. For a polynomial h of degree less than K , its agreements with f are the roots on D of

$$P = S - (X - \beta)h.$$

This is monic of degree $bK = N/b$, with lower terms of degree at most K . A root bound on P alone would be too large. To obtain the double roots, set

$$Q = P^b - L_D, \quad \Omega = P'Q + \lambda P.$$

Since $S^b = L_D - \lambda(X - \beta)$, the entire L_D contribution cancels:

$$Q = -\lambda(X - \beta) - (X - \beta)^b h^b, \quad \deg Q \leq bK.$$

The derivative of S is constant, since its terms have exponents $0, 1, b, b^2, \dots$. The term of degree K in $(X - \beta)h$ has zero derivative, since the characteristic divides K . Hence $\deg P' \leq K - 2$ and $\deg \Omega \leq (b+1)K - 2$. Also $Q' = -\lambda$ gives $\Omega' = P''Q$. At every agreement point $P = L_D = 0$, both Ω and Ω' vanish. Each such point is therefore a double root. But $P(\beta)^b = L_D(\beta) \neq 0$, so $\Omega(\beta) = \lambda P(\beta) \neq 0$. Hence Ω is nonzero and has at most $\deg \Omega/2 \leq (b+1)K/2 - 1$ distinct agreement points. This proves the individual bound for f . Finally $f(x) = R(x)/(x - \beta) + (\lambda\beta)^{1/b}g(x)$ on D proves the challenge shift.

For the binary padding assertion, we use the same double-root argument after accounting for the multiplier A . Put $F = AS - (X - \beta)h$, $Q = F^2 + A^2L_D$, and $D_0 = AF' - A'F$. Since S' is constant,

$$D_0 = A^2S' - A(h + (X - \beta)h') + A'(X - \beta)h, \quad \deg D_0 \leq w + K - 1.$$

The last bound uses $\deg h < K$ and $2w \leq w + K - 1$. Every second derivative is zero in characteristic two, so $D'_0 = 0$ without any restriction on A' . Also $Q = \lambda A^2(X - \beta) + (X - \beta)^2 h^2$, so $\deg Q \leq 2K$ and $Q' = \lambda A^2$. Thus

$$\Omega = D_0Q + \lambda A^3F$$

has derivative zero and degree at most $\max\{w + 3K - 1, N/2 + 4w\} \leq w + 3K - 1$. Every agreement point is a root of Ω , hence a double root, whereas $\Omega(\beta) = \lambda A(\beta)^4 S(\beta) \neq 0$. This gives at most $\lfloor (w + 3K - 1)/2 \rfloor$ agreement points, as claimed. An explaining polynomial h for Ag gives roots of $A - (X - \beta)h$, a nonzero polynomial of degree at most K . Interpolation again gives both equalities. $\square$

3.4 Boolean polynomials and witnesses

The Gold construction in Lemma 5.12 first produces polynomials taking only the values zero and one on the domain, with a controlled derivative. The following conversion turns their complementary root sets into witnesses for one fixed received pair, separating this step from counting the polynomials.

Definition 3.14 (Boolean functions, supports, and balance). Let U be a finite binary vector space. A *Boolean function* on U is a map $\varphi : U \rightarrow \mathbb{F}_2$. Its *support* is $\text{supp}(\varphi) = \{x \in U : \varphi(x) = 1\}$. It is *balanced* if $|\text{supp}(\varphi)| = |U|/2$. When $\mathbb{F}$ has characteristic two and $U \subseteq \mathbb{F}$, a *Boolean polynomial* on U is a polynomial in $\mathbb{F}[X]$ whose values on U lie in $\mathbb{F}_2$.

The coefficients of a Boolean polynomial need not lie in $\mathbb{F}_2$. The condition concerns its values on the domain. For the Gold construction, we also use the degree of a Boolean function in binary coordinates, which is different from the degree of its univariate representative.

Definition 3.15 (Quadratic Boolean functions and polar forms). A Boolean function $\psi : U \rightarrow \mathbb{F}_2$ is *quadratic* if, in binary linear coordinates $x_1, \dots, x_d$, it can be written as

$$\psi(x) = c + \sum_i b_i x_i + \sum_{i < j} a_{ij} x_i x_j, \quad c, b_i, a_{ij} \in \mathbb{F}_2.$$

Its *polar form* is the bilinear form

$$B_\psi(x, y) = \psi(x + y) + \psi(x) + \psi(y) + \psi(0).$$

The *polar radical* is $\text{rad}(B_\psi) = \{u \in U : B_\psi(x, u) = 0 \text{ for all } x \in U\}$. The *polar rank* is the rank of the matrix $(B_\psi(e_i, e_j))_{i,j}$ in any basis of U . An *alternating binary matrix* is a symmetric matrix over $\mathbb{F}_2$ with zero diagonal.

The polar matrix is alternating, so its rank is even. The rank and radical do not depend on the chosen basis. In coordinates the polar radical is the null space of the polar matrix, so it has $|U|/2^r$ elements when the polar rank is r . A vector u lies in it exactly when $\psi(x + u) + \psi(x)$ does not depend on x . In suitable coordinates, the polar radical is spanned by the coordinate directions that occur in no cross term of ψ . If ψ is moreover constant on the polar radical, then ψ is constant on each of its cosets, and every level set of ψ is a union of such cosets. Unless specified otherwise, the radical in our binary Gold construction means this polar radical; ψ need not vanish on it.

Lemma 3.16 (From Boolean polynomials to witnesses). Let D be binary additive of size $N \geq 8$ in a finite field $\mathbb{B}$, put $K = N/4$ and $\lambda = L'_D$, and fix $\beta \in \mathbb{F} \setminus D$ in a finite extension. Suppose $H \in \mathbb{B}[X]$ has degree $N - T$, all its roots are distinct and lie in D , and

$$H^2 + H = (L_D/\lambda)H', \quad 2 \leq T < N/2, \quad T \text{ even}.$$

Then

$$P = \sqrt{H'/\lambda} \frac{L_D}{H}, \quad P^2 = L_D + \frac{L_D}{H}, \quad R = \sqrt{L_D - \lambda X}$$

are polynomials, P has exactly T roots on D , and $\deg(P + R) = T/2$. For the fixed pair

$$f(x) = \frac{R(x) + \sqrt{\lambda\beta}}{x - \beta}, \quad g(x) = \frac{1}{x - \beta},$$

the challenge $a = P(\beta) + \sqrt{L_D(\beta)}$ is nonzero and has a witness of degree at most $T/2 - 1$ with exactly T agreements. Moreover,

$$a^2 = \frac{L_D(\beta)}{H(\beta)}, \quad \text{agr}_K(f) \leq 3N/8 - 1, \quad \text{agr}_K(g) = \text{CA}_K(f, g) = K.$$

In particular, distinct values $H(\beta)$ give distinct nonzero challenges for this same pair.

Proof. Since the roots of H are distinct and lie in D , $H \mid L_D$; the derivative H' is a square in characteristic two. The assumed identity $H^2 + H = (L_D/\lambda)H'$ gives the displayed formula for P^2 , so $P^2 = L_D/H$ at every point of D . At a root of H , the polynomial L_D/H is nonzero because the roots of L_D are simple, so P is nonzero there. At every other point of D , the same identity reduces to $H^2 + H = 0$ and gives $H = 1$ and hence $P = 0$. Thus its root count is T . Also $(P + R)^2 = L_D/H - \lambda X$ has degree T , giving the correction degree. Write $S = R + \sqrt{\lambda\beta}$. Since $S(\beta)^2 = L_D(\beta)$,

$$h_a = \frac{S + a + P}{X - \beta}$$

is a polynomial of degree at most $T/2 - 1$, and $f(x) + a g(x) - h_a(x) = P(x)/(x - \beta)$ at every $x \in D$. Evaluating $P^2 = L_D + L_D/H$ at β gives $a^2 = L_D(\beta)/H(\beta)$; $H(\beta) \neq 0$ because all its roots lie in D . Finally Lemma 3.13 supplies the agreement bounds. $\square$

The hypotheses on H describe the agreement set directly. Let $A \subseteq D$ be the set of T points where $H = 1$. Then $L_D/H = (\lambda/c)L_A$ for a nonzero constant c , and the identity $(P + R)^2 = L_D/H - \lambda X$ from the proof reads

$$L_A = \frac{c}{\lambda} (P + R)^2 + cX.$$

Thus the locator of A is a square plus a linear term; equivalently, its derivative is the nonzero constant c . Conversely, if $A \subseteq D$ has $2 \leq |A| < N/2$ and $L'_A = c$ is a nonzero constant, then $H = (c/\lambda)L_D/L_A$ satisfies the hypotheses. These are exactly the sets on which a polynomial agrees with R at twice its degree, the most that the bound stated before Lemma 3.13 allows. Every affine subspace of D of positive dimension is such a set. The hyperplanes, of size exactly $N/2$, are treated in Theorem 4.7 for the same pair (f, g) , and Section 5 constructs superpolynomially many such sets that are not subspaces.

3.5 Padding and collision averaging

The preceding tools give a received pair at a particular rate and one challenge for each polynomial. We finish with two operations used to obtain the final parameters: adding agreement points to raise the rate, and keeping many challenges distinct when evaluations collide.

Definition 3.17 (Locator padding). Let $B \subseteq D$ have size w and locator L_B . The *padding* of inputs f, g and an explaining polynomial H_z by B is

$$\tilde{f} = L_B f, \quad \tilde{g} = L_B g, \quad \tilde{H}_z = L_B H_z.$$

The same multiplier is used for the two inputs and every selected witness.

If $f + zg$ agrees with H_z exactly on A_z , the padded combination agrees with $\tilde{H}_z$ exactly on $A_z \cup B$. A witness of degree less than K becomes one of degree less than $K + w$, so the new message length must allow this increase. The challenge z is unchanged.

Only new points increase agreement. The next lemma chooses one padding set whose overlap with every old agreement set is at most the average wT/N plus a controlled error.

Lemma 3.18 (Balanced padding). Let D have size N , and let $S_1, \dots, S_M \subseteq D$ all have size T , with $M \geq 1$. For every integer $1 \leq w < N$, there is a subset $B \subseteq D$ of size exactly w such that, simultaneously for all i ,

$$|B \cap S_i| \leq \frac{w}{N}|S_i| + \Delta, \quad |B \cup S_i| \geq w + \left(1 - \frac{w}{N}\right)|S_i| - \Delta,$$

where $\Delta = \sqrt{(w/2) \ln(2M)}$.

Proof. The lower bound on the union size follows from the intersection bound via $|B \cup S_i| = w + T - |B \cap S_i|$.

Choose a uniformly random w -element subset of D . For a fixed set of size T , sample those w points without replacement and reveal one at a time whether the sampled point belongs to the fixed set. After j draws with r_j successes, the conditional expectation of the final intersection size is $Z_j = r_j + (w - j)(T - r_j)/(N - j)$. At each step, the two possible values of Z_j differ by at most one, and the conditional mean of $Z_j - Z_{j-1}$ is zero. A centered variable of range one has exponential moment at most $e^{t^2/8}$: its log moment generating function has second derivative at most $1/4$. Iterating this bound and optimizing Markov's inequality gives

$$\Pr[|B \cap S_i| - wT/N \geq u] \leq e^{-2u^2/w}.$$

At the stated Δ , the failure probability for each of the M sets is at most $1/(2M)$. Summing these probabilities shows that all intersection bounds hold simultaneously with probability at least $1/2$. $\square$

Distinct corrections can give the same challenge. The following averaging bound, used in the pole reductions of Ben-Sasson et al. [5, Section 6] and Crites and Stewart [17, Theorem 2], bounds that loss without requiring a field large enough to give every correction a different value. In our Gold and decision-tree constructions, the parameter choices are poles outside the domain. Bounding the total number of collisions across these poles guarantees one pole with many distinct challenges.

Lemma 3.19 (Collision averaging). Suppose $M \geq 1$ indexed values are computed for each of $r > 0$ parameter choices. If the total number of unordered colliding index pairs, summed over all choices, is at most F , some choice gives at least

$$\max \left\{ M - \lfloor F/r \rfloor, \left\lceil \frac{rM^2}{rM + 2F} \right\rceil \right\}$$

distinct values. At most one of them is zero.

Proof. Choose a parameter with at most F/r colliding pairs. Group indices that give the same value. If the nonempty groups have sizes $v_1, \dots, v_u$, then $M - u = \sum_i (v_i - 1) \leq \sum_i \binom{v_i}{2} \leq \lfloor F/r \rfloor$. Also

$$M^2 \leq u \sum_i v_i^2 = u \left(M + 2 \sum_i \binom{v_i}{2} \right) \leq u(M + 2F/r).$$

Both bounds hold at the same choice. $\square$

4 Subspace-locator constructions

The constructions in this section use subspaces of the domain as agreement sets, as outlined in Section 2.3. They apply to every binary additive domain D of size N .

- At rate $1/16$ and $N \geq 32$, there are $(N - 1)(N - 2)/6$ exceptional challenges at every agreement from $N/8 + 1$ to $N/4 - 1$, a range that contains the largest integer below Johnson, when D lies in a proper subfield of the challenge field (Theorem 4.1). In an arbitrary challenge field of size q , a collision bound in terms of q replaces this count (Corollary 4.2).
- At every fixed rate ρ , every challenge is exceptional at an agreement fixed strictly between ρ and $\sqrt{\rho}$, when the challenge field has size polynomial in N and N is sufficiently large (Theorem 4.5).
- At rate $1/4$ and $N \geq 8$, there are exactly $2N - 2$ exceptional challenges at agreement $1/2$ in every challenge field larger than D (Theorem 4.7). The received pair of this theorem is also the one used by the Gold construction of Section 5.

4.1 Quadratically many exceptional challenges on arbitrary additive domains

Let $N = 16K$, so that the rate is $1/16$. Section 2.3 constructs a pair with one exceptional challenge for each codimension-two subspace of the domain, when the domain lies in a proper subfield $\mathbb{B}$ of the challenge field. Theorem 4.1 proves in addition that these are all the exceptional challenges, and bounds the agreement of each input. Corollary 4.2 then treats challenge fields with no such subfield.

Theorem 4.1 (Quadratic count at rate $1/16$). Let $D \subseteq \mathbb{B}$ be a binary additive domain of size $N = 16K$, where $K \geq 2$ is a power of two, and let $\mathbb{F} \supsetneq \mathbb{B}$ be a finite field. Put $M = (N - 1)(N - 2)/6$, the number of codimension-two subspaces of D . There is a pair f, g over $\mathbb{F}$ such that:

1. $\text{agr}_K(f) \leq 2K$ and $\text{agr}_K(g) = \text{CA}_K(f, g) = 2K - 1$;
2. for every integer $2K + 1 \leq T \leq 4K - 1$, the set $\text{Bad}_T(f, g)$ is the same set of M nonzero challenges, and each of them has maximum agreement exactly $4K - 1 = N/4 - 1$;
3. $\text{Bad}_{4K}(f, g)$ is empty.

If $[\mathbb{F} : \mathbb{B}] \geq 3$, the pair can be chosen with $\text{agr}_K(f) = 2K - 1$ as well.

The Johnson threshold $\sqrt{N(K - 1)}$ lies strictly between $4K - 3$ and $4K - 2$, since $(4K - 3)^2 < 16K(K - 1) < (4K - 2)^2$ for $K \geq 2$. The count M therefore holds at $T = 4K - 3 = N/4 - 3$, the largest integer below Johnson, where the agreement exceeds the common agreement by $N/8 - 2$ positions. The proof uses an element $\theta \in \mathbb{F} \setminus \mathbb{B}$, which gives a second coordinate over $\mathbb{B}$ in which to record a locator coefficient. A third coordinate, available when $[\mathbb{F} : \mathbb{B}] \geq 3$, is used to lower the agreement of f .

Proof. Let W range over the codimension-two linear subspaces of D , and write

$$L_W = X^{4K} + a_W X^{2K} + b_W X^K + V_W, \quad \deg V_W \leq K/2.$$

The coefficients a_W, b_W lie in $\mathbb{B}$ and determine W (Lemma 3.9 with $s = 2$). Choose $\theta \in \mathbb{F} \setminus \mathbb{B}$. We first work with the pair

$$f_0 = X^{8K-1} + \theta X^{4K-1}, \quad g = X^{2K-1},$$

and obtain f from f_0 in Step 5.

Step 1: witnesses. As in Section 2.3, put $z_W = a_W^3 + b_W^2 + \theta a_W$. Then

$$\begin{aligned} P_W &= L_W^2 + (a_W^2 + \theta)L_W = X^{8K} + \theta X^{4K} + z_W X^{2K} + C_W, \\ C_W &= (a_W^2 + \theta)(b_W X^K + V_W) + V_W^2. \end{aligned} \tag{4.1}$$

Every term of C_W is divisible by X , and $\deg C_W \leq K$, so $H_W = C_W/X$ is a polynomial of degree less than K . At a nonzero point of D , the difference $f_0 + z_W g - H_W$ equals $P_W/X = L_W(L_W + a_W^2 + \theta)/X$. The second factor does not vanish there: $L_W(x)$ and a_W^2 belong to $\mathbb{B}$, whereas θ does not. At zero, f_0 and g vanish, but $H_W(0) = (a_W^2 + \theta)L'_W$ is nonzero, because the roots of L_W are simple. Hence $f_0 + z_W g$ agrees with H_W exactly on $W \setminus \{0\}$, a set of $4K - 1$ points.

Step 2: the challenges are distinct. The elements $1, \theta$ are linearly independent over $\mathbb{B}$. If $z_W = z_{W'}$, comparing the coefficients of θ gives $a_W = a_{W'}$, and comparing the remaining coefficients then gives $b_W^2 = b_{W'}^2$, hence $b_W = b_{W'}$ and $W = W'$. So the M subspaces give M distinct challenges.

Step 3: every challenge with more than $2K$ agreements is some z_W . Suppose that $f_0 + zg$ agrees with a polynomial h , $\deg h < K$, on a set S of more than $2K$ points. We show that $z = z_W$ and $h = H_W$ for some W . To do so, we split the agreement into its coordinates over $\mathbb{B}$, eliminate between the coordinates of 1 and θ to show that the polynomial from the θ coordinate has the shape of a codimension-two locator, and then show that L_D is an additive polynomial in it.

Expand z and the coefficients of h in a $\mathbb{B}$ -basis of $\mathbb{F}$ beginning with 1, θ . The coefficients of f_0 and g lie in $\mathbb{B} + \mathbb{B}\theta$, so in every other coordinate j , the polynomial $z_j X^{2K-1} - h_j$ vanishes on S . It has degree at most $2K - 1$, so it is zero, and $z_j = h_j = 0$. We may thus write

$$z = z_0 + \theta a, \quad h = h_0 + \theta h_1, \quad z_0, a \in \mathbb{B}, \quad h_0, h_1 \in \mathbb{B}[X].$$

The coordinates of θ and of 1 say that $X^{4K-1} + aX^{2K-1} + h_1$ and $X^{8K-1} + z_0X^{2K-1} + h_0$ vanish on S . Multiplying by X , the polynomials

$$P_1 = X^{4K} + aX^{2K} + Xh_1, \quad P_0 = X^{8K} + z_0X^{2K} + Xh_0$$

vanish on S . Their combination

$$P_1^2 + P_0 + a^2P_1 = (z_0 + a^3)X^{2K} + (Xh_1)^2 + a^2Xh_1 + Xh_0 \quad (4.2)$$

has degree at most $2K$ and vanishes on the more than $2K$ points of S , so it is zero. Since $\deg(Xh_i) \leq K$, comparison of coefficients above degree K yields

$$Xh_1 = bX^K + V, \quad \deg V \leq K/2, \quad V(0) = 0, \quad b^2 = z_0 + a^3.$$

Thus $P_1 = X^{4K} + aX^{2K} + bX^K + V$. We now identify P_1 as a subspace locator. Write

$$L_D = X^{16K} + d_8X^{8K} + d_4X^{4K} + \text{terms of degree at most } 2K$$

and set $\eta = d_8 + a^4$ and $\xi = d_4 + b^4 + \eta a^2$. The polynomial $L_D + P_1^4 + \eta P_1^2 + \xi P_1$ has degree at most $2K$ and vanishes on S , so

$$L_D = P_1^4 + \eta P_1^2 + \xi P_1. \quad (4.3)$$

In particular, P_1 divides L_D , and differentiation gives $L'_D = \xi P'_1 \neq 0$. Thus P_1 has $4K$ distinct roots, all in D . Equation (4.3) says that $L_D = A \circ P_1$ for the additive polynomial $A = X^4 + \eta X^2 + \xi X$, and $P_1(0) = 0$, so P_1 is additive by Lemma 3.10. Its roots therefore form a codimension-two subspace $W \leq D$, and $P_1 = L_W$, so that $a = a_W$, $b = b_W$, and $V = V_W$. The relation $b^2 = z_0 + a^3$ now gives $z = z_W$, and (4.2) gives $Xh_0 = V^2 + a^2(bX^K + V)$, so $Xh = C_W$ and $h = H_W$.

Together with Step 1, this shows that for the pair f_0, g the challenges with more than $2K$ agreements are exactly the z_W , and that each has maximum agreement exactly $4K - 1$.

Step 4: common agreement. The word g differs from every polynomial of degree less than K by a nonzero polynomial of degree $2K - 1$. It therefore has at most $2K - 1$ agreements with any codeword, which also bounds the common agreement of any pair containing g . To attain $2K - 1$, choose a binary subspace $U \leq D$ of size $2K$. The remainders r_1, r_2, r_3 of X^{2K}, X^{4K}, X^{8K} modulo L_U are additive of degree at most K , with zero constant term. Thus r_1/X and $(r_3 + \theta r_2)/X$ have degree less than K and match g and f_0 simultaneously on $U \setminus \{0\}$.

Step 5: individual agreement of the first input. For $\sigma \in \mathbb{F}$, the pair $f = f_0 + \sigma g$ and g has the same common agreement, and $f + zg = f_0 + (z + \sigma)g$, so its exceptional sets are those of f_0, g translated by σ . By Step 3, $\text{agr}_K(f) \leq 2K$ whenever σ is not one of the challenges z_W . We show that $\sigma = \sqrt{d_4} \in \mathbb{B}$ is such an element. If $\sigma = z_W$, the coefficient of θ would force $a_W = 0$, and the remaining coefficient would give $b_W^2 = \sigma$. Then $\xi = d_4 + b_W^4 = 0$ in (4.3), contradicting $L'_D = \xi L'_W \neq 0$. With this σ , the challenges $z_W + \sigma$ are distinct, and they are nonzero because their witnesses have $4K - 1 > 2K$ agreements. This proves the three parts of the theorem.

When $[\mathbb{F} : \mathbb{B}] \geq 3$, choose instead $\sigma \notin \mathbb{B} + \mathbb{B}\theta$, so that $1, \theta, \sigma$ are linearly independent over $\mathbb{B}$. Choose a $\mathbb{B}$ -linear functional on $\mathbb{F}$ that vanishes at 1 and θ and takes the value 1 at σ . Applying it to the coefficients of an explaining polynomial for $f = X^{8K-1} + \theta X^{4K-1} + \sigma X^{2K-1}$ gives an explaining polynomial for $g = X^{2K-1}$ on the same set. Hence $\text{agr}_K(f) \leq \text{agr}_K(g) \leq 2K - 1$, and the remainders of Step 4 attain equality. In particular zero is not exceptional, and the three parts hold as before. $\square$

Decoding lists at rate $1/8$. For each counted challenge $z = z_W + \sigma$, the polynomial $H_W - zg$ agrees with the fixed word f on $N/4 - 1$ positions. Its degree is $2K - 1 < N/8$, and its leading coefficient is $-z$, so distinct challenges give distinct codewords of the code of rate $1/8$. These quadratic lists have agreement approaching $1/4$, below the asymptotic Johnson threshold $\sqrt{1/8}$ for their rate, so they do not extend the near-Johnson list-size result of Section 5 to arbitrary additive domains.

Corollary 4.2 (Any finite field containing the evaluation domain). Let $\mathbb{F}$ be a finite field of size q , let $D \subseteq \mathbb{F}$ be a binary additive domain of size $N = 16K$ with $K \geq 2$ a power of two, and put $M = (N - 1)(N - 2)/6$. There is a scalar $\theta \in \mathbb{F}$ such that the pair

$$f = X^{8K-1} + \theta X^{4K-1}, \quad g = X^{2K-1}$$

has $\text{CA}_K(f, g) = 2K - 1$ and at least

$$\max \left\{ M - \left\lfloor \frac{\binom{M}{2}}{q} \right\rfloor, \left\lceil \frac{qM}{q + M - 1} \right\rceil \right\}$$

distinct exceptional challenges, each with at least $4K - 1$ agreements. In particular, $q \geq M$ gives more than $M/2$ distinct challenges, and $q > \binom{M}{2}$ makes all M distinct. If $D = \mathbb{F}$, at least $N - 5$ of the N challenges are exceptional.

Proof. Use the locator coefficients and the polynomials H_W of Step 1 in the proof of Theorem 4.1. For every $\theta \in \mathbb{F}$, the difference $f + z_W g - H_W$ vanishes on $W \setminus \{0\}$, giving at least $4K - 1$ agreements. Step 4 of that proof gives common agreement exactly $2K - 1$.

The coefficient pair (a_W, b_W) determines W (Lemma 3.9). For two distinct subspaces, the affine functions

$$\theta \mapsto a_W^3 + b_W^2 + \theta a_W$$

coincide for at most one θ if their a_W coefficients differ. If those coefficients agree, their b_W coefficients differ, so the functions never coincide. Thus the total number of collisions over all q choices of θ is at most $\binom{M}{2}$. Lemma 3.19, with $r = q$ and $F = \binom{M}{2}$, gives both bounds at one value of θ . When $D = \mathbb{F}$, so that $q = N$, the second bound is the ceiling of

$$\frac{NM}{N + M - 1} = N - 6 + \frac{24}{N + 4},$$

which is $N - 5$ since $N \geq 32$. $\square$

4.2 Every challenge exceptional at every fixed rate

This subsection proves that at every fixed rate ρ , and for challenge fields of size at most N^a , every challenge is exceptional at an agreement fixed strictly between ρ and $\sqrt{\rho}$, once the domain is sufficiently large (Theorem 4.5). The proof has two parts. Lemma 4.3 replaces codimension two by codimension s , which gives one challenge for each of the $\Theta_s(N^s)$ subspaces of codimension s , at rate 2^{-s-2} . The theorem applies the lemma on a small subspace D_0 of the domain and adds common agreement points outside D_0 to reach rate ρ . Taking $s > 2a$ makes the subspaces so numerous that every element of the challenge field occurs as a challenge.

Lemma 4.3 (Unpadded locator construction). Let $D \subseteq \mathbb{B} \subseteq \mathbb{F}$ be a binary additive domain of size $N = 2^d$ in a finite field $\mathbb{F}$ of size q , and let $s \geq 2$ with $d \geq 2s$. Put

$$K = N/2^{s+2}, \quad M = \left\lfloor \frac{d}{s} \right\rfloor_2.$$

There is a pair over $\mathbb{F}$ with $\text{agr}_K(g) = \text{CA}_K(f, g) = 2K - 1$ and at least $\lceil qM/(q + M - 1) \rceil$ distinct exceptional challenges at agreement $4K - 1$. One of these challenges may be zero. If $[\mathbb{F} : \mathbb{B}] \geq s + 1$, a pair can instead be chosen with

$$\text{agr}_K(f) = \text{agr}_K(g) = \text{CA}_K(f, g) = 2K - 1, \quad |\text{Bad}_{4K-1}(f, g) \setminus \{0\}| \geq M.$$

The guaranteed agreement sets are the codimension- s subspaces of D , which have size $N/2^s = 4K$, with the point zero removed. There are M of them. The hypothesis $d \geq 2s$ ensures that the first s nonleading locator coefficients determine the subspace (Lemma 3.9).

Proof. Let W range over the codimension- s subspaces of D , and write

$$L_W = \sum_{i=0}^{d-s} a_i X^{4K/2^i}, \quad a_0 = 1.$$

Step 1: witnesses. For $0 \leq j < s$, the power $L_W^{2^{s-1-j}}$ is linearized with leading term $X^{N/2^{j+1}}$. We combine these powers with coefficients b_j chosen so that, for $1 \leq j < s$, the coefficient of $X^{N/2^{j+1}}$ in the combination is a prescribed parameter $\theta_j \in \mathbb{F}$, the same for every W . Explicitly, set

$$b_0 = 1, \quad b_j = \theta_j + \sum_{i < j} b_i a_{j-i}^{2^{s-1-i}} \quad (1 \leq j < s).$$

Then

$$P_W = \sum_{j=0}^{s-1} b_j L_W^{2^{s-1-j}} = X^{N/2} + \sum_{j=1}^{s-1} \theta_j X^{N/2^{j+1}} + z_W X^{2K} + C_W, \quad \deg C_W \leq K, \quad C_W(0) = 0,$$

where

$$z_W = \sum_{j=0}^{s-1} b_j a_{s-j}^{2^{s-1-j}}. \quad (4.4)$$

The terms before $z_W X^{2K}$ do not depend on W . Divide their sum by X to define the first input f , and take $g = X^{2K-1}$ as the second input. Since P_W vanishes on W , the polynomial C_W/X , of degree less than K , agrees with $f + z_W g$ on the $4K - 1$ points of $W \setminus \{0\}$.

Step 2: collisions. We show that different subspaces give different affine functions of the parameters. Each b_j is an affine function of $\theta_1, \dots, \theta_j$ whose coefficients are polynomials in the locator coefficients, so by (4.4) z_W is affine in the parameters. Its coefficients are triangular in the locator coefficients: writing $[\theta_j]z_W$ for the coefficient of θ_j ,

$$[\theta_{s-k}]z_W = a_k^{2^{k-1}} + F_k(a_1, \dots, a_{k-1}) \quad (1 \leq k < s),$$

and the constant term is $a_s^{2^{s-1}} + F_s(a_1, \dots, a_{s-1})$, for polynomials F_k that do not depend on W . For example,

$$[\theta_{s-1}]z_W = a_1, \quad [\theta_{s-2}]z_W = a_2^2 + a_1^3,$$

where for $s = 2$ the second expression is the constant term. To see this, use induction on j in the recurrence for b_j . The coefficient of θ_t in b_j is 1 for $j = t$ and a polynomial in $a_1, \dots, a_{j-t}$ for $j > t$, and the part of b_j free of the parameters is a polynomial in $a_1, \dots, a_j$. In (4.4), the summand $j = s - k$ therefore contributes $a_k^{2^{k-1}}$ to $[\theta_{s-k}]z_W$, and each later summand contributes a polynomial in $a_1, \dots, a_{k-1}$. The summand $j = 0$ contributes $a_s^{2^{s-1}}$ to the constant term, and each later summand contributes a polynomial in $a_1, \dots, a_{s-1}$. Since raising to a power of two is a bijection of $\mathbb{F}$, these expressions recover $a_1, \dots, a_s$ one after another, and $a_1, \dots, a_s$ determine W (Lemma 3.9). Two distinct subspaces therefore give distinct affine functions of the parameters, and two distinct affine functions agree on at most a $1/q$ fraction of $\mathbb{F}^{s-1}$. The total number of colliding pairs over all q^{s-1} parameter choices is thus at most $q^{s-2} \binom{M}{2}$, and Lemma 3.19 supplies a parameter choice with at least $\lceil qM/(q + M - 1) \rceil$ distinct challenges.

Step 3: common agreement. The word g differs from every polynomial of degree less than K by a nonzero polynomial of degree $2K - 1$, so $\text{agr}_K(g) \leq 2K - 1$, and the same bound holds for the common agreement. To attain it, choose a subspace $U \leq D$ of size $2K$. Reducing every power X^{2^i} in the numerators of the two inputs modulo L_U gives an additive remainder of degree at most K with zero constant term. After division by X , these are explaining polynomials of degree less than K on $U \setminus \{0\}$, which gives $2K - 1$ simultaneous agreements.

Step 4: the second pair. When $[\mathbb{F} : \mathbb{B}] \geq s + 1$, choose $1, \theta_1, \dots, \theta_{s-1}, \tau$ linearly independent over $\mathbb{B}$, and add τg to the first input. The locator coefficients lie in $\mathbb{B}$, so each z_W lies in the span of $1, \theta_1, \dots, \theta_{s-1}$ over $\mathbb{B}$, and its coordinates there are the coefficients computed in Step 2. Hence the z_W are distinct. The challenges of the new pair are the $z_W + \tau$. They are distinct, and their τ coordinate is one, so none is zero. Projection onto the τ coordinate bounds the agreement of the new first input by $\text{agr}_K(g) \leq 2K - 1$, and Step 3 applies to the new pair as well. $\square$

Taking $s = 3$ in Lemma 4.3 gives an explicit cubic count on every prescribed binary additive domain.

Corollary 4.4 (Cubic count at rate $1/32$). Let $D \subseteq \mathbb{B}$ be binary additive of size $N = 2^d$, with $d \geq 6$, and let $[\mathbb{F} : \mathbb{B}] \geq 4$. At $K = N/32$, there is one pair satisfying

$$\text{agr}_K(f) = \text{agr}_K(g) = \text{CA}_K(f, g) = N/16 - 1$$

and having at least

$$\frac{(N-1)(N-2)(N-4)}{168}$$

distinct nonzero exceptional challenges at agreement $N/8 - 1$.

Proof. Apply Lemma 4.3 with $s = 3$ and expand $\begin{bmatrix} d \\ 3 \end{bmatrix}_2$. $\square$

Theorem 4.5 (Every fixed rate on every additive domain). Fix $0 < \rho < 1$ and an integer $s \geq 2$. There are constants $\rho < \alpha_{\rho,s} < \sqrt{\rho}$ and $c_{\rho,s} > 0$ such that the following hold for every sufficiently large binary additive domain D of size N in a finite field $\mathbb{F}$ of size q , with

$$K = \lfloor \rho N \rfloor, \quad T = \lceil \alpha_{\rho,s} N \rceil.$$

1. There is a pair with $\text{agr}_K(g) = \text{CA}_K(f, g) = K$ and

$$\frac{|\text{Bad}_T(f, g) \setminus \{0\}|}{q} \geq \frac{1}{1 + q/(c_{\rho,s} N^s)} - \frac{1}{q}. \quad (4.5)$$

In particular, $q \geq N^s$ gives $\Omega_{\rho,s}(N^s)$ exceptional challenges.

2. If $q \leq N^a$ for a fixed $a \geq 1$ with $s > 2a$, there is a pair with $\text{agr}_K(g) = \text{CA}_K(f, g) = K$ and

$$\text{Bad}_T(f, g) = \mathbb{F}.$$

Here zero is exceptional as well.

3. If $D \subseteq \mathbb{B} \subseteq \mathbb{F}$, there is a pair with

$$\text{agr}_K(f) = \text{agr}_K(g) = \text{CA}_K(f, g) = K, \quad |\text{Bad}_T(f, g) \setminus \{0\}| \geq \frac{|\mathbb{B}|}{1 + |\mathbb{B}|/(c_{\rho,s} N^s)} - 1.$$

If moreover $[\mathbb{F} : \mathbb{B}] \geq s + 1$, there is a pair with these three agreements equal to K that satisfies (4.5).

For the pairs of the first two parts, the first input f has at least as many codewords of the code of message length $K + 1$ at agreement T as the pair has exceptional challenges.

The proof takes $\alpha_{\rho,s} = \rho + 2^{-r-s-2}$ for an integer r depending only on ρ and s , so the agreement exceeds the common agreement by about $2^{-r-s-2}N$ positions. The first part with $s = 2$ gives a lower bound of order N^2 at every fixed rate when $q \geq N^2$. The third part with $|\mathbb{B}| \geq N^s$ gives $\Omega_{\rho,s}(N^s)$ exceptional challenges even when $\mathbb{F}$ is a quadratic extension of $\mathbb{B}$.

Proof. Put $\kappa = 2^{-s-2}$, and choose $\mu = 2^{-r}$, for a sufficiently large integer r , such that

$$2\mu\kappa < \rho, \quad \rho < 1 - \mu(1 - 2\kappa), \quad \rho + \mu\kappa < \sqrt{\rho}.$$

Set $\alpha_{\rho,s} = \rho + \mu\kappa$. Let $D_0 \leq D$ be a subspace of size $n = \mu N$, and put

$$K_0 = \kappa n, \quad w = K - 2K_0 + 1.$$

For sufficiently large N , the first inequality makes w positive, and the second gives $w \leq N - n$, so that a set of w points fits outside D_0 . The third places $\alpha_{\rho,s}$ below $\sqrt{\rho}$.

The seed pair. Apply Lemma 4.3 on D_0 , whose dimension is at least $2s$ for large N . It gives polynomial inputs f_0 and $g_0 = X^{2K_0-1}$, and at least $\lceil qM/(q + M - 1) \rceil$ distinct challenges, where $M = \left\lceil \frac{\log_2 n}{s} \right\rceil_2 \geq (n/2^s)^s = c_{\rho,s} N^s$ with $c_{\rho,s} = 2^{-(r+s)s}$, by the size bound for Gaussian binomial coefficients. Each challenge has a witness of degree less than K_0 that agrees with the combination on at least $4K_0 - 1$ points of D_0 .

Padding. Evaluate the polynomial inputs and witnesses on all of D , and multiply them by the locator L_E of a set $E \subseteq D \setminus D_0$ of size w (Definition 3.17). The padded witnesses have degree at most $K_0 - 1 + w = K - K_0$, which is less than K . Every point of E is a new agreement, so each challenge now has at least

$$(4K_0 - 1) + w = K + 2K_0$$

agreements. Since $K + 2K_0 \geq (\rho + 2\mu\kappa)N - 1$ and $T \leq (\rho + \mu\kappa)N + 1$, this is at least T for large N . The padded second input $g = L_E g_0$ is monic of degree K , so it agrees with any polynomial of degree less than K on at most K points. Interpolating both inputs on any K points then gives $\text{agr}_K(g) = \text{CA}_K(f, g) = K$.

The first part. Discarding at most one zero challenge leaves at least

$$\frac{qM}{q + M - 1} - 1 \geq \frac{q}{1 + q/M} - 1 \geq \frac{q}{1 + q/(c_{\rho,s}N^s)} - 1$$

nonzero exceptional challenges, which is (4.5).

The second part. If $M > (q - 1)^2$, then $qM/(q + M - 1) > q - 1$, so the number of distinct challenges is q and every element of $\mathbb{F}$ is exceptional, including zero. For $q \leq N^a$ and $s > 2a$, the inequality $M \geq c_{\rho,s}N^s > (q - 1)^2$ holds for every sufficiently large N .

The third part. First let $[\mathbb{F} : \mathbb{B}] \geq s + 1$, and use the second pair of Lemma 4.3 on D_0 as the seed. Its M challenges are distinct and nonzero, and its first input contains the term τg_0 with τ independent of the other coefficients over $\mathbb{B}$. After padding, projection onto the τ coordinate bounds the agreement of the first input by that of the second, which is K , and interpolation attains K . All M challenges remain exceptional, and $M \geq q/(1 + q/M)$ gives (4.5). For an arbitrary proper extension, apply the first part with $\mathbb{B}$ as the challenge field, and then apply Lemma 3.12 to pass to $\mathbb{F}$. The conversion preserves the counted nonzero challenges and makes both individual agreements equal to the common agreement K , with the same message length and agreement.

Decoding lists. If h_z has degree less than K and explains $f + zg$, then $h_z - zg$ agrees with f on the same positions and has degree at most K . Its coefficient of X^K is $-z$, so distinct challenges give distinct codewords of the code of message length $K + 1$. $\square$

The pair of the first two parts controls only $\text{agr}_K(g)$. When every challenge is exceptional, zero is too, so f itself agrees with a codeword on at least $T > K$ positions. This is why the third part, with both individual agreements equal to K , uses a separate pair.

A finite instance of the same padding, applied to the quadratic count of Corollary 4.2, bears on an early binary-field implementation.

Corollary 4.6 (Rate 1/8 at finite length). Let D be a binary additive domain of size $N = 2^d$, with $d \geq 6$, in a finite field $\mathbb{F}$ of size q , and put

$$K = \frac{N}{8}, \quad M = \frac{(N/2 - 1)(N/2 - 2)}{6}.$$

There is a pair with $\text{agr}_K(g) = \text{CA}_K(f, g) = K$ and at least $\lceil qM/(q + M - 1) \rceil$ distinct exceptional challenges at agreement $3N/16$. The same holds on every translate of D . For $N = 2^{20}$ and $q = 2^{64}$, this gives more than 4.58×10^{10} exceptional challenges, so the exceptional probability is greater than $2^{-28.585}$.

Proof. Choose a subspace $D_0 \leq D$ of size $n = N/2$ and put $K_0 = n/16 = N/32$. Corollary 4.2 on D_0 gives polynomial inputs f_0 and $g_0 = X^{2K_0-1}$, and at least $\lceil qM/(q+M-1) \rceil$ distinct challenges whose witnesses have degree less than K_0 and at least $4K_0 - 1$ agreements on D_0 . Evaluate these polynomials on all of D , and multiply the inputs and witnesses by the locator L_E of a set $E \subseteq D \setminus D_0$ of size

$$w = K - 2K_0 + 1 = \frac{N}{16} + 1.$$

The padded witnesses have degree less than $K_0 + w < K$, and every point of E is a new agreement, so each selected challenge has at least

$$(4K_0 - 1) + w = \frac{3N}{16}$$

agreements. The padded second input $L_E g_0$ is monic of degree K , so it agrees with any polynomial of degree less than K on at most K positions. Interpolating both inputs on any K positions attains this bound, which gives $\text{agr}_K(g) = \text{CA}_K(f, g) = K$. For a translate $D + c$, substitute $X - c$ for X in the inputs and witnesses; degrees and agreement sets are preserved. The numerical values follow by direct computation: with $N = 2^{20}$ and $q = 2^{64}$, the lower bound $\lceil qM/(q+M-1) \rceil$ equals $45,812,722,234 > 2^{64-28.585}$. $\square$

The 2018 implementation of Ben-Sasson, Bentov, Horesh, and Riabzev [4, Appendix B.8] targeted 60 bits of security over a 64-bit binary field, with two independent repetitions of the FRI commitment phase and 22 query repetitions at rate $1/8$, each query selecting one of the two sets of committed oracles. A Johnson-based analysis gives a query-error term of about $(\sqrt{1/8})^{22} = 2^{-33}$ [6, Theorem 8.3]; reaching the target with 22 queries would need a proximity gap down to agreement about 15.1%. But on their affine binary domains, at 18.75% agreement and $N = 2^{20}$, both challenges are exceptional for the pair above with probability greater than $2^{-57.17}$, so an analysis that counts every exceptional challenge as an error cannot certify the target.

4.3 Exceptional probability approaching one at half agreement

At rate $1/4$, hyperplanes give exactly $2N - 2$ exceptional challenges at agreement $1/2$, which is the asymptotic Johnson threshold $\sqrt{\rho}$ at this rate. When the challenge field has size $2N$, the exceptional probability is $1 - 1/N$. This construction also supplies the received pair used in Section 5, where more general agreement sets give larger counts slightly below half agreement.

Theorem 4.7 (Hyperplanes at half agreement). Let $\mathbb{F}$ be a finite field of characteristic two, and let $D \subseteq \mathbb{F}$ be an affine flat of size $N = 2^d$, $d \geq 3$. Put $K = N/4$. There is a pair with inputs and challenges in $\mathbb{F}$ satisfying

$$\text{CA}_K(f, g) = K, \quad \text{agr}_K(f) \leq 3N/8 - 1, \quad \text{agr}_K(g) = K,$$

and

$$|\text{Bad}_{N/2}(f, g)| = 2N - 2.$$

All these exceptional challenges are nonzero. If $|\mathbb{F}| = 2N$, then $\text{Bad}_{N/2}(f, g) = \mathbb{F} \setminus \{0, s\}$ for some $s \neq 0$, giving exceptional probability exactly $1 - 1/N$.

Proof. Choose $\beta \in \mathbb{F} \setminus D$, put $\lambda = L'_D$ and

$$R = \sqrt{L_D - \lambda X}, \quad S = R + \sqrt{\lambda \beta}, \quad f(x) = \frac{S(x)}{x - \beta}, \quad g(x) = \frac{1}{x - \beta}.$$

Lemma 3.13 gives the individual and common-agreement bounds. For every affine hyperplane H of D , its locator L_H has degree $N/2$, with all lower terms of degree at most K . The same holds for S , so this is the pole reduction of Lemma 3.11 with shared part S and corrections $L_H - S$. Set $z_H = L_H(\beta) - S(\beta)$. Then

$$h_H = \frac{S + z_H - L_H}{X - \beta}$$

is a polynomial of degree at most $K - 1$: its numerator has degree at most K and vanishes at β . At every $x \in D$ we have $f(x) + z_H g(x) - h_H(x) = L_H(x)/(x - \beta)$, so h_H agrees with $f + z_H g$ exactly on H .

All $2N - 2$ challenges z_H are distinct. The locators of parallel hyperplanes differ by a nonzero constant. Nonparallel hyperplanes intersect in K points, so their nonzero locator difference, of degree at most K , cannot also vanish at β . The bound on $\text{agr}_K(f)$ shows that zero is not among them.

To prove that these are all the exceptional challenges, suppose a polynomial h of degree less than K agrees with $f + zg$ at $N/2$ points. The numerator of $f + zg - h$ is $F = S + z - (X - \beta)h$, monic of degree $N/2$, splitting into distinct roots in D . Hence $F \mid L_D$. Since

$$F^2 - L_D = -\lambda(X - \beta) + z^2 - (X - \beta)^2 h^2$$

has degree at most $2K = N/2$ and is divisible by F , it equals cF . Its derivative is $-\lambda \neq 0$, so $c \neq 0$. Thus $L_D = A \circ F$ for the additive polynomial $A = X^2 - cX$. After subtracting constant terms, Lemma 3.10 shows that F is a constant plus an additive polynomial. Its root set is therefore an affine hyperplane of D . This proves the exact count in every containing field. Put $s = S(\beta) = \sqrt{L_D(\beta)} \neq 0$. No z_H equals s , since that would give $L_H(\beta) = 0$. When $|\mathbb{F}| = 2N$, the exceptional challenges are consequently exactly $\mathbb{F} \setminus \{0, s\}$. $\square$

5 Gold constructions: superpolynomially many exceptions near Johnson

We use the received pair of Theorem 4.7, choosing its pole to obtain many more exceptional challenges slightly below half agreement. The agreement sets now come from quadratic Boolean functions rather than hyperplanes. The proof constructs their polynomials using Gold moment equations and counts them through their polar matrices. Sections 5.3–5.5 prove the counting bound stated next, Section 5.6 changes the rate, and Sections 5.7 and 5.8 treat Binus64 and Longfellow.

5.1 The counting bound and its consequences

In the theorem below, L is the guaranteed number of polynomials, T is their root count on D , and δ bounds the number of exterior points where two distinct members can coincide. Here $2t$ is the rank of the quadratic functions, and $\Delta \geq 1$ is a density requirement.

Theorem 5.1 (The Gold counting bound). Let $\mathbb{B} = \mathbb{F}_{2^m}$ and let $D \subseteq \mathbb{B}$ be binary additive of dimension d , with $N = 2^d$. Choose $2 \leq t \leq \lfloor d/2 \rfloor$, put $\iota = 1$ for even d and $\iota = 0$ for odd d , and suppose

$$\Delta = m - t(m - d + \iota) \geq 1.$$

Set

$$L = 2^{2t} (2^\Delta - 1) \begin{bmatrix} \lfloor d/2 \rfloor \\ t \end{bmatrix}_4, \quad T = \frac{N}{2} - \frac{N}{2^{t+1}}, \quad \delta = \frac{N}{2^{2t}}.$$

Here $\begin{bmatrix} \lfloor d/2 \rfloor \\ t \end{bmatrix}_4$ is a Gaussian binomial coefficient (Section 3.1); it lies between $4^{t(\lfloor d/2 \rfloor - t)}$ and four times that value. There is a received word over $\mathbb{B}$ whose decoding list at threshold T , for message length $N/4$, has size at least L . For every finite extension $\mathbb{F} \supseteq \mathbb{B}$ with $q = |\mathbb{F}| > N$, there is one received pair over $\mathbb{F}$ satisfying $\text{agr}_{N/4}(g) = \text{CA}_{N/4}(f, g) = N/4$ and having at least

$$Z = \max \left\{ L - \left\lfloor \frac{\delta \binom{L}{2}}{q - N} \right\rfloor, \left\lfloor \frac{L(q - N)}{q - N + \delta(L - 1)} \right\rfloor \right\} \quad (5.1)$$

distinct nonzero exceptional challenges at agreement T . The same pair can be chosen with $\text{agr}_{N/4}(f) \leq 3N/8 - 1$. At least Z of its nonzero exceptional challenges each admit an explaining polynomial of degree at most $T/2 - 1$. The same conclusions hold on every affine translate of D .

The containing field. The polynomials come from alternating binary matrices of rank $2t$ that satisfy $t - 1$ equations with values in $\mathbb{B}$ (Section 5.3). A larger t raises T toward $N/2$ and lowers δ , but each equation costs up to m binary degrees of freedom, so $\Delta \geq 1$ is a density requirement: for $m = d + c$ it allows t proportional to d , and for $m \geq 2d$ it fails for every $t \geq 2$. To apply Theorem 5.1, choose for $\mathbb{B}$ the smallest subfield of the challenge field containing D . It depends on which elements D contains, not only on its dimension.

LeanVM works over $\mathbb{F}_{2^{64}} = \mathbb{F}_2[u]/(u^{64} + u^4 + u^3 + u + 1)$ and evaluates on the domains $\text{span}_{\mathbb{F}_2}\{1, u, \dots, u^{d-1}\}$ [38]. For $D = \text{span}_{\mathbb{F}_2}\{1, u, \dots, u^{21}\}$, a field containing D contains $\mathbb{F}_2(u) = \mathbb{F}_{2^{64}}$, so the smallest choice is $m = 64$. With $d = 22$ and $\iota = 1$, this gives $\Delta = 64 - 43t < 1$ for every $t \geq 2$, placing this domain outside the parameter range of Theorem 5.1. Flock's domains are the spans of $1, u, \dots, u^{d-1}$ for a generator u of $\mathbb{F}_{2^{128}}$ over $\mathbb{F}_2$, with $d \leq 24$ [23]. There $m = 128$, and these domains are outside the range for the same reason. In both systems d depends on the size of the instance, and $d = 22$ occurs in both at rate $1/2$. Section 6 gives explicit finite bounds on such domains, at agreement thresholds farther below Johnson.

5.2 Exceptional counts and probabilities near Johnson

Letting t grow with N gives superpolynomial counts near Johnson over a challenge field of *quasipolynomial* size $N^{O(\log N)}$. With a fixed extension degree instead, the agreement still approaches Johnson and the exceptional probability stays constant.

Corollary 5.2 (Dense additive domains). Fix an integer $c \geq 0$, and put

$$\theta_c = \min\{1/4, 1/(c+1)\}, \quad t = \min\left\{\lfloor d/4 \rfloor, \left\lfloor \frac{d+c-1}{c+1} \right\rfloor\right\}.$$

For every sufficiently large d and every additive d -space $D \subseteq \mathbb{B} = \mathbb{F}_{2^{d+c}}$, with $N = 2^d$, there are quarter-rate decoding lists over $\mathbb{B}$ and received pairs over a containing field $\mathbb{F}$ with the following parameters:

$$\begin{aligned} T/N &= 1/2 - \Theta_c(N^{-\theta_c}), \\ \log_2(\text{list size}) &\geq \theta_c(1 - 2\theta_c)(\log_2 N)^2 - O_c(\log N), \\ \log_2 |\text{Bad}_T(f, g) \setminus \{0\}| &\geq \theta_c(1 - 2\theta_c)(\log_2 N)^2 - O_c(\log N), \\ \text{CA}_{N/4}(f, g) &= N/4, \quad \Pr_{z \in \mathbb{F}}[z \in \text{Bad}_T(f, g) \setminus \{0\}] = \Omega_c(N^{-1+2\theta_c}). \end{aligned}$$

The field can be chosen with

$$\log_2 |\mathbb{F}| = \theta_c(1 - 2\theta_c)(\log_2 N)^2 + O_c(\log N).$$

In particular, for $c \leq 3$ the list size and the exceptional count are at least $N^{(1/8-o(1))\log_2 N}$, the Johnson deficit is $\Theta(N^{-1/4})$, and the exceptional probability is $\Omega(N^{-1/2})$. The decoding list is over an alphabet of size $2^c N$.

Proof. The selected t is at least two for large d , and

$$\Delta = d + c - t(c + \iota) \geq d + c - t(c + 1) \geq 1.$$

Also $t = \theta_c d + O_c(1)$. The Gaussian product formula gives

$$\log_2 \begin{bmatrix} n \\ t \end{bmatrix}_4 = 2t(n - t) + O(1), \quad n = \lfloor d/2 \rfloor.$$

Consequently the polynomial count in Theorem 5.1 satisfies $\log_2 L = \theta_c(1 - 2\theta_c)d^2 + O_c(d)$.

Write $\delta = N/2^{2t}$ and $q_0 = N + \delta(L - 1)$. Choose q to be the largest power of $|\mathbb{B}|$ with $q \leq q_0$. For large d , $q_0 \geq 2|\mathbb{B}|N$. Thus $q > q_0/|\mathbb{B}|$, $q \geq 2N$, and $\delta(L - 1)/(2|\mathbb{B}|) < q - N \leq \delta(L - 1)$. The nonzero count in (5.1) therefore obeys

$$Z \geq \frac{q - N}{2\delta} - 1 > \frac{L - 1}{4|\mathbb{B}|} - 1, \quad \frac{Z}{q} \geq \frac{1 - N/q}{2\delta} - \frac{1}{q} \geq \frac{1}{8\delta}$$

for sufficiently large d . These inequalities give the stated count and probability bounds, and $\log_2 q = \log_2 L + O_c(d)$ gives the field size. $\square$

Corollary 5.3 (Fixed extension degree). Fix an integer $e \geq 2$. For all sufficiently large n , put $N = 2^{2n-1}$, $\mathbb{B} = \mathbb{F}_{2N}$ and $\mathbb{F} = \mathbb{F}_{(2N)^e}$. On every binary hyperplane $D \subset \mathbb{B}$, there is one pair with

$$\text{CA}_{N/4}(f, g) = \text{agr}_{N/4}(g) = N/4, \quad \text{agr}_{N/4}(f) \leq 3N/8 - 1,$$

and, at $T = N/2 - 2^{e-3/2}\sqrt{N}$,

$$|\text{Bad}_T(f, g) \setminus \{0\}| \geq (2^{1-2e} - o(1))|\mathbb{F}|.$$

On the full field $D = \mathbb{B} = \mathbb{F}_N$, with $N = 2^{2n}$ and $\mathbb{F} = \mathbb{F}_{N^e}$, the same individual and common-agreement bounds hold, and at $T = N/2 - 2^{e-2}\sqrt{N}$ we have

$$|\text{Bad}_T(f, g) \setminus \{0\}| \geq (4^{1-e} - o(1))|\mathbb{F}|.$$

In particular, $q = N^2$ permits agreement $N/2 - \sqrt{N}$ with exceptional probability at least $1/4 - o(1)$.

Proof. In Theorem 5.1, take $d = 2n - 1$, $m = 2n$ and $t = n - e$. For $n \geq e + 2$ these parameters are admissible, and

$$\Delta = n + e, \quad \delta = 2^{2e-1}, \quad L = 2^{2n-2e}(2^{n+e} - 1) \begin{bmatrix} n-1 \\ e-1 \end{bmatrix}_4.$$

For $q = (2N)^e$, the Gaussian product gives $L/q \rightarrow \infty$. Dividing (5.1) by q therefore gives a lower bound tending to $1/\delta$; the agreement bounds follow from the same theorem.

For the full-field case, take $d = m = 2n$ and $t = n - e + 1$. Then

$$\Delta = n + e - 1, \quad \delta = 4^{e-1}, \quad L = 2^{2n-2e+2}(2^{n+e-1} - 1) \begin{bmatrix} n \\ e-1 \end{bmatrix}_4.$$

For fixed e , the product formula gives $\log_2(L/N^e) = n - 2e^2 + 3e - 1 + O_e(1)$, so again $L/q \rightarrow \infty$. Dividing (5.1) by q again gives a lower bound tending to $1/\delta$. $\square$

Theorem 5.4 (No fixed polynomial exceptional bound below Johnson). Fix an agreement fraction $1/4 < a < 1/2$ and a proposed polynomial bound $C_0 N^b$, where $C_0, b > 0$. For arbitrarily large code lengths N , there is a rate- $1/4$ Reed–Solomon code over a binary field $\mathbb{F}$ and two received words f, g with the following properties:

1. The two words have common agreement exactly $N/4$. That is, the largest number of positions on which f and g simultaneously match a pair of codewords is $N/4$.
2. For more than $C_0 N^b$ distinct challenges $z \in \mathbb{F}$, the combination $f + zg$ agrees with a codeword on at least aN positions.

The field size is polynomial in N , with an exponent that depends only on b .

Proof. Take $e = \max\{2, \lfloor b \rfloor + 1\}$, so $e > b$. We construct examples for arbitrarily large powers of two N . The evaluation domain D is an $\mathbb{F}_2$ -hyperplane in a field $\mathbb{B}$ of size $2N$, and the received words and challenges take values in an extension $\mathbb{F}$ of size $(2N)^e$. The code consists of evaluations on D of polynomials in $\mathbb{F}[X]$ of degree less than $N/4$, so its rate is $1/4$.

Apply Corollary 5.3. Its agreement fraction tends to $1/2$, so eventually $T \geq \lceil aN \rceil$, and its count is $\Omega_e(N^e) > C_0 N^b$. $\square$

Function on D	Polynomial in $\mathbb{B}[X]$
linear function with label ω	ℓ_ω , with $\ell_\omega^2 + \ell_\omega = \omega^2 \Lambda$ (Lemma 5.5)
coordinate x_i	$\ell_i = \ell_{\omega_i}$
product $x_i x_j$	$\ell_i \ell_j + \omega_i \omega_j \Lambda$
quadratic function ψ with matrix A and label ω	Q , with $Q^2 + Q = \Lambda Q'$ (Lemma 5.6)
polar radical of ψ	roots in D of $J = Q' - Q'(0)$
zeros of $\psi + \kappa$	roots of $H = Q + \kappa$, when $\deg H$ equals their number
ones of $\psi + \kappa$	roots on D of $P = R + C$ (Lemma 5.12)

Table 5: Functions on D and the polynomials that represent them in Section 5.3.

5.3 From quadratic functions to polynomials with many roots

Throughout this subsection, $D \subseteq \mathbb{B}$ is binary additive of dimension d , with $N = 2^d$ and monic locator

$$L_D = \sum_{i=0}^d \lambda_i X^{2^i}, \quad \lambda_d = 1, \quad \lambda_0 \neq 0.$$

We normalize the locator so that its derivative is one:

$$\Lambda = \frac{L_D}{\lambda_0} = \sum_{i=0}^d \mu_i X^{2^i}, \quad \eta = \lambda_0^{-1/2},$$

so that $\mu_0 = 1$ and $\mu_d = \eta^2$.

We keep the polynomial $R = \sqrt{L_D - \lambda_0 X}$ of Theorem 4.7, which depends only on D , and look for sets $E \subseteq D$ with polynomials $P = R + C$ that vanish on E and have $\deg C = |E|/2$. The word $R|_D$ then agrees with the codeword of C on E . As in Section 2.2, such a polynomial exists when the locator of E is a square plus a multiple of X , that is, when its derivative is constant: since $R^2 = L_D + \lambda_0 X$, a locator $L_E = c(C^2 + \lambda_0 X)$ gives $(R + C)^2 = L_D + L_E/c$, which vanishes on E . Locators of affine subspaces always have this form. Section 4 used them, and the hyperplanes of Theorem 4.7 are the level sets of the nonzero linear Boolean functions. Here E is the set of ones of a *quadratic* Boolean function. There are many more such sets of size close to $N/2$, but they are not subspaces, and the Gold moment equations are what gives their locators a constant derivative. In the notation below, E is the set of ones of $\psi + \kappa$ and H is the polynomial of $\psi + \kappa$. The moment equations make $\deg H$ equal to the number of zeros of $\psi + \kappa$, so H is a scalar multiple of $L_{D \setminus E}$ and L_D/H is a scalar multiple of L_E (Remark 5.11).

The argument passes between functions $D \rightarrow \mathbb{F}_2$ and polynomials over $\mathbb{B}$. Since $\mathbb{F}_2 \subseteq \mathbb{B}$, every function $D \rightarrow \mathbb{F}_2$ is the restriction of exactly one polynomial of degree less than N (Definition 3.6). We write φ and ψ for functions on D , and ℓ , Q , and H for the polynomials representing them. Table 5 summarizes the correspondences proved below.

Linear functions. Quadratic Boolean functions on D are built from linear functions $D \rightarrow \mathbb{F}_2$, so we first represent these by polynomials.

Lemma 5.5 (Labels of linear functions). Every $\mathbb{F}_2$ -linear function $\varphi : D \rightarrow \mathbb{F}_2$ agrees on D with exactly one polynomial $\ell \in \mathbb{B}[X]$ that is a combination of $X, X^2, X^4, \dots, X^{N/2}$. The coefficient of X in ℓ has a square root $\omega \in \mathbb{B}$. We call ω the *label* of φ and write ℓ_ω for ℓ .

1. The polynomial ℓ_ω satisfies $\ell_\omega^2 + \ell_\omega = \omega^2 \Lambda$.
2. The labels form a binary d -space $\widehat{D} \subseteq \mathbb{B}$, the *label space* of D . The map $\omega \mapsto \ell_\omega|_D$ is an $\mathbb{F}_2$ -linear bijection from $\widehat{D}$ onto the space of linear functions $D \rightarrow \mathbb{F}_2$.
3. For $\omega \neq 0$, the polynomial ℓ_ω has degree $N/2$ and leading coefficient $\eta\omega$.

For example, if $D = \mathbb{B} = \mathbb{F}_{2^m}$, then $\ell_\omega = \sum_{i=0}^{m-1} \omega^{2^{i+1}} X^{2^i}$ restricts to $x \mapsto \text{Tr}(\omega^2 x)$, and $\widehat{D} = \mathbb{B}$. In general $\widehat{D}$ differs from D .

Proof. Evaluating the polynomials $\sum_{i=0}^{d-1} c_i X^{2^i}$ on a binary basis of D is a $\mathbb{B}$ -linear map between two d -dimensional spaces. A polynomial in its kernel vanishes on all of D by additivity, and a nonzero one has fewer than N roots, so the kernel is zero. So exactly one such ℓ matches φ on the basis, and then on all of D because both are additive.

The polynomial $\ell^2 + \ell$ is linearized of degree at most N and vanishes on D , so it is a constant multiple of L_D . Comparing coefficients of X gives $\ell^2 + \ell = \omega^2 L_D / \lambda_0 = \omega^2 \Lambda$, and comparing coefficients of X^N gives the third part. For the second part, $\varphi \mapsto \ell$ and $\ell \mapsto \omega$ are additive, and $\omega = 0$ forces $\ell^2 = \ell$, so ℓ is constant and hence zero. $\square$

Quadratic functions. Fix a basis $\omega_1, \dots, \omega_d$ of the label space $\widehat{D}$ and write $\ell_i = \ell_{\omega_i}$. By Lemma 5.5, the functions $x \mapsto x_i = \ell_i(x)$ are binary linear coordinates on D , namely those of the basis of D dual to $\ell_1, \dots, \ell_d$. For an alternating binary $d \times d$ matrix A and a label $\omega \in \widehat{D}$, define a function $\psi : D \rightarrow \mathbb{F}_2$ and a polynomial $Q \in \mathbb{B}[X]$ by

$$\psi(x) = \sum_{i < j} A_{ij} x_i x_j + \ell_\omega(x), \quad Q = \sum_{i < j} A_{ij} (\ell_i \ell_j + \omega_i \omega_j \Lambda) + \ell_\omega. \quad (5.2)$$

Every quadratic Boolean function on D that vanishes at zero is of this form for exactly one pair (A, ω) , and A is its polar matrix. The entries of A and the label ω are the free parameters of the construction. We write ψ_A for the function with $\omega = 0$, and

$$J = \sum_{i < j} A_{ij} (\omega_i^2 \ell_j + \omega_j^2 \ell_i), \quad \varepsilon_A = \sum_{i < j} A_{ij} \omega_i \omega_j,$$

which depend only on A . The polynomial J is linearized of degree at most $N/2$. Recall from Definition 3.15 that the polar radical of ψ is the null space of A in the coordinates x_i : it consists of the $u \in D$ for which $\psi(x+u) + \psi(x)$ does not depend on x , and it has $N/2^{\text{rank } A}$ elements.

Lemma 5.6 (The polynomial of a quadratic function). Let ψ , Q , J , and ε_A be as above.

1. The polynomial Q has degree less than N , satisfies $Q(0) = 0$, and agrees with ψ on D .
2. Its derivative is $Q' = J + \varepsilon_A + \omega^2$, and

$$Q^2 + Q = \Lambda Q'. \quad (5.3)$$

3. The polar radical of ψ is $\{y \in D : J(y) = 0\}$.

Proof. Since Λ vanishes on D , the polynomial Q agrees with ψ there. By the third part of Lemma 5.5, $\ell_i \ell_j$ and $\omega_i \omega_j \Lambda$ have the same leading term $\eta^2 \omega_i \omega_j X^N$, so $\deg Q < N$; also $Q(0) = 0$. The formula for Q' follows from $\ell'_i = \omega_i^2$ and $\Lambda' = 1$. Both sides of (5.3) are additive in Q , so it suffices to check the identity on each

summand of Q . For ℓ_ω it is the first part of Lemma 5.5. For $p = \ell_i \ell_j + \omega_i \omega_j \Lambda$, substituting $\ell_i^2 = \ell_i + \omega_i^2 \Lambda$ and $\ell_j^2 = \ell_j + \omega_j^2 \Lambda$ gives

$$p^2 + p = \Lambda(\omega_i^2 \ell_j + \omega_j^2 \ell_i + \omega_i \omega_j) = \Lambda p',$$

because the terms $\omega_i^2 \omega_j^2 \Lambda^2$ cancel.

For the third part, fix $y \in D$ with coordinates $y_i = \ell_i(y) \in \mathbb{F}_2$. The polynomials ℓ_i , ℓ_ω , and Λ are additive, so

$$Q(X + y) + Q(X) + Q(y) = \sum_{i < j} A_{ij}(y_j \ell_i + y_i \ell_j) = \ell_{\omega'}, \quad \omega' = \sum_{i < j} A_{ij}(y_j \omega_i + y_i \omega_j).$$

On D this polynomial takes the values of the polar form $B_\psi(\cdot, y)$. By the second part of Lemma 5.5, it vanishes on D exactly when $\omega' = 0$. Since the y_i lie in $\mathbb{F}_2$, we have $\omega'^2 = J(y)$, so y lies in the polar radical exactly when $J(y) = 0$. $\square$

The moment equations. If the degree of $H = Q + \kappa$ equals the number of zeros of $\psi + \kappa$, then H is a scalar multiple of the locator of that zero set. The following equations on A lower $\deg Q$ to that number when A has rank $2t$.

Definition 5.7 (Gold moments). Let $\mathbb{B}$ be a finite field of characteristic two, and let $\omega_1, \dots, \omega_d \in \mathbb{B}$ be linearly independent over $\mathbb{F}_2$. For an alternating binary $d \times d$ matrix A and an integer $k \geq 1$, the k -th *Gold moment* of A is

$$M_k(A) = \sum_{i < j} A_{ij}(\omega_i \omega_j^{2^k} + \omega_j \omega_i^{2^k}) \in \mathbb{B}.$$

Each summand is the polarization of $x \mapsto x^{2^k+1}$, the power function studied by Gold [28], and each moment is $\mathbb{F}_2$ -linear in the entries of A . For matrices of rank $2t$ on a full field, the equations $M_k(A) = 0$ for $1 \leq k < t$ correspond to those by which Berman, Shany, and Tamo [10, Theorem IV.1] characterize the quadratic functions whose supports are minimum-weight codewords of extended BCH codes; theirs are the squares of ours, written in symplectic coordinates.

Lemma 5.8 (Moment equations and the coefficients of J). Write $J = \sum_{i=0}^{d-1} J_i X^{2^i}$. Then $J_0 = 0$, and for $2 \leq t \leq d/2$ the following are equivalent:

1. $M_1(A) = \dots = M_{t-1}(A) = 0$;
2. $J_1 = \dots = J_{t-1} = 0$;
3. $J_{d-t+1} = \dots = J_{d-1} = 0$, that is, $\deg J \leq N/2^t$.

When they hold,

$$J = \sum_{i=t}^{d-1} J_i X^{2^i} = \widehat{J}^{2^t}, \quad \widehat{J} = \sum_{i=t}^{d-1} J_i^{2^{-t}} X^{2^{i-t}}, \quad \deg \widehat{J} \leq \frac{N}{2^{2t}}, \quad (5.4)$$

where $a^{2^{-r}}$ denotes the 2^r -th root of a in $\mathbb{B}$ (Figure 4).

Proof. For a label $\omega \in \widehat{D}$, let $\omega^{(i)}$ be the coefficient of X^{2^i} in ℓ_ω , and write $\omega_k^{(i)}$ for $\omega = \omega_k$, so that $J_i = \sum_{j < k} A_{jk}(\omega_j^2 \omega_k^{(i)} + \omega_k^2 \omega_j^{(i)})$. Comparing coefficients in $\ell_\omega^2 + \ell_\omega = \omega^2 \Lambda$ gives

$$\omega^{(0)} = \omega^2, \quad \omega^{(i)} = (\omega^{(i-1)})^2 + \mu_i \omega^2 \quad (1 \leq i \leq d-1), \quad \omega^{(d-1)} = \eta \omega.$$

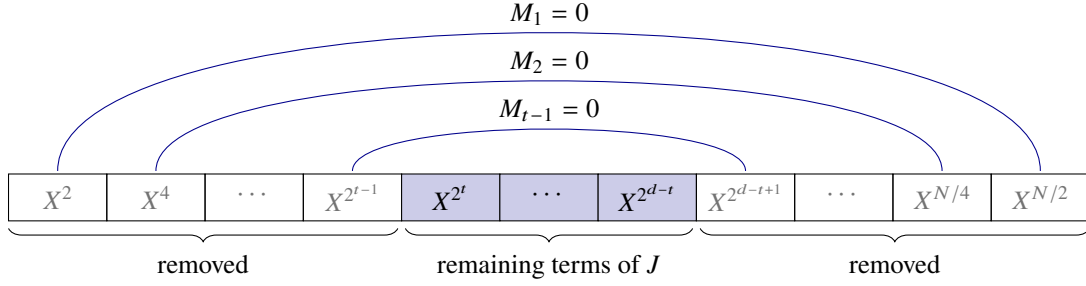


Figure 4: How the Gold moment equations control $\deg Q'$ (Lemma 5.8). The nonconstant part J of Q' is additive, and its possible terms are $X^2, X^4, \dots, X^{N/2}$. Once $M_1 = \dots = M_{k-1} = 0$, the equation $M_k = 0$ removes the terms X^{2^k} and $X^{2^{d-k}}$, one at each end. The $t-1$ equations leave only $X^{2^t}, \dots, X^{2^{d-t}}$. The picture is drawn for $t \geq 4$; for $t = 2$ only $M_1 = 0$ is imposed and only X^2 and $X^{N/2}$ are removed. Removing the high terms bounds $\deg Q'$ by $N/2^t$, and removing the low terms makes J a 2^t -th power.

Solving upward gives $\omega^{(i)} = \sum_{s=0}^i \mu_{i-s}^{2^s} \omega^{2^{s+1}}$. In J_i the terms with $s = 0$ cancel, and $\omega_j^2 \omega_k^{2^{s+1}} + \omega_k^2 \omega_j^{2^{s+1}} = (\omega_j \omega_k^{2^s} + \omega_k \omega_j^{2^s})^2$, so

$$J_i = \sum_{s=1}^i \mu_{i-s}^{2^s} M_s(A)^2.$$

Thus $J_0 = 0$. Since $\mu_0 = 1$, the moment $M_i(A)^2$ occurs in J_i with coefficient one, and induction on i shows that the first two conditions are equivalent. Solving downward instead, with $\omega^{(i-1)} = \sqrt{\omega^{(i)}} + \sqrt{\mu_i} \omega$, induction on s gives constants $\nu_{s,r} \in \mathbb{B}$ with $\omega^{(d-1-s)} = \sum_{r=0}^s \nu_{s,r} \omega^{2^{-r}}$: start with $\nu_{0,0} = \eta$, and step with $\nu_{s+1,0} = \sqrt{\mu_{d-1-s}}$ and $\nu_{s+1,r+1} = \sqrt{\nu_{s,r}}$. Since $\omega_j^2 \omega_k^{2^{-r}} + \omega_k^2 \omega_j^{2^{-r}} = (\omega_j \omega_k^{2^{r+1}} + \omega_k \omega_j^{2^{r+1}})^{2^{-r}}$,

$$J_{d-1-s} = \sum_{r=0}^s \nu_{s,r} M_{r+1}(A)^{2^{-r}}.$$

Here $\nu_{s,s} = \eta^{2^{-s}} \neq 0$, so induction on s shows that the first and third conditions are equivalent. Under these conditions only the coefficients $J_t, \dots, J_{d-t}$ remain, and every remaining exponent is divisible by 2^t . $\square$

Lemma 5.9 (Rank under the moment equations). Let $2 \leq t \leq d/2$, and let $A \neq 0$ satisfy $M_1(A) = \dots = M_{t-1}(A) = 0$. Then A has rank at least $2t$. If its rank is exactly $2t$, and V is the polar radical, of size $N/2^{2t}$, then

$$J = J_{d-t} L_V^{2^t}, \quad J_{d-t} \neq 0, \quad \deg J = \frac{N}{2^t}.$$

Proof. By Lemma 5.6 and (5.4), the polar radical V is the set of roots of $\widehat{J}$ in D . Since $A \neq 0$, we have $V \neq D$, so $\widehat{J} \neq 0$, and $|V| = N/2^{\text{rank } A}$ is at most $\deg \widehat{J} \leq N/2^{2t}$. If the rank is $2t$, the polynomial $\widehat{J}$ vanishes on all $N/2^{2t}$ points of V , so it is a constant multiple of L_V . $\square$

Level sets. The next lemma concerns only the functions on D and does not use the moment equations.

Lemma 5.10 (Level sets of a quadratic function). Let A have rank $2t$ with $1 \leq t \leq d/2$, let V be its polar radical, and put $T = N/2 - N/2^{t+1}$. Exactly 2^{2t} labels $\omega \in \widehat{D}$ make ψ vanish on V . For each of them, ψ is constant on every coset of V , and exactly one $\kappa \in \mathbb{F}_2$ makes $\psi + \kappa$ take the value one at T points of D and the value zero at the other $N - T$.

Proof. For $v \in V$ and $x \in D$, we have $\psi_A(x + v) = \psi_A(x) + \psi_A(v)$, so ψ_A is linear on V . The function ψ vanishes on V exactly when ℓ_ω agrees with ψ_A on V . By Lemma 5.5, exactly 2^{2t} labels ω have this property, one for each extension to D of the linear function $\psi_A|_V$. Fix one. Then $\psi(x + v) = \psi(x)$ for $v \in V$, and the signed sum $\sigma = \sum_{x \in D} (-1)^{\psi(x)}$ satisfies

$$\sigma^2 = \sum_{u \in D} (-1)^{\psi(u)} \sum_{x \in D} (-1)^{B_\psi(x, u)} = N|V| = \frac{N^2}{2^{2t}},$$

because the inner sum is N for $u \in V$, where $\psi(u) = 0$, and zero otherwise. So $\sigma = \pm N/2^t$. The function $\psi + \kappa$ takes the value one at $(N - (-1)^\kappa \sigma)/2$ points, which equals T exactly when $(-1)^\kappa \sigma > 0$. $\square$

Matching the degree to the number of zeros. The rank of A and the moment equations bound the same degree from opposite sides.

Remark 5.11 (Rank, moments, and degree). Let A have rank $2r > 0$, choose ω and κ as in Lemma 5.10, and let $H = Q + \kappa$ be the polynomial of $\psi + \kappa$. By (5.3), $H^2 + H = \Lambda H'$ with $H' = J + \varepsilon_A + \omega^2$, and $J \neq 0$, so $\deg H = (N + \deg J)/2$. The polynomial H is nonzero and vanishes at the zeros of $\psi + \kappa$, so

$$\deg H \geq \frac{N}{2} + \frac{N}{2^{r+1}}, \quad \text{that is,} \quad \deg J \geq \frac{N}{2^r}.$$

By Lemma 5.8, the equations $M_1(A) = \cdots = M_{t-1}(A) = 0$ hold exactly when $\deg J \leq N/2^t$. Together these give $r \geq t$ again, and for $r = t$ the degree of H equals the number of zeros of $\psi + \kappa$. Then every root of H lies in D . The next lemma uses this case.

Lemma 5.12 (Gold moments give polynomials with many roots). Fix a basis $\omega_1, \dots, \omega_d$ of the label space $\widehat{D}$, let $2 \leq t \leq d/2$, and put

$$T = \frac{N}{2} - \frac{N}{2^{t+1}}, \quad R = \sqrt{L_D - \lambda_0 X} = \sum_{i=1}^d \sqrt{\lambda_i} X^{2^{i-1}}.$$

Each alternating binary $d \times d$ matrix A of rank $2t$ with $M_1(A) = \cdots = M_{t-1}(A) = 0$ gives 2^{2t} distinct monic polynomials

$$P = R + C \in \mathbb{B}[X], \quad \deg C = \frac{T}{2} = \frac{N}{4} - \frac{N}{2^{t+2}},$$

one for each label ω of Lemma 5.10. The roots of P on D are the T points where $\psi + \kappa$ takes the value one. The polynomials from different matrices are also distinct. Every polynomial P of this family has the following properties.

1. It satisfies

$$P'(P^2 + L_D) = \lambda_0 P. \tag{5.5}$$

2. Its set of roots on D is a union of cosets of a subspace of D of dimension $d - 2t$.

3. It takes the same value as any other polynomial of the family at at most $N/2^{2t}$ points outside D , in any field containing $\mathbb{B}$.

Proof. Fix such a matrix A , with polar radical V , and one of the 2^{2t} labels ω of Lemma 5.10, with its κ . Let $H = Q + \kappa$ be the polynomial of $\psi + \kappa$. By Lemma 5.6, $H^2 + H = \Lambda H'$ with $H' = Q'$.

The polynomial P . By Lemmas 5.8 and 5.9, $H' = J + \varepsilon_A + \omega^2 = U^2$ with $U = \widehat{J}^{2^{t-1}} + \sqrt{\varepsilon_A + \omega^2}$ of degree $N/2^{t+1}$. Since $t \geq 2$, every exponent in U is even and $U' = 0$. Leading terms in $H^2 + H = \Lambda U^2$ give $\deg H = N/2 + N/2^{t+1} = N - T$ and $\text{lc}(H) = \eta \text{lc}(U)$. So H has as many zeros in D as its degree: its roots are simple and lie in D . Since $N \geq 2^{2t} \geq 16$, the number T is even with $2 \leq T < N/2$, and Lemma 3.16 applies with $\lambda = \lambda_0$. It gives the polynomial

$$P = \eta U \frac{L_D}{H}, \quad P^2 = L_D + \frac{L_D}{H}, \quad \deg(P + R) = \frac{T}{2},$$

whose roots on D are the T points where $\psi + \kappa = 1$. If E is this set, then $L_D/H = L_E/\text{lc}(H)$, so $L_E = \text{lc}(H) (C^2 + \lambda_0 X)$ with $C = P + R$, the form announced at the start of this subsection. By Lemma 5.10 they form a union of cosets of V , which is the second property, and P is monic because $\text{lc}(H) = \eta \text{lc}(U)$. Dividing $H^2 + H = \eta^2 L_D U^2$ by $\eta^2 U^2 H$ gives $P = (H + 1)/(\eta U)$. Differentiating $\eta U P = H + 1$ gives $P' = U/\eta$, and then $P'(P^2 + L_D) = (U/\eta)(L_D/H) = P/\eta^2 = \lambda_0 P$, which is the first property.

Distinctness. The derivative $P' = U/\eta$ determines $Q' = U^2$. Two polynomials satisfying (5.3) with the same derivative differ by a polynomial Y with $Y^2 = Y$, a constant, and $Q(0) = 0$; so Q' determines Q . In turn Q determines ψ , hence the pair (A, ω) . So distinct pairs (A, ω) give distinct polynomials P .

Collisions outside D . Let $P_1 \neq P_2$ belong to the family, and let $\beta \notin D$, in a field containing $\mathbb{B}$, satisfy $P_1(\beta) = P_2(\beta)$. Since $P(\beta)^2 + L_D(\beta) = L_D(\beta)/H(\beta) \neq 0$, (5.5) gives $P'_1(\beta) = P'_2(\beta)$, that is, $U_1(\beta) = U_2(\beta)$. By the formula for U ,

$$U_1 + U_2 = G^{2^{t-1}}, \quad G = \widehat{J}_1 + \widehat{J}_2 + \varepsilon_0, \quad \deg G \leq \frac{N}{2^{2t}},$$

for a constant ε_0 . By the previous paragraph, $U_1 \neq U_2$, so $G \neq 0$, and β is one of its at most $N/2^{2t}$ roots. $\square$

Rank two. For $d \geq 3$, Lemma 3.16 also applies at polar rank two, where there is no moment equation, and it recovers the subspace-locator polynomials of Theorem 4.1. For a quadratic Boolean function of polar rank two that vanishes on its polar radical, as in Lemma 5.10, the smaller level set is a coset of that radical, of codimension two. Take it to be a subspace $W \leq D$ with locator $L_W = X^{N/4} + a_W X^{N/8} + \dots$. Then $L_D = L_W^4 + u_W L_W^2 + v_W L_W$ with $u_W, v_W \in \mathbb{B}$, so $\lambda_0 = v_W L'_W$, and $H = L_D/(v_W L_W)$ has $3N/4$ simple roots in D and satisfies

$$H^2 + H = H \cdot \frac{L_W(L_W^2 + u_W)}{v_W} = \frac{L_D}{\lambda_0} H'.$$

The lemma, with $T = N/4$, gives $P = L_W^2 + \sqrt{u_W} L_W$, and comparing coefficients of $X^{N/2}$ gives $\sqrt{u_W} = a_W^2 + \sqrt{\lambda_{d-1}}$. This is the polynomial $L_W^2 + (a_W^2 + \theta) L_W$ from the proof of Theorem 4.1, with $\theta = \sqrt{\lambda_{d-1}}$. Here $P + R$ has degree $N/8$, which puts agreement $N/4$ below Johnson; Theorem 4.1 takes $\theta \notin \mathbb{B}$ to reach it.

5.4 Counting matrices of rank $2t$

Lemma 5.13 (Rank- $2t$ solutions of the moment equations). Let $D \subseteq \mathbb{F}_{2^m}$ be binary additive of dimension d , let $\omega_1, \dots, \omega_d$ be a basis of its label space, and let $2 \leq t \leq n = \lfloor d/2 \rfloor$, with ι and $\Delta \geq 1$ as in Theorem 5.1. Let C be the space of alternating binary $d \times d$ matrices A with $M_1(A) = \dots = M_{t-1}(A) = 0$, and let C_{2r} be the set of its matrices of rank $2r$. Then

$$|C_{2t}| \geq \begin{bmatrix} n \\ t \end{bmatrix}_4 (2^\Delta - 1). \quad (5.6)$$

Proof. An alternating matrix has $\binom{d}{2}$ free binary entries, and each of the $t - 1$ moment equations imposes at most m binary linear constraints, so $|C| \geq 2^{\binom{d}{2} - m(t-1)}$. By Lemma 5.9, C_{2r} is empty for $0 < r < t$. It remains to count the matrices of rank exactly $2t$.

For alternating matrices A and B , put

$$\langle A, B \rangle = \sum_{i < j} A_{ij} B_{ij} \in \mathbb{F}_2, \quad \chi_B(A) = (-1)^{\langle A, B \rangle}.$$

For $0 \leq j \leq n$ and a matrix A of rank $2r$, the sum $\pi_j(r) = \sum_{\text{rank } B=2j} \chi_B(A)$ depends only on r ; these are the numbers $F_j^{(d)}(r)$ of Schmidt [40, Proposition 3.3], whose pairing of the quadratic function with polar matrix A and the alternating matrix B is $\langle A, B \rangle$. The moment identity of Delsarte and Goethals [20, Eq. (29)], also stated in [40, Eq. (13)], gives for $0 \leq s, r \leq n$

$$\sum_{j=0}^s \begin{bmatrix} n-j \\ n-s \end{bmatrix}_4 \pi_j(r) = 2^{(d-\iota)s} \begin{bmatrix} n-r \\ s \end{bmatrix}_4. \quad (5.7)$$

Let $C_{2j}^\perp$ be the set of rank- $2j$ matrices B with $\langle A, B \rangle = 0$ for every $A \in C$. The sum of χ_B over C is $|C|$ for such B and zero for other B . Summing over all B of rank $2j$ and grouping the A by rank,

$$\sum_{r=0}^n |C_{2r}| \pi_j(r) = |C| |C_{2j}^\perp|.$$

Multiply by $\begin{bmatrix} n-j \\ n-s \end{bmatrix}_4$, sum over $0 \leq j \leq s$, apply (5.7), and take $s = n - t$. On the left, only $r = 0$ and $r = t$ remain: the Gaussian binomial vanishes for $r > t$, and C_{2r} is empty for $0 < r < t$. On the right, keep the term $j = 0$. This gives

$$2^{(d-\iota)(n-t)} \left(\begin{bmatrix} n \\ t \end{bmatrix}_4 + |C_{2t}| \right) \geq |C| \begin{bmatrix} n \\ t \end{bmatrix}_4, \quad \text{so} \quad |C_{2t}| \geq \begin{bmatrix} n \\ t \end{bmatrix}_4 \left(\frac{|C|}{2^{(d-\iota)(n-t)}} - 1 \right).$$

Inserting the bound on $|C|$ and the identity $\binom{d}{2} - m(t-1) - (d-\iota)(n-t) = \Delta$, checked separately for even and odd d , proves (5.6). $\square$

5.5 Proof of the counting bound

Proof of Theorem 5.1. By Lemmas 5.13 and 5.12, applied to a basis of the label space, there are L distinct polynomials $P_i = R + C_i$ ($1 \leq i \leq L$) as in Lemma 5.12, with $\deg C_i = T/2 < N/4$. On the roots of P_i , the word $R|_D$ agrees with the codeword $C_i|_D$. The C_i are distinct of degree less than N , so this is the decoding list.

For the pair, let $\beta \in \mathbb{F} \setminus D$ and apply Lemma 3.11 with message length $N/4$ to $f_0(x) = R(x)/(x - \beta)$ and $g(x) = 1/(x - \beta)$. This gives $\text{agr}_{N/4}(g) = \text{CA}_{N/4}(f_0, g) = N/4$, and each $z_i = C_i(\beta)$ is exceptional at agreement T with a witness of degree $T/2 - 1$. Since $z_i = z_j$ exactly when $P_i(\beta) = P_j(\beta)$, the colliding pairs, summed over the $q - N$ poles, number at most δ_2^L , and Lemma 3.19 gives a pole with at least Z distinct values z_i . Finally, by Lemma 3.13 for $b = 2$, replacing f_0 by $f(x) = \sqrt{\lambda_0/(x - \beta)}$ translates the challenges by a constant and gives $\text{agr}_{N/4}(f) \leq 3N/8 - 1 < T$. So zero is not exceptional, and all Z challenges are nonzero. For an affine translate $D + a$, substitute $X - a$ for X and $\beta + a$ for β . $\square$

5.6 Increasing agreement and rate by padding

The unused degree in Theorem 5.1 lets us add agreement points by multiplying the inputs and witnesses by a subspace locator. We choose the subspace to control its overlap with the old agreement sets. Corollary 5.15

reaches rate $1/2$, Corollary 5.16 the rates $\rho \geq 5/8$ at agreement near $(1 + \rho)/2$, and Corollary 5.17 every fixed rate at agreement a constant above the rate.

Lemma 5.14 (Adding an additive set of common roots). Let D be a binary additive space of dimension d , with $N = 2^d$, and let $\beta \notin D$. Suppose the received pair $f(x) = R(x)/(x - \beta)$, $g(x) = 1/(x - \beta)$ has L distinct selected nonzero challenges with witnesses of degree less than K_0 . Suppose each agreement set has size T and is invariant under translation by a subspace of dimension $d - 2t$. Fix $2t \leq s < d$, and put

$$w = 2^s, \quad K = K_0 + w < N, \quad p_{d,s,r} = \frac{2^{r(d-s)} \begin{bmatrix} d-r \\ s-r \end{bmatrix}_2}{\begin{bmatrix} d \\ s \end{bmatrix}_2}.$$

There is a received pair with common agreement exactly K and at least $\lceil p_{d,s,2t} L \rceil$ selected nonzero challenges at agreement

$$T + w \left(1 - \frac{T}{N} \right).$$

Proof. Put $r = 2t$ and choose an s -dimensional subspace B of D uniformly at random. For a fixed codimension- r subspace V , the condition $B + V = D$ forces $\dim(B \cap V) = s - r$. Choose this intersection first. In the quotient by it, $B/(B \cap V)$ must complement $V/(B \cap V)$; relative to one complement, all choices are graphs of linear maps. Hence there are

$$\begin{bmatrix} d-r \\ s-r \end{bmatrix}_2 2^{r(d-s)}$$

successful subspaces, giving probability exactly $p_{d,s,r}$. The Gaussian product formula also gives

$$p_{d,s,r} = \prod_{j=0}^{r-1} \frac{1 - 2^{j-s}}{1 - 2^{j-d}}.$$

If an agreement set S is invariant under translation by V and $B + V = D$, every coset of V meets B in exactly 2^{s-2t} points. Consequently $|B \cap S| = wT/N$. Averaging over B shows that one choice has this property for at least $\lceil p_{d,s,2t} L \rceil$ selected challenges. Pad by this B (Definition 3.17). Each padded witness has degree less than K , and its agreement set is exactly $S_z \cup B$, of size $T + w - wT/N$, proving the claimed threshold.

The second input is $L_B(x)/(x - \beta)$, with $L_B(\beta) \neq 0$ and $\deg L_B \leq K$. Lemma 3.11 gives exact common agreement K . $\square$

Corollary 5.15 (Gold families at rate $1/2$). Under the hypotheses of Theorem 5.1, suppose $2t \leq d - 2$, and let Z be its bound (5.1). On the same domain and over the same challenge field, there is a pair with

$$\text{CA}_{N/2}(f, g) = N/2, \quad |\text{Bad}_{T_{1/2}}(f, g) \setminus \{0\}| \geq \lceil p_{d,d-2,2t} Z \rceil, \quad T_{1/2} = \frac{5N}{8} - \frac{3N}{2^{t+3}}.$$

Consequently the dense-domain quasipolynomial counts also hold at rate $1/2$ and agreement tending to $5/8$, with common-agreement gap tending to $1/8$.

Proof. For each distinct nonzero challenge, choose one witness from Theorem 5.1. Its agreement set is the root set of the corresponding polynomial P_i , which by the second property in Lemma 5.12 is invariant under translation by a subspace of dimension $d - 2t$. Its degree is below $N/4$. Apply Lemma 5.14 with $K_0 = N/4$ and $s = d - 2$. The new message length is $N/2$, the selected proportion is $p_{d,d-2,2t}$, and the agreement is $T + (N/4)(1 - T/N) = T_{1/2}$. The product formula gives $p_{d,d-2,2t} \geq 1 - 2^{2t+2-d}$, since its numerator is at least $1 - \sum_{j < 2t} 2^{j-d+2}$ and each factor of its denominator is less than one. For the choices of t in Corollary 5.2 we have $t \leq d/4$, so $p_{d,d-2,2t} = 1 - o(1)$. $\square$

The agreement tends to $5/8$, below the rate- $1/2$ Johnson threshold $1/\sqrt{2}$. Section 6 gives a different construction that also applies to sparse domains.

Multiplying every polynomial by one common locator moves these lists to every fixed rate $\rho \geq 5/8$. This costs a fixed fraction of the agreement gap, but the agreement stays a constant above the rate.

Corollary 5.16 (Higher rates on every dense binary domain). Fix integers $c \geq 0$ and $r \geq 1$ and a rate ρ with

$$1 - 3 \cdot 2^{-r-2} \leq \rho < 1 - 2^{-r-2}.$$

For every sufficiently large d and every additive d -space $D \subseteq \mathbb{B} = \mathbb{F}_{2^{d+c}}$, put $N = 2^d$ and $K = \lfloor \rho N \rfloor$. There is an integer T with

$$\frac{T}{N} = \frac{1 + \rho}{2} - 2^{-r-3} - o(1)$$

such that the following hold.

1. Some word in $\mathbb{B}^D$ agrees with at least $N^{\Omega_{c,r}(\log N)}$ polynomials of degree less than K over $\mathbb{B}$ on at least T points each.
2. Over an extension $\mathbb{F}$ of $\mathbb{B}$ with $|\mathbb{F}| = N^{O_{c,r}(\log N)}$, there is a pair with

$$\text{agr}_K(g) = \text{CA}_K(f, g) = K, \quad |\text{Bad}_T(f, g) \setminus \{0\}| \geq N^{\Omega_{c,r}(\log N)}.$$

The limiting agreement fraction exceeds ρ by $(1 - \rho)/2 - 2^{-r-3} > 0$ and is below $\sqrt{\rho}$. The windows for $r \geq 1$ cover every rate in $[5/8, 1)$.

For instance, $r = 1$ and $\rho = 5/8$ give agreement tending to $3/4$.

Proof. Choose a subspace $D_0 \subseteq D$ of codimension r , and put $N_0 = |D_0| = 2^{-r}N$. Then $|\mathbb{B}| = 2^{c+r}N_0$, so Corollary 5.2 applies to D_0 with $c + r$ in place of c . As in the proof of Theorem 5.1, it supplies polynomials $R + C_i$ over $\mathbb{B}$, for $1 \leq i \leq L$, with distinct C_i of degree less than $N_0/4$, each with exactly T_0 roots in D_0 , where

$$T_0 = N_0/2 - o(N_0), \quad \log_2 L = \Omega_{c,r}((\log N)^2), \quad \log_2 L = O((\log N)^2).$$

Let $S_i \subseteq D_0$ be the root set of $R + C_i$.

Put $K_0 = N - 3N_0/4$ and $w = K - K_0$. The hypothesis on ρ gives $0 \leq w < N_0/2$. If $w = 0$, put $B = \emptyset$. Otherwise apply Lemma 3.18 inside D_0 to the sets $S_1, \dots, S_L$. It gives a set $B \subseteq D_0$ of size w with

$$|B \cup S_i| \geq T_1, \quad T_1 = \left\lceil w + \left(1 - \frac{w}{N_0}\right) T_0 - \sqrt{(w/2) \ln(2L)} \right\rceil = \frac{N_0 + w}{2} - o(N),$$

for every i , because $\ln L = O((\log N)^2)$. If $w = 0$, the same holds with $T_1 = T_0$. Put

$$\Pi = L_{D \setminus D_0} L_B, \quad \deg \Pi = N - N_0 + w = K - N_0/4.$$

Each polynomial $\Pi(R + C_i) = \Pi R + \Pi C_i$ vanishes on $(D \setminus D_0) \cup B \cup S_i$, a set of size at least

$$T = N - N_0 + T_1 = N - N_0 + \frac{N_0 + w}{2} - o(N) = \frac{N + K}{2} - \frac{N_0}{8} - o(N),$$

which is the stated agreement because $K = \rho N + O(1)$ and $N_0 = 2^{-r}N$. The polynomials ΠC_i are distinct, have coefficients in $\mathbb{B}$, and have degree less than K . The word $(\Pi R)|_D$ agrees with each of them on at least T points. This proves the first part.

For the second part, let $\mathbb{F}$ be the smallest extension of $\mathbb{B}$ with $|\mathbb{F}| \geq NL$; its size is at most $|\mathbb{B}|NL = N^{O_{c,r}(\log N)}$. For large d , at least $|\mathbb{F}|/2$ of its elements lie outside $\mathbb{B}$. For such a pole β , we have $\Pi(\beta) \neq 0$, since the roots of Π lie in D . Hence two values $(\Pi C_i)(\beta)$ and $(\Pi C_j)(\beta)$ collide only if β is a root of $C_i - C_j$, which happens for fewer than $N_0/4$ poles. Summed over all poles outside $\mathbb{B}$, there are at most $(N_0/4)\binom{L}{2}$ colliding pairs. Lemma 3.19 gives a pole $\beta \notin \mathbb{B}$ with at least

$$L - \frac{(N_0/4)\binom{L}{2}}{|\mathbb{F}|/2} \geq L - \frac{L}{4}$$

distinct values $z_i = (\Pi C_i)(\beta)$, at most one of them zero. Apply Lemma 3.11 at this pole, with message length K , to the polynomials $\Pi R + \Pi C_i$. It gives the pair $f(x) = \Pi(x)R(x)/(x - \beta)$, $g(x) = 1/(x - \beta)$ with $\text{agr}_K(g) = \text{CA}_K(f, g) = K$, and each z_i lies in $\text{Bad}_T(f, g)$. At least $3L/4 - 1$ of them are distinct and nonzero.

For the final claims, the gap is positive exactly when $\rho < 1 - 2^{-r-2}$. Also $(1 + \rho)/2 - \sqrt{\rho} = (1 - \sqrt{\rho})^2/2$. Since $\rho \geq 5/8$ gives $(1 + \sqrt{\rho})^2 > 3$, and $1 - \rho \leq 3 \cdot 2^{-r-2}$,

$$\frac{(1 - \sqrt{\rho})^2}{2} = \frac{(1 - \rho)^2}{2(1 + \sqrt{\rho})^2} < \frac{3 \cdot 2^{-2r-4}}{2} \leq 2^{-r-3},$$

so the limiting agreement is below $\sqrt{\rho}$. The window for r is $[1 - 3 \cdot 2^{-r-2}, 1 - 2^{-r-2})$; consecutive windows overlap, and the first begins at $5/8$. $\square$

Padding outside D_0 alone reaches every fixed rate.

Corollary 5.17 (Every fixed rate on every dense binary domain). Fix an integer $c \geq 0$, a rate $0 < \rho < 1$, and an integer $r \geq 1$ with $2^{-r-2} < \min\{\rho, (1 - \rho)/3, \sqrt{\rho} - \rho\}$. For every sufficiently large d and every additive d -space $D \subseteq \mathbb{B} = \mathbb{F}_{2^{d+c}}$, with $N = 2^d$ and $K = \lfloor \rho N \rfloor$, the two conclusions of Corollary 5.16 hold for an integer T with $T/N = \rho + 2^{-r-2} - o(1)$. The limiting agreement fraction lies strictly between ρ and $\sqrt{\rho}$. The same holds on every translate $D + a$ with $a \in \mathbb{B}$.

Proof. Take D_0 , $N_0 = 2^{-r}N$, the polynomials $R + C_i$, and their root sets S_i as in the preceding proof, and put $w = K - N_0/4$. For large d the number $N_0/4 = 2^{-r-2}N$ is an integer below ρN , so $w \geq 0$, and $K \leq \rho N < N - 3N_0/4$ gives $w < N - N_0$. For any set $E \subseteq D \setminus D_0$ of size w and $\Pi = L_E$, each $\Pi(R + C_i)$ vanishes on $E \cup S_i$, a set of size $T = w + T_0 = K + N_0/4 - o(N)$, and the ΠC_i are distinct polynomials over $\mathbb{B}$ of degree less than $w + N_0/4 = K$. The roots of Π lie in D , so the rest of that proof applies unchanged. For a translate, substitute $X - a$ for X . $\square$

5.7 A concrete bound for Binius64

Binius64 uses the field $\mathbb{F}_{2^{128}} = \mathbb{F}_2[X]/(X^{128} + X^7 + X^2 + X + 1)$ for its codewords and its challenges [12]. It fixes a basis $\beta_0, \dots, \beta_{127}$ of this field over $\mathbb{F}_2$ with

$$\beta_0 = 1, \quad \beta_{i-1} = \beta_i^2 + \beta_i \quad (1 \leq i \leq 127),$$

and encodes a message of length 2^k at rate 2^{-r} on the domain $V_d = \text{span}_{\mathbb{F}_2}\{\beta_0, \dots, \beta_{d-1}\}$ of dimension $d = k + r$.

These domains lie in small subfields. Put $A(X) = X^2 + X$. The recurrence says $A(\beta_i) = \beta_{i-1}$ and $A(\beta_0) = 0$, so 32 successive applications of A send each of $\beta_0, \dots, \beta_{31}$ to zero. Two applications of A give $X^4 + X$, four give $X^{16} + X$, and 32 give $X^{2^{32}} + X$, whose roots are the elements of $\mathbb{F}_{2^{32}}$. Hence $V_{32} = \mathbb{F}_{2^{32}}$, and $V_d \subseteq \mathbb{F}_{2^{32}}$ for every $d \leq 32$. A subspace of $\mathbb{F}_{2^{128}}$ of the same dimension that lies in no proper subfield has $m = 128$ in Theorem 5.1, outside its range for $d \leq 32$.

As an example we take $d = 27$, the domain for messages of length 2^{25} at rate $1/4$ and of length 2^{26} at rate $1/2$. On this domain we obtain a rate- $1/4$ example with common agreement 25% but exceptional combinations agreeing with a codeword on more than 49.4% of the domain. Such combinations occur with probability greater than 2^{-30} when the challenge is uniform in $\mathbb{F}_{2^{128}}$. The Johnson agreement threshold at this rate is 50%. The following corollary gives the precise bounds.

Corollary 5.18 (A 128-bit-field example). Let D be any binary 27-space in $\mathbb{F}_{2^{32}}$, or any affine translate. Put $N = 2^{27}$, $K = 2^{25}$, and $\mathbb{F} = \mathbb{F}_{2^{128}}$. There is a fixed pair over $\mathbb{F}$ with $\text{CA}_K(f, g) = K$ and more than 3.4248×10^{29} distinct nonzero exceptional challenges at agreement

$$\frac{T}{N} = \frac{16193}{32768} \approx 0.49417.$$

For a uniformly sampled challenge in $\mathbb{F}$, the exceptional probability is greater than $2^{-29.889}$. The pair can be chosen so that both inputs are individually far, with

$$\text{agr}_K(f) \leq \frac{193N}{512} - 1, \quad \text{agr}_K(g) = \frac{N}{4}.$$

Proof. We first apply Theorem 5.1, then use the remaining degree allowance to increase agreement by locator padding. It suffices to prove the linear-domain case; translation gives the affine cases. With $d = 27$ and $m = 32$, the hypothesis of Theorem 5.1 is $\Delta = 32 - 5t \geq 1$, so $t = 6$ is the largest admissible choice. It gives $\Delta = 2$, $\delta = 2^{15}$, and

$$L = 2^{12} \cdot 3 \left[\begin{matrix} 13 \\ 6 \end{matrix} \right]_4 \approx 3.45167 \times 10^{29}.$$

Some members of this family may give the same challenge. With $q = 2^{128}$, the first bound in equation (5.1) retains the larger number of distinct challenges, namely

$$Z = L - \left\lfloor \frac{\delta \binom{L}{2}}{q - N} \right\rfloor \approx 3.45161 \times 10^{29}$$

nonzero challenges at agreement $T_0 = 63N/128$. The witnesses have degree less than $K_0 = N/4 - N/256$.

The degree bound leaves room to multiply both inputs and their witnesses by a locator of degree $w = N/256$. This adds agreement wherever that locator vanishes. Apply Lemma 5.14 with $s = 19$ and $w = 2^{19} = N/256$. By the second property in Lemma 5.12, each agreement set is a union of cosets of the radical of its quadratic polar form. That radical has dimension $d - 2t = 15$, which supplies the translation invariance required by the padding lemma. Here

$$p_{27,19,12} = \prod_{j=0}^{11} \frac{1 - 2^{j-19}}{1 - 2^{j-27}} \approx 0.9922399879.$$

The final message length is $K_0 + w = K$, the nonzero count after padding is $Z' = \lceil p_{27,19,12} Z \rceil \approx 3.424826 \times 10^{29}$, and the agreement is $T_0 + w(1 - T_0/N) = 16193N/32768$. Finally $128 - \log_2 Z' = 29.888054438 \dots$

To obtain the additional bounds on each input individually, use the first input of Lemma 3.13 before padding. Its numerator differs from the fixed polynomial used in Theorem 5.1 by a polynomial of degree at most $N/8$. For the received word this adds a fixed polynomial of degree at most $N/8 - 1 < K_0$ and a scalar multiple of g , so the witness degrees remain strictly below K and the agreement sets are unchanged. This first input has agreement below T_0 , so all selected challenges are nonzero. The padding locator has degree $w = N/256$, and the padded bound in that lemma gives $3N/8 + w/2 - 1 = 193N/512 - 1$. The agreement of the padded second input, and the common agreement of the pair, remain exactly K . $\square$

Attributes	e	N	Common agreement K	Combination agreement T	T/N
1	4151	3230	461	845	26.16%
2	4265	3318	474	858	25.86%
3	4307	3352	478	862	25.72%
4	4415	3436	490	874	25.44%

Table 6: Longfellow’s version-7 binary code parameters and the agreement $T = K + 384$ of Corollary 5.19.

The combination agreement is about 0.58 percentage points below Johnson and 24.42 percentage points above the inputs’ common agreement. Thus the counterexample also rules out any permitted proximity loss smaller than this common-agreement gap (Section 3.1). Before padding, the same construction gives a single received word with L nearby codewords over the smaller field $\mathbb{F}_{2^{32}}$ at agreement 63/128.

At rate $1/2$ on the same domain and over the same 128-bit field, Corollary 5.15 gives common agreement $1/2$ and more than 3.45123×10^{29} nonzero exceptional challenges at agreement 317/512. The lower bound on the count is $\lceil p_{27,25,12}Z \rceil$. Its common-agreement gap is 61/512 and its exceptional probability exceeds $2^{-29.877}$.

5.8 A concrete bound for Google’s Longfellow

Longfellow’s evaluation domains are not additive. Each of the four domains we analyze contains an affine subspace of 2048 points, and the Gold construction on that subspace, padded on the remaining points, gives a counterexample on the whole domain (Corollary 5.19). We first describe the domains, following the specification [27] and version 7 of the implementation [26].

The domains. The challenge field is $\mathbb{F}_{2^{128}}$. Longfellow fixes an element g such that $1, g, \dots, g^{15}$ is a basis of the subfield $\mathbb{F}_{2^{16}}$ over $\mathbb{F}_2$ [27, Section 2.2.2]. For an integer $0 \leq j < 2^{16}$ with bits $j_0, \dots, j_{15}$, put $\text{inj}(j) = \sum_i j_i g^i$. This map is $\mathbb{F}_2$ -linear in the bits, so it sends the integers $c2^k, \dots, (c+1)2^k - 1$ to an affine subspace of dimension k .

A row of the prover’s witness has e entries, where $e < 2^{16}$ is fixed for each circuit. It holds the values at $\text{inj}(0), \dots, \text{inj}(e-1)$ of a polynomial of degree less than $K = \lfloor (e+1)/9 \rfloor$. The first $2K-1$ positions hold the message and the further evaluations that determine a product of two rows. The prover reveals combinations of rows through their values at these positions, and for zero knowledge it commits only to the remaining positions, which are the ones the verifier queries. The tests therefore concern the Reed–Solomon code of message length K on

$$S = \{\text{inj}(j) : 2K-1 \leq j < e\}, \quad N = |S| = e - 2K + 1.$$

Writing $e+1 = 9K+r$ with $0 \leq r \leq 8$ gives $N = 7K+r$, so the rate is at most $1/7$. The run $2K-1, \dots, e-1$ starts and ends inside a block, so S is not an affine subspace. Table 6 lists the four configurations.

Corollary 5.19 (Longfellow’s version-7 codes). Let (e, N, K) be one of the four rows of Table 6, let S be the corresponding domain, and put $\mathbb{F} = \mathbb{F}_{2^{128}}$. There is a fixed pair over $\mathbb{F}$ with $\text{CA}_K(f, g) = K$ and at least 5,843,376 distinct nonzero exceptional challenges at agreement $T = K + 384$. For a uniformly sampled challenge in $\mathbb{F}$, the exceptional probability is greater than $2^{-105.522}$.

Proof. In all four rows $2K-1 \leq 2048$ and $e \geq 4096$, so S contains

$$U = \{\text{inj}(j) : 2048 \leq j < 4096\} = g^{11} + \text{span}_{\mathbb{F}_2}\{1, g, \dots, g^{10}\},$$

an affine 11-space in $\mathbb{F}_{2^{16}}$. The Gold family of Lemma 5.12 and Lemma 5.13, translated to U , with $d = 11$, $m = 16$, $t = 2$, and $\Delta = 6$, supplies

$$L = 16(2^6 - 1) \begin{bmatrix} 5 \\ 2 \end{bmatrix}_4 = 5,843,376$$

distinct polynomials $P_i = R + C_i$, each with 768 roots in U and $\deg C_i = 384$. Let A be the locator of any $K - 384$ points in $S \setminus U$. Then $AP_i = AR + AC_i$ has correction degree K and at least $K + 384$ roots in S . Pole reduction on S (Lemma 3.11) gives common agreement exactly K and combination agreement at least $T = K + 384$.

Each nonzero polynomial $A(C_i - C_j)$ or AC_i has degree at most K . Thus at most $K \binom{L}{2} + L < 2^{128} - N$ poles cause a challenge collision or a zero challenge. Some pole outside S therefore retains all L nonzero challenges, giving probability $L/2^{128} = 2^{-105.521629\dots} > 2^{-105.522}$. $\square$

The common agreement K is about 14.3% of N , the least possible, since any two words agree with a pair of codewords on any K positions. The exceptional combinations have agreement between 25.44% and 26.16%, about 12 percentage points below the Johnson agreement of about 37.8%. Longfellow's security analysis uses the unique-decoding radius, which corresponds to agreement about 57.1%, so the corollary does not contradict it [26]. The specification states a security target of at least 115 bits [27, Section 5.1], and the implementation records about 109 bits of statistical security. A proximity-gap guarantee for these codes at agreement T/N or lower, with proximity loss below 384 positions, has error greater than $2^{-105.522}$, which is too large for either figure. The thresholds between T/N and Johnson remain open.

5.9 Superpolynomial decoding lists and exceptional sets at further rates

This subsection extends the Gold construction in two directions. Theorem 5.22 leaves characteristic two. For every fixed prime power b it works on the full field $\mathbb{F}_{b^{2n}}$ or a hyperplane in it, at rate $1/b^2$, and gives superpolynomial decoding lists with agreement approaching the Johnson threshold $1/b$, over an alphabet of size N in the full-field case (Corollary 5.23). Over sufficiently large extension fields it also gives superpolynomially many exceptional challenges for one received pair. Corollary 5.24 returns to binary fields. With b a power of two, restriction to a dense binary domain and padding give both kinds of bounds at every fixed rate, with agreement strictly between the rate and Johnson.

The proof follows that of Theorem 5.1, with b th powers in place of squares (as before Lemma 3.13) and a classical family of quadratic forms in place of the Gold moments. For $b = 2$ the new theorem adds nothing to Theorem 5.1; the comparison follows Corollary 5.23.

5.9.1 Quadratic-form constructions in every characteristic

Definition 5.20 (Quadratic forms, radicals, and rank). Let W be a vector space over $\mathbb{F}_b$, where b is a prime power. A *quadratic form* $\psi : W \rightarrow \mathbb{F}_b$ is a function represented by a homogeneous polynomial of degree two in linear coordinates. Its polar form is $B_\psi(x, y) = \psi(x + y) - \psi(x) - \psi(y)$. Its *quadratic radical* is

$$\text{rad}(\psi) = \{u \in W : B_\psi(x, u) = 0 \text{ for every } x \in W, \psi(u) = 0\}.$$

The *rank* of ψ is the codimension of $\text{rad}(\psi)$ in W .

In contrast to the polar radical in Definition 3.15, this definition also requires $\psi(u) = 0$. We use the quadratic rank throughout this subsection. A form ψ induces a form with zero radical on the quotient $W/\text{rad}(\psi)$. A form of rank $2t$ has *elliptic type* if this induced form is an orthogonal sum of $t - 1$ hyperbolic planes, each equivalent to xy , and one plane on which the form vanishes only at zero. The induced form then has

nondegenerate polar form, so the polar radical of ψ equals $\text{rad}(\psi)$ and ψ vanishes on it. For a function χ that is a quadratic form plus a linear function plus a constant, we write $B_\chi(x, y) = \chi(x + y) - \chi(x) - \chi(y) + \chi(0)$, which is again bilinear.

As in Section 5.3, ψ and χ denote functions, and Q and G denote polynomials representing them.

Write $\text{Tr}_j = \text{Tr}_{\mathbb{F}_{b^j}/\mathbb{F}_b}$.

Proposition 5.21 (The trace family). Let b be a prime power, $m = 2n$, $\mathbb{B} = \mathbb{F}_{b^m}$, and $2 \leq t \leq n$. Consider the quadratic forms on $\mathbb{B}$

$$\psi(x) = \sum_{i=t}^{n-1} \text{Tr}_m(a_i x^{b^i+1}) + \text{Tr}_n(a_n x^{b^n+1}), \quad a_i \in \mathbb{B}, \quad a_n \in \mathbb{F}_{b^n}.$$

1. At least $(b^t - 1) \begin{bmatrix} n \\ t \end{bmatrix}_{b^2}$ of these forms have rank $2t$ and *elliptic* type [40, Theorems 5.6 and 4.9].
2. A form of rank $2t$ and elliptic type on a space of size N has exactly $N/b - (b-1)N/b^{t+1}$ zeros.
3. The canonical representative Q of ψ is a combination of monomials $X^{b^j+b^k}$ with $0 \leq j < k < m$ and $t \leq k - j \leq m - t$. Its derivative is

$$Q' = \sum_{i=t}^{n-1} (a_i X^{b^i} + a_i^{b^{m-i}} X^{b^{m-i}}) + a_n X^{b^n},$$

which contains only powers X^{b^i} with $t \leq i \leq m - t$.

4. The polar form of ψ determines ψ within the family, in every characteristic.
5. For every $\xi \in \mathbb{B}^*$, the dilation $x \mapsto \xi x$ maps the family to itself and preserves rank and type.

Proof. For the first part, the family is closed under addition, so the inner distribution that Schmidt computes for it in [40, Theorems 5.6 and 4.9] is the distribution of the ranks and types of its members. In [40, Theorem 4.9], take $q = b$, $m = 2n$, $\delta = s = t$, and $\tau = -1$. Only the term $j = 0$ remains, and the number of members of rank $2t$ and elliptic type is

$$\frac{1}{2}(b^t - 1) \begin{bmatrix} n \\ t \end{bmatrix}_{b^2} (1 - (-1)) = (b^t - 1) \begin{bmatrix} n \\ t \end{bmatrix}_{b^2}.$$

For the second part, let z_j be the number of zeros of an elliptic form with zero radical on a space of dimension $2j$. A plane on which the form vanishes only at zero has $z_1 = 1$. Adding a hyperbolic plane xy , which has $2b - 1$ zeros and takes each nonzero value $b - 1$ times, gives

$$z_j = (2b - 1)z_{j-1} + (b - 1)(b^{2j-2} - z_{j-1}) = bz_{j-1} + (b - 1)b^{2j-2},$$

so $z_t = b^{2t-1} - (b - 1)b^{t-1}$. Multiplying by the size N/b^{2t} of the radical gives the stated count. For the third, expand the traces and reduce exponents using $x^{b^m} = x$:

$$\text{Tr}_m(a_i x^{b^i+1}) = \sum_{k=0}^{m-1} a_i^{b^k} x^{b^{k+i}+b^k}, \quad \text{Tr}_n(a_n x^{b^n+1}) = \sum_{k=0}^{n-1} a_n^{b^k} x^{b^{k+n}+b^k},$$

with the index $k + i$ read modulo m . The two indices in each monomial differ by i or $m - i$, both between t and $m - t$, and every exponent is less than b^m . A monomial $X^{b^j+b^k}$ with $j < k$ has nonzero derivative only when $j = 0$, where the derivative is X^{b^k} . In the first sum, one of the two exponents is b^0 exactly for the summation indices 0 and $m - i$, and in the second sum only for the summation index 0 . These terms give the displayed formula.

For the fourth part, the family is closed under subtraction, so it suffices to show that a member ψ with zero polar form is zero. Let Q be its canonical representative. For each $y \in \mathbb{B}$, the polynomial $Q(X + y) - Q(X) - Q(y)$ has degree less than $|\mathbb{B}|$ and takes the values $B_\psi(x, y) = 0$ on $\mathbb{B}$, so it is the zero polynomial. Differentiating in X gives $Q'(X + y) = Q'(X)$. Since Q' is additive, $Q'(y) = 0$ for every $y \in \mathbb{B}$, and $\deg Q' < |\mathbb{B}|$ forces $Q' = 0$. The distinct powers of X in the formula for Q' then give $a_i = 0$ for every i . The last part holds because a_i is replaced by $a_i \xi^{b^i+1}$, with $\xi^{b^n+1} \in \mathbb{F}_{b^n}$, and a linear change of variable preserves rank and type. $\square$

Theorem 5.22 (Quadratic-form families on full fields and hyperplanes). Let b be a prime power, $m = 2n$, and $\mathbb{B} = \mathbb{F}_{b^m}$. Let $D = \mathbb{B}$ or an $\mathbb{F}_b$ -hyperplane in $\mathbb{B}$, and write $d = \dim_{\mathbb{F}_b} D$, $h = m - d \in \{0, 1\}$, and $N = b^d$. Choose $2 \leq t \leq n - h$, and put

$$K = \frac{N}{b^2}, \quad T = \frac{N}{b} - \frac{(b-1)N}{b^{t+1}}, \quad L = b^{2t} \frac{b^t - 1}{b - 1} \left[\begin{matrix} n - h \\ t \end{matrix} \right]_{b^2}, \quad \delta = \frac{(b-1)N}{b^{2t}}.$$

Then there is a received word on D over $\mathbb{B}$ with at least L distinct codewords of $C_K(D; \mathbb{B})$, each agreeing with it on exactly T coordinates. For every finite extension $\mathbb{F} \supseteq \mathbb{B}$, with $q = |\mathbb{F}| > N$, there is a received pair satisfying $\text{agr}_K(g) = \text{CA}_K(f, g) = K$ and having at least Z distinct nonzero exceptional challenges at agreement T , where Z is given by (5.1) with these values of L , δ , and q . The pair can be chosen to satisfy $\text{agr}_K(f) \leq (b+1)N/(2b^2) - 1 < T$.

Proof. The proof follows Section 5.3 and the proof of Theorem 5.1, with b th powers in place of squares. Steps 1 to 4 below correspond to Lemmas 5.6, 5.8, 5.9, and 5.10, and Steps 5 to 7 to the three parts of the proof of Lemma 5.12. The differences are these: the trace family replaces the moment equations and their count; translates of a form replace the added linear functions, and elliptic type replaces the signed-sum count; G has multiple roots, so the conversion to P is direct; and distinctness holds only up to factors in $\mathbb{F}_b^*$.

The forms. We show that D carries at least $(b^t - 1) \left[\begin{matrix} n - h \\ t \end{matrix} \right]_{b^2}$ quadratic forms of rank $2t$ and elliptic type, each induced by a form of Proposition 5.21. For $D = \mathbb{B}$ this is the first part of that proposition. Otherwise $D = \{x : \text{Tr}_m(x/v) = 0\}$ for some $v \in \mathbb{B}^*$, and the $\mathbb{F}_b$ -linear map $s_v(X) = X - v^{1-b}X^b$ has kernel $\mathbb{F}_b v$ and image D , since $s_v(vy) = v(y - y^b)$ and $\text{Tr}_m(y - y^b) = 0$. By the last part of Proposition 5.21, dilations permute the forms of rank $2t$ and elliptic type and act transitively on nonzero vectors, so every nonzero vector lies in the radicals of equally many of them. Counting pairs of such a form and a nonzero vector of its radical, at least

$$(b^t - 1) \left[\begin{matrix} n \\ t \end{matrix} \right]_{b^2} \cdot \frac{b^{m-2t} - 1}{b^m - 1} = (b^t - 1) \left[\begin{matrix} n - 1 \\ t \end{matrix} \right]_{b^2}$$

of them have v in their radical (Section 3.1). Such a form is constant on the cosets of $\mathbb{F}_b v$, so it equals $\psi_D \circ s_v$ for a form ψ_D on D of the same rank and type, and different forms give different ψ_D . Let $Q_{\mathbb{B}}$ be the canonical polynomial of the trace form, and let Q_D be the polynomial of degree less than N representing ψ_D . Then $Q_{\mathbb{B}}$ and $Q_D \circ s_v$ have degree less than $bN = |\mathbb{B}|$ and agree on $\mathbb{B}$, so

$$Q_{\mathbb{B}} = Q_D \circ s_v \tag{5.8}$$

as polynomials. From now on ψ denotes a selected form on D , Q denotes its polynomial of degree less than N , and V denotes its radical, of size N/b^{2t} . Since ψ has elliptic type, V is also its polar radical.

Step 1: the identity for Q . Write $L_D = \sum_{i=0}^d \lambda_i X^{b^i}$, with $\lambda_d = 1$, and put $\lambda = \lambda_0$. First, $\deg Q \leq N/b + N/b^{t+1}$: for $D = \mathbb{B}$, the monomials $X^{b^j+b^k}$ of the third part of Proposition 5.21 have degree at most $b^{m-1} + b^{m-1-t}$, and for a hyperplane (5.8) gives $\deg Q = \deg Q_{\mathbb{B}}/b$. The polynomial $Q^b - Q$ vanishes on

D because ψ has values in $\mathbb{F}_b$, so $Q^b - Q = L_D Y$ with $\deg Y \leq b \deg Q - N \leq N/b^t$. Differentiating gives $-Q' = \lambda Y + L_D Y'$, which forces $Y' = 0$, so

$$Q^b - Q = -\frac{L_D}{\lambda} Q'. \quad (5.9)$$

Step 2: the window of Q' . We claim that $Q' = \sum_{i=t}^{d-t} g_i X^{b^i}$. For $D = \mathbb{B}$ this is the third part of Proposition 5.21. For a hyperplane, $s'_v = 1$ gives $Q'_\mathbb{B} = Q' \circ s_v$. If Q' has degree $e \geq 1$, the composition has degree be , so e is a power of b . Since every power $s_v^{b^i}$ contains only powers X^{b^j} , removing the leading term of Q' and inducting on the degree shows that Q' contains only powers X^{b^i} ; a constant term would survive in the composition, so there is none. In

$$Q' \circ s_v = \sum_i y_i (X^{b^i} - v^{(1-b)b^i} X^{b^{i+1}}),$$

the lowest and highest indices with $y_i \neq 0$ produce the powers X^{b^i} and $X^{b^{i+1}}$. As $Q'_\mathbb{B}$ contains only X^{b^i} with $t \leq i \leq m - t$, the indices of Q' lie between t and $m - t - 1 = d - t$.

Step 3: the roots of Q' are the radical. For $y \in D$, the polynomial $B_Q(X, y) = Q(X + y) - Q(X) - Q(y)$ has degree less than N and represents $B_\psi(\cdot, y)$ on D . Since $L_D(X + y) = L_D(X)$, $Q(y)^b = Q(y)$, and Q' is additive by Step 2, applying (5.9) at $X + y$ and at X gives

$$B_Q(X, y)^b - B_Q(X, y) = -\frac{L_D(X)}{\lambda} Q'(y).$$

If $Q'(y) = 0$, then $B_Q(X, y)$ is a constant vanishing at $X = 0$, hence zero. If $Q'(y) \neq 0$, it is a nonzero polynomial of degree less than N , so it does not vanish on all of D . Thus $V = \{y \in D : Q'(y) = 0\}$, and $Q' \neq 0$ because $V \neq D$. By Step 2, Q' is the b^t -th power of a linearized polynomial of degree at most N/b^{2t} that vanishes on V , so $Q' = \text{lc}(Q') L_V^{b^t}$.

Step 4: translates. For $u \in D$ put

$$\psi_u(x) = \psi(x - u) = \psi(x) - B_\psi(x, u) + \psi(u),$$

represented by the polynomial $G = Q(X - u)$. The linear function $B_\psi(\cdot, u)$ depends exactly on the class of u modulo V , so each form gives b^{2t} distinct functions ψ_u . Different forms give different functions, because $B_{\psi_u} = B_\psi$ and the polar form determines the form within the family (the fourth part of Proposition 5.21 and (5.8)). Altogether there are at least $b^{2t}(b^t - 1) \binom{n-h}{t}_{b^2} = (b - 1)L$ functions ψ_u . Each has exactly T zeros on D by the second part of Proposition 5.21, and it vanishes on $u + V$, because ψ vanishes on its radical. Since $L_D(X - u) = L_D(X)$, the identity (5.9) also holds for G , and by Step 3, $G' = Q'(X - u) = \text{lc}(Q') L_V(X - u)^{b^t}$. The roots of G' are the points of $u + V$, each with multiplicity b^t .

Step 5: the polynomial $P = G/F$. Since G' is a b^t -th power, there is a polynomial F , a constant multiple of $L_V(X - u)^{b^{t-1}}$, with $G' = -\lambda F^b$. Then $G^b - G = L_D F^b$, the roots of F are the points of $u + V$, each with multiplicity b^{t-1} , and $\deg F = N/b^{t+1}$. At a point of $u + V$, the right side vanishes to order $b^t + 1$ and G^b to higher order than G , so G has multiplicity exactly $b^t + 1$ there. Every other root of G is simple, since G' does not vanish there, and lies in D , since it is a root of $L_D F^b$. Thus the roots of G are the T zeros of ψ_u on D , and

$$P = \frac{G}{F}$$

is a polynomial with the same T roots. Counting multiplicities gives $\deg G = T + N/b^t$, so $\deg P = N/b$, and comparing leading coefficients in $G^b - G = L_D F^b$ shows that P is monic. Dividing by F^b gives

$$P^b = L_D + \frac{G}{F^b}, \quad F^{b-1}(P^b - L_D) = P, \quad (5.10)$$

where G/F^b is a polynomial of degree T whose roots are the zeros of ψ_u . With $R = (L_D - \lambda X)^{1/b} = \sum_{i=1}^d \lambda_i^{1/b} X^{b^{i-1}}$ and $C = P - R$, we get $C^b = \lambda X + G/F^b$, so $\deg C = T/b < K$.

Step 6: distinctness. The second identity in (5.10) determines F^{b-1} , hence F up to a factor in $\mathbb{F}_b^*$, and then $G = PF$ up to the same factor. So at least L of the polynomials P are distinct.

Step 7: collisions outside D . Let $P_1 \neq P_2$, with $P_i = G_i/F_i$, agree at some $\beta \notin D$. The common value and $P_i(\beta)^b - L_D(\beta)$ are nonzero, because all roots of P_i and G_i/F_i^b lie in D , so (5.10) gives $F_1(\beta) = \zeta F_2(\beta)$ for some $\zeta \in \mathbb{F}_b^*$. Since $\zeta^{b^{t-1}} = \zeta$, the polynomial $F_1 - \zeta F_2$ is the b^{t-1} -th power of a polynomial of degree at most N/b^{2t} , and it is nonzero. Indeed, if $F_1 = \zeta F_2$, then $F_1^{b-1} = F_2^{b-1}$, and subtracting the second identity in (5.10) for P_2 from that for P_1 gives $F_1^{b-1}(P_1 - P_2)^b = P_1 - P_2$. The left side has larger degree than the right unless $P_1 = P_2$. Hence two distinct polynomials agree at at most $\delta = (b-1)N/b^{2t}$ points outside D .

The received words. The proof of Theorem 5.1 now applies with message length K . The word $R|_D$ agrees with the codeword $-C_i|_D$ on the T roots of $P_i = R + C_i$, which gives the decoding list. Lemmas 3.11 and 3.19 give the pair and the stated number of distinct challenges. Replacing the first input by the one of Lemma 3.13 translates the challenges and gives $\text{agr}_K(f) \leq (b+1)N/(2b^2) - 1$. For $t \geq 2$,

$$T - \left(\frac{(b+1)N}{2b^2} - 1 \right) \geq \frac{(b-1)(b-2)N}{2b^3} + 1 > 0,$$

so zero is not exceptional and all the selected challenges are nonzero. $\square$

Corollary 5.23 (Decoding lists approaching Johnson). Fix a prime power b . For $N = b^{2n}$ and all sufficiently large n , the full-length Reed–Solomon code over $\mathbb{F}_N$ of dimension $K = N/b^2$ has a received word with at least $N^{\Omega_b(\log N)}$ distinct codewords agreeing on a fraction

$$\frac{1}{b} - \Theta_b(N^{-1/4}) = \sqrt{K/N} - \Theta_b(N^{-1/4})$$

of its coordinates. The received word can be chosen as $r(x) = x^{N/b}$. In particular, $b = 2^k$ gives rate 4^{-k} for every fixed integer $k \geq 1$, over an alphabet of size N .

Proof. Apply Theorem 5.22 with $D = \mathbb{F}_N$ and $t = \lfloor n/2 \rfloor$. Since $L_D = X^N - X$, the received word in its proof is $R = X^{N/b}$.

The Gaussian product formula gives

$$\log_b \left[\begin{matrix} n \\ t \end{matrix} \right]_{b^2} = 2t(n-t) + O_b(1).$$

Consequently the list-size lower bound in the theorem satisfies

$$\log_b L = 2t(n-t) + 3t + O_b(1) = \frac{n^2}{2} + O_b(n).$$

As $\log_b N = 2n$, this is $L = N^{\Omega_b(\log N)}$. The agreement formula follows from $T/N = b^{-1} - (b-1)b^{-t-1}$ and $t = n/2 + O(1)$. $\square$

For fixed b , the same choice $t = \lfloor n/2 \rfloor$ in Theorem 5.22, with a sufficiently large containing field, also gives quasipolynomial exceptional sets. Their fractional common-agreement gap approaches $(b-1)/b^2$. For example, $b = 4$ gives rate $1/16$ and agreement approaching $1/4$, while $b = 3$ gives rate $1/9$ and agreement approaching $1/3$. These are fields of fixed characteristic, so the examples do not contradict bounds for prime fields or sufficiently large characteristic.

For $b = 2$, Theorem 5.1 gives at least as large a count at the same rate and agreement, on the full field and on its hyperplanes, and a strictly larger one when $t < n$: its factor is $2^{2n-t} - 1$ in place of $2^t - 1$. It also allows every additive domain with $\Delta \geq 1$. The count is larger because Theorem 5.1 uses every alternating form of rank $2t$ that satisfies the moment equations. In characteristic two an added linear function and, if necessary, the complement give each such form a level set of size T . For $b > 2$ a level set of a quadratic function has size T only if it is a translate of the zero set of a form of elliptic type, so Theorem 5.22 counts those forms alone.

5.9.2 Superpolynomial lists and exceptional sets at every fixed binary rate

Theorem 5.22 gives rates $1/b^2$. Restriction to a prescribed dense binary domain, followed by balanced padding, gives superpolynomial decoding lists and exceptional sets at any fixed rate. The agreement remains a positive constant above the rate, but strictly below Johnson. Corollary 5.17 already gives such bounds; here the agreement is $\alpha_{b,c}(\rho)$ and both individual agreements equal the common one.

Corollary 5.24 (Every fixed rate on dense binary domains). Fix a binary codimension $c \geq 0$ and a binary power $b > 2^c$. Let $\mathbb{B} = \mathbb{F}_{b^{2n}}$, and let $D \subseteq \mathbb{B}$ be any affine binary subspace of codimension c , of size $N = |\mathbb{B}|/2^c$. Fix a rate ρ with

$$\frac{2^c}{b^2} < \rho < 1 - \frac{2^c}{b} + \frac{2^c}{b^2},$$

and put

$$K = \lfloor \rho N \rfloor, \quad \alpha_{b,c}(\rho) = \frac{1}{b} + \left(\rho - \frac{2^c}{b^2} \right) \left(1 - \frac{1}{b} \right).$$

There are received words on D , over the alphabet $\mathbb{B}$ of size $2^c N$, with $N^{\Omega_b(\log N)}$ distinct codewords of $C_K(D; \mathbb{B})$ at agreement at least $\alpha_{b,c}(\rho) - O_{b,c}(N^{-1/4})$ as a fraction of the domain. There are also pairs on D , over extensions $\mathbb{F} \supseteq \mathbb{B}$ of size $N^{O_{b,c}(\log N)}$, with $\text{agr}_K(f) = \text{agr}_K(g) = \text{CA}_K(f, g) = K$ and $N^{\Omega_b(\log N)}$ distinct nonzero exceptional challenges at that agreement. The estimates are uniform over D . Moreover,

$$\rho < \alpha_{b,c}(\rho) < \sqrt{\rho}.$$

For every fixed c and $\rho \in (0, 1)$, a sufficiently large fixed binary power b places ρ in this interval.

Proof. We restrict the full-field agreement sets of Theorem 5.22 to D and then use the unused degree to add points to each of them.

Restriction. Apply Theorem 5.22 on $\mathbb{B}$ with $t = \lfloor n/2 \rfloor$ and message length $K_0 = |\mathbb{B}|/b^2$. As in Corollary 5.23, it gives $L = N^{\Omega_b(\log N)}$ polynomials $R + C_i$ with distinct C_i of degree less than K_0 , and by Step 5 of the proof of Theorem 5.22 the roots of $R + C_i$ in $\mathbb{B}$ are the zeros of a translate ψ_u of a quadratic form of rank $2t$. For $v \in \mathbb{F}_b^*$, the binary quadratic function $\text{Tr}_{\mathbb{F}_b/\mathbb{F}_2}(v\psi_u)$ has polar rank $2t \log_2 b$ on $\mathbb{B}$: replacing the second argument of the polar form by its $\mathbb{F}_b$ -multiples shows that its binary polar radical is the polar radical over $\mathbb{F}_b$. After a translation, D is a subspace of codimension c , and restricting to it deletes c rows and columns of the polar matrix, so the polar radical of the restriction has at most $2^{2c}N/b^{2t}$ points. For a quadratic Boolean function χ on a binary space of size N , the computation of σ^2 in the proof of Lemma 5.10

gives $(\sum_x (-1)^{\chi(x)})^2 = N \sum_{y \in \text{rad}(B_\chi)} (-1)^{\chi(y) + \chi(0)} \leq N |\text{rad}(B_\chi)|$. Since $\mathbf{1}_{y=0} = b^{-1} \sum_{v \in \mathbb{F}_b} (-1)^{\text{Tr}_{\mathbb{F}_b/\mathbb{F}_2}(vy)}$,

$$|\{x \in D : \psi_u(x) = 0\}| = \frac{N}{b} + \frac{1}{b} \sum_{v \in \mathbb{F}_b^*} \sum_{x \in D} (-1)^{\text{Tr}_{\mathbb{F}_b/\mathbb{F}_2}(v\psi_u(x))} \geq \frac{N}{b} - \frac{b-1}{b} \cdot \frac{2^c N}{b^t} = \frac{N}{b} - O_{b,c}(N^{3/4}),$$

because $b^t \geq b^{(n-1)/2}$ and $N \leq b^{2n}$. Let T_0 be the integer part of this bound, and for each i choose a set $S_i \subseteq D$ of exactly T_0 roots of $R + C_i$. The C_i remain distinct on D , since their degrees are below $K_0 < N$.

Padding. Put $w = K - K_0$, which is positive for large N because $\rho > 2^c/b^2$. Lemma 3.18 gives a set $B \subseteq D$ of size w with

$$|B \cup S_i| \geq T_0 + w \left(1 - \frac{T_0}{N}\right) - O(\sqrt{N \log L}) = \alpha_{b,c}(\rho)N - O_{b,c}(N^{3/4})$$

for every i . The word $(L_B R)|_D$ agrees with each of the distinct codewords $-(L_B C_i)|_D$, of degree less than K , on $B \cup S_i$. This proves the claim for received words.

Received pairs. The polynomials $L_B(R + C_i) = L_B R + L_B C_i$ have distinct corrections $L_B C_i$ of degree less than K , and each vanishes on $B \cup S_i$. Take an extension $\mathbb{F}_0 \supseteq \mathbb{B}$ with $|\mathbb{F}_0| > N + K \binom{L}{2}$; extension degree $O_{b,c}(\log N)$ suffices. Each nonzero polynomial $L_B(C_i - C_j)$ has fewer than K roots, so some $\beta \in \mathbb{F}_0 \setminus D$ is a root of none of them. Lemma 3.11 at this pole gives the pair $f(x) = L_B(x)R(x)/(x - \beta)$, $g(x) = 1/(x - \beta)$ with $\text{agr}_K(g) = \text{CA}_K(f, g) = K$, and the L challenges $(L_B C_i)(\beta)$ are distinct. At most one of them is zero, and each has the agreement bound above. Finally, Lemma 3.12 in a quadratic extension of $\mathbb{F}_0$ makes both individual agreements and the common agreement exactly K , keeps the challenges distinct and nonzero, and keeps the field size $N^{O_{b,c}(\log N)}$.

The inequalities. First, $\alpha_{b,c}(\rho) - \rho = (1 - 2^c/b + 2^c/b^2 - \rho)/b > 0$. Second, $\alpha_{b,c}(\rho) \leq \alpha_{b,0}(\rho) < \sqrt{\rho}$, since for $\sqrt{\rho} > 1/b$

$$\alpha_{b,0}(\rho) - \sqrt{\rho} = \left(1 - \frac{1}{b}\right) \left(\sqrt{\rho} - \frac{1}{b}\right) \left(\sqrt{\rho} - 1 - \frac{1}{b(b-1)}\right) < 0.$$

□

6 Decision-tree constructions at half agreement and half rate

This section proves the decision-tree results outlined in Section 2.4. Let D be a binary additive domain of size N , and let the challenge field be any field of size $q > N$ that contains D . For each height h with $\log_2 N \geq 2^h - 1$:

- at rate $1/2 - 2^{-h-1}$ and agreement $1/2$, there are $\Omega_h(\min\{N^{2^h-1}, q/N\})$ exceptional challenges when $h \geq 2$ (Corollary 6.7);
- at rate $1/2$ and agreement $1/2 + 2^{-h-1}$, there are $\Omega_h(\min\{N^{2^h-h-1}, q/N\})$ exceptional challenges when $h \geq 3$ (Theorem 6.10).

Section 6.1 converts any family of equal-size unions of large affine flats into exceptional challenges for one received pair. Its bound uses the points that two sets share, which leave fewer possible collisions outside D . Section 6.2 counts the sets that trees of height h produce. Different trees can produce the same set, so we count the Boolean functions that the trees compute. Section 6.3 counts the sets that avoid a fixed subspace W , whose locator supplies the additional agreement points at rate $1/2$. Section 6.4 evaluates the resulting bound for the parameters of LeanVM and Flock.

6.1 From unions of flats to exceptional challenges

Both constructions use the following consequence of pole reduction. In it, T_0 is the common size of the sets, w is the degree gap supplied by their flats, and W is the reserved set: it is empty in the first construction and a subspace of size w in the second. The message length is K and the agreement is T .

Lemma 6.1 (Unions of flats give exceptional challenges). Let $D \subseteq \mathbb{F}$ be binary additive of size N , with $q = |\mathbb{F}| > N$. Let $w \geq 1$ be an integer, and let $W \subseteq D$ be empty or of size w . Let $\mathcal{A}$ be a family of $M \geq 1$ distinct nonempty subsets of $D \setminus W$ of a common size T_0 , each a disjoint union of affine flats of size at least $2w$. Put

$$K = T_0 - w + |W|, \quad T = T_0 + |W|,$$

write I_x for the number of sets of $\mathcal{A}$ containing x , and let F be any number with

$$F \geq (K - |W|) \binom{M}{2} - \sum_{x \in D \setminus W} \binom{I_x}{2}. \quad (6.1)$$

Then there is a pair of words on D with

$$\text{CA}_K(f, g) = \text{agr}_K(g) = K, \quad \text{agr}_K(f) \leq T - 1,$$

and at least

$$Z(M, F) = \max \left\{ M - \left\lfloor \frac{F}{q - N} \right\rfloor, \left\lceil \frac{(q - N)M^2}{(q - N)M + 2F} \right\rceil \right\} \quad (6.2)$$

distinct nonzero exceptional challenges at agreement T . If $F \leq NM^2/8$, then $Z(M, F) \geq \min\{M/2, q/N\}$.

The right side of (6.1) bounds the number of triples of two sets and a pole for which the two sets give the same challenge. The sum subtracts the points that two sets share, since a shared point is a common root inside D and leaves one fewer possible collision outside D . The first term of $Z(M, F)$ is the better one when collisions are rare, and the second when the sets outnumber the available challenges.

Proof. We write L_S for the locator of a set S , and $L_\emptyset = 1$.

Step 1: shared coefficients. An affine flat of size 2^r with $r \geq 1$ has locator X^{2^r} plus terms of degree at most 2^{r-1} (Section 3.2). For $A \in \mathcal{A}$, multiply the locators of its flats. Using a nonleading term of any factor lowers the degree by at least w , so

$$L_A = X^{T_0} + G_A, \quad \deg G_A \leq T_0 - w.$$

Put $R = X^{T_0} L_W$ and $C_A = L_W G_A$. Then $R + C_A = L_{W \cup A}$ is monic of degree T with all its roots in D , and $\deg C_A \leq K$, where $1 \leq K < T \leq N$. Distinct sets give distinct corrections C_A .

Step 2: pole reduction. For each $\beta \in \mathbb{F} \setminus D$, the second pair of Lemma 3.11 has the stated common and individual agreements. Its second input is $1/(x - \beta)$; the overview's $L_W(x)/(x - \beta)$ equals $L_W(\beta)/(x - \beta)$ plus a polynomial of degree less than w , so it gives the same exceptional set up to the factor $L_W(\beta)$. For each A it gives the nonzero challenge $L_{W \cup A}(\beta)$, with a witness of degree less than K that agrees with the combination exactly on $W \cup A$.

Step 3: collisions. Two sets $A \neq A'$ give the same challenge at β exactly when β is a root of $C_A - C_{A'}$. This nonzero polynomial has degree at most K and vanishes on $W \cup (A \cap A')$, so it has at most $K - |W| - |A \cap A'|$ roots outside D . Summing over unordered pairs, and using $\sum_{\{A, A'\}} |A \cap A'| = \sum_x \binom{I_x}{2}$, the total number of colliding pairs over all $q - N$ poles is at most the right side of (6.1). Lemma 3.19 gives a pole with at least $Z(M, F)$ distinct challenges.

Step 4: the simplified bound. Since q and N are powers of two, $q \geq 2N$. If $2F \leq NM^2/4$, the second term of $Z(M, F)$ is at least

$$\frac{(q - N)M}{q - N + NM/4} \geq \min \left\{ \frac{M}{2}, \frac{2(q - N)}{N} \right\} \geq \min \left\{ \frac{M}{2}, \frac{q}{N} \right\}. \quad \square$$

6.2 Counting balanced tree supports

We now construct many sets with this decomposition, as supports of balanced Boolean functions (Definition 3.14). For example, for independent linear functionals s, a, b , the function $(1 + s)a + sb$ tests s and then outputs a or b ; its support is the union of the flats $\{s = 0, a = 1\}$ and $\{s = 1, b = 1\}$ (Section 2.4, Figure 2). The root sets of the overview are these supports, and its leaves are the flats.

To count the functions we must recognize when two trees define the same one. We do this with two invariants of a Boolean function: the directions it ignores, and the linear functionals it depends on.

Definition 6.2 (Translation periods and essential coordinates). For a Boolean function $\varphi : U \rightarrow \mathbb{F}_2$ on a finite binary vector space U , its *translation-period space* is

$$\text{Per}(\varphi) = \{u \in U : \varphi(x + u) = \varphi(x) \text{ for every } x \in U\}.$$

Write U^* for the space of linear functionals $U \rightarrow \mathbb{F}_2$, and $E^\perp \leq U$ for the common kernel of a subspace $E \leq U^*$. The *essential dual space* of φ is the space of linear functionals vanishing on $\text{Per}(\varphi)$, and its dimension is the *essential dimension* of φ .

A period is a direction that φ ignores. The function φ can be written in terms of the functionals in its essential dual space, and of no smaller space of functionals, so the essential dimension is the least number of linear tests that determine φ . In linear coordinates $x_1, \dots, x_d$ on U , every Boolean function is a unique polynomial in which each variable has exponent at most one. Products are reduced using $x_i^2 = x_i$. The *degree* of the function is the degree of this polynomial; it is preserved by invertible affine changes of coordinates.

For $h \geq 3$, a function computed by such a tree of height h determines the first test and the two functions computed below it (Lemma 6.5), so a recursive definition counts each function once. At height two this fails. On a three-dimensional space the support of $(1 + s)a + sb$ consists of four points, which can be split into two lines in three ways, and each way gives a different first test for the same function. We therefore define height two by properties of the function, and show in Lemma 6.4 that these are the functions computed by trees of height two with three independent functionals.

Definition 6.3 (Tree functions). Put $t_h = 2^h - 1$, and let U be a finite binary vector space. A *height-two tree function* on U is a balanced Boolean function of degree two and essential dimension three. For $h \geq 3$, a Boolean function φ on U is a *height- h tree function* if there are a nonzero $s \in U^*$, a point p with $s(p) = 1$, and subspaces $L_0, L_1 \leq (\ker s)^*$ such that:

1. L_0 and L_1 have dimension t_{h-1} , and $L_0 \cap L_1 = 0$;
2. the restriction φ_0 of φ to $\ker s$ is a height- $(h - 1)$ tree function with essential dual space L_0 ;
3. the function $\varphi_1 : x \mapsto \varphi(p + x)$ on $\ker s$ is a height- $(h - 1)$ tree function with essential dual space L_1 .

We call s a *root functional* of φ and φ_0, φ_1 its *children*.

In coordinates s, x, y adapted to s, L_0 , and L_1 , such a function is

$$\varphi = (1 + s)\varphi_0(x) + s\varphi_1(y).$$

It tests s and then evaluates one of two trees of height $h - 1$. The condition $L_0 \cap L_1 = 0$ says that the two subtrees use independent functionals, which is what makes the number of functions large. A path makes h tests, whereas the function has essential dimension $t_h = 1 + 2t_{h-1}$: the first number gives the size of the flats, and the second gives the number of functions.

Lemma 6.4 (Structure of tree functions). Fix $h \geq 2$ and a binary vector space U of dimension $d \geq t_h$.

1. Every height- h tree function on U is balanced and has degree h and essential dimension t_h . Its support is a union of 2^{h-1} disjoint affine flats of codimension h .
2. The height- h tree functions are closed under invertible affine changes of coordinates and under complementation.
3. Let φ be a Boolean function on U and let $P \leq \text{Per}(\varphi)$. Then φ is a height- h tree function exactly when the function it induces on U/P is one.
4. There are exactly 56 height-two tree functions on a space of dimension three.

Proof. We use induction on h . A Boolean function φ on U and the function it induces on the quotient by a subspace $P \leq \text{Per}(\varphi)$ have the same degree and essential dimension, and one is balanced exactly when the other is. This proves the third part at height two.

Height two. On $\mathbb{F}_2^3$ there are $\binom{8}{4} = 70$ four-point sets, of which 14 are affine planes. The indicator of a four-point set equals one at an even number of points, so it has no cubic term, and it is affine exactly when the set is a plane. The balanced functions of degree two on $\mathbb{F}_2^3$ are therefore the indicators of the 56 nonplanar sets. None has a nonzero period, which would split its support into two parallel lines, whose union is a plane. So all 56 have essential dimension three, which is the fourth part. Any partition of a nonplanar support into two pairs writes it as a union of two nonparallel affine lines, and a linear functional separating them is the first test of a tree of height two for the function. Affine changes and complementation preserve the 56 sets. This proves the first two parts on $\mathbb{F}_2^3$. On U , a height-two tree function with essential dual space E is induced from one on the three-dimensional quotient $U/E^\perp$, and the first two parts follow on U .

The recursive step. Let $h \geq 3$, put $r = t_{h-1}$, and let φ be a height- h tree function with data s, L_0, L_1 . By induction the height- $(h - 1)$ tree functions are closed under translations, and changing the point p translates φ_1 , so the definition holds for every choice of p . Each child is balanced with 2^{h-2} disjoint flats of codimension $h - 1$ in its slice, so φ is balanced and its support has the stated form. A period $u \in \ker s$ of φ is a period of both children, that is, a vector of $(L_0 + L_1)^\perp$, and conversely. Here $\perp$ denotes the annihilator in $\ker s$. A period $u \notin \ker s$ would make a translate of one child equal to the other. A function of the functionals in L_0 that is also a function of those in L_1 is constant on $L_0^\perp + L_1^\perp = \ker s$, which contradicts balance. Hence $\text{Per}(\varphi) = (L_0 + L_1)^\perp$ has dimension $d - 1 - 2r = d - t_h$. Affine changes and complementation transport the data and the children, possibly exchanging the two slices.

For the degree, choose coordinates on U consisting of s , coordinates x and y whose restrictions to $\ker s$ are bases of L_0 and L_1 and which vanish at p , and further coordinates z . Then

$$\varphi = (1 + s)\varphi_0(x) + s\varphi_1(y), \quad (6.3)$$

where φ_0, φ_1 have degree $h - 1$ by induction. Let $\Omega_0(x)$ and $\Omega_1(y)$ be their parts of degree $h - 1$. The part of φ of degree h is $s(\Omega_0 + \Omega_1)$, which is nonzero because Ω_0 and Ω_1 involve different variables.

For the third part, the data s, L_0, L_1 vanish on $\text{Per}(\varphi)$, so they are defined on U/P . Every period lies in $\ker s$ and is a period of both children, so the children are defined on the two slices of U/P , with the same essential dual spaces. By the induction hypothesis applied to the children, the function induced on U/P is a height- h tree function with these data, and conversely. $\square$

The next lemma is what allows us to count tree functions by their recursive data.

Lemma 6.5 (The root functional is unique). Let $h \geq 3$. A height- h tree function φ has only one root functional s : it is the only nonzero linear functional ℓ for which $\ell\varphi$ has degree at most h . It determines the child φ_0 and, once the point p is fixed, the child φ_1 , and hence their essential dual spaces L_0 and L_1 .

Proof. Use the coordinates s, x, y, z and the notation of (6.3). First, $s\varphi = s\varphi_1(y)$ has degree at most h . Conversely, write $\ell = as + u(x) + v(y) + c(z)$ with $a \in \mathbb{F}_2$ and linear forms u, v, c . The part of $\ell\varphi$ of degree $h+1$ is s times the part of degree h of

$$(u + v + c)(\Omega_0 + \Omega_1).$$

The products $v\Omega_0$, $c\Omega_0$, $u\Omega_1$, and $c\Omega_1$ need no reduction, and their monomials contain, respectively, $h-1$ variables x and one y ; $h-1$ variables x and one z ; one x and $h-1$ variables y ; and $h-1$ variables y and one z . The remaining products $u\Omega_0$ and $v\Omega_1$ involve only x and only y . Since $h-1 \geq 2$, these six kinds of monomials are all different, so each product vanishes in degree h . As Ω_0 and Ω_1 are nonzero, $v = c = 0$ and $u = 0$, so $\ell = s$. The functional s determines the restrictions of φ to its two slices, which are the children. $\square$

At height two the kinds of $v\Omega_0$ and $u\Omega_1$ coincide and the two products can cancel. This is the algebraic form of the three root decompositions of one function noted before Definition 6.3.

Lemma 6.6 (Counting tree functions). Fix $h \geq 2$ and a binary vector space U of dimension $d \geq t_h$. The number of height- h tree functions on U is

$$B_h(d) = \left[\begin{matrix} d \\ t_h \end{matrix} \right]_2 C_h, \quad C_2 = 56, \quad C_h = (2^{t_h} - 1) \left[\begin{matrix} 2t_{h-1} \\ t_{h-1} \end{matrix} \right]_2 2^{t_{h-1}^2} C_{h-1}^2 \quad (h \geq 3),$$

and C_h of them have any prescribed essential dual space. For fixed h , $B_h(d) = \Theta_h(2^{dt_h})$. Every point of U lies in the supports of exactly half of these functions.

Proof. First let $d = t_h$. For $h = 2$ the count is the fourth part of Lemma 6.4. Let $h \geq 3$ and $r = t_{h-1}$, so $d = 2r + 1$. There are $2^{t_h} - 1$ choices of s ; fix a point p for each. There are then $\left[\begin{smallmatrix} 2r \\ r \end{smallmatrix} \right]_2 2^{r^2}$ ordered pairs of complementary r -spaces L_0, L_1 in the $2r$ -dimensional space $(\ker s)^*$, and by induction C_{h-1} children with each prescribed essential dual space. By Lemma 6.5 different choices give different functions, which proves the recurrence for C_h .

In general, by the third part of Lemma 6.4, the tree functions with a prescribed essential dual space E are induced from the C_h tree functions on the t_h -dimensional space $U/E^\perp$, and there are $\left[\begin{smallmatrix} d \\ t_h \end{smallmatrix} \right]_2$ spaces E . The Gaussian coefficient has order 2^{dt_h} for fixed h . Finally, complementation pairs the functions, and each point lies in the support of exactly one function of each pair. $\square$

Corollary 6.7 (Half agreement on the whole domain). Let $D \subseteq \mathbb{F}$ be binary additive of size $N = 2^d$, with $q = |\mathbb{F}| > N$. Fix $h \geq 2$ with $d \geq t_h = 2^h - 1$, and put

$$T = N/2, \quad K = N/2 - N/2^{h+1}, \quad M = B_h(d), \quad F = K \binom{M}{2} - N \binom{M/2}{2},$$

where B_h is defined in Lemma 6.6. There is a pair of words on D with

$$\text{CA}_K(f, g) = \text{agr}_K(g) = K, \quad \text{agr}_K(f) \leq T - 1,$$

and at least $Z(M, F)$ distinct nonzero exceptional challenges at agreement T , with Z as in (6.2). For fixed h , this count is $\Omega_h(\min\{N^{2^h-1}, q/N\})$. In particular, at rate $3/8$ it is $\Omega(\min\{N^3, q/N\})$ at agreement $1/2$, and hence cubic in N when $q \geq N^4$.

Proof. Apply Lemma 6.1 to the supports of the height- h tree functions on D , with W empty, $T_0 = N/2$, and $w = N/2^{h+1}$. By Lemmas 6.4 and 6.6, these are M distinct unions of flats of size $N/2^h = 2w$, and every point lies in exactly $M/2$ of them, so (6.1) holds with equality. Since $F = \frac{1}{2}[(N/4 - w)M^2 + wM] \leq NM^2/8$, the count is at least $\min\{M/2, q/N\}$, and $M = \Theta_h(N^{2^h-1})$. $\square$

6.3 Rate one half: supports avoiding a subspace

To reach rate $1/2$ we keep the same flats and reserve a subspace W of size $w = N/2^{h+1}$ for additional agreement points (Figure 3). The supports must now be disjoint from W . We impose this recursively, in a form that is easy to count. The root functional is required to vanish on W . Then W lies in the slice where it equals zero, the other slice is disjoint from W whatever its child is, and the child on the first slice must again avoid W .

Definition 6.8 (Tree functions avoiding a subspace). Let $W \leq U$ be a subspace of codimension $h + 1$. A height-two tree function on U is W -avoiding if it vanishes on W . For $h \geq 3$, a height- h tree function is W -avoiding if its root functional s vanishes on W and its restriction φ_0 to $\ker s$ is W -avoiding.

The support of a W -avoiding tree function is disjoint from W . For $h \geq 3$ there may be other tree functions with this property. We do not count them, and a lower bound on the number of supports is all we need.

Lemma 6.9 (Counting tree supports that avoid a subspace). Let $h \geq 2$, let U be a binary vector space of dimension $d \geq t_h$, and let $W \leq U$ have codimension $h + 1$. The number $M_h(d)$ of W -avoiding height- h tree functions on U satisfies

$$M_2(d) = 28(6 \cdot 2^{d-3} - 5),$$

$$M_h(d) = (2^{h+1} - 1) M_{h-1}(d-1) 2^{t_{h-1}^2} \begin{bmatrix} d-1-t_{h-1} \\ t_{h-1} \end{bmatrix}_2 C_{h-1} \quad (h \geq 3),$$

with C_{h-1} as in Lemma 6.6. For each fixed h , $M_h(d) = \Theta_h(2^{d(2^h-h-1)})$.

Proof. We use induction on h , counting the functions by their recursive data.

Step 1: height two. A height-two tree function φ is $ab + e + c$ with linearly independent $a, b, e \in U^*$ and $c \in \mathbb{F}_2$. Indeed, on its three-dimensional essential quotient its polar form (Definition 3.15) is nonzero and alternating, so it has rank two and is the polar form of ab for independent a, b ; then $\varphi + ab$ is affine, say $e + c$, and $e \notin \langle a, b \rangle$ because the essential dimension is three. Conversely, each such expression is a height-two tree function. The function determines $E = \langle a, b \rangle$, which is spanned by the functionals $x \mapsto \varphi(x+y) + \varphi(x) + \varphi(y) + \varphi(0)$, and the functions with a given E are the $ab + e + c$ with $e \notin E$, for any fixed basis a, b of E . Let $W^\perp \leq U^*$ be the three-dimensional space of functionals vanishing on W . There are three cases.

- If $E \leq W^\perp$, then ab vanishes on W , so the function vanishes on W exactly when $c = 0$ and $e \in W^\perp \setminus E$. The seven spaces E give $7 \cdot 4 = 28$ functions.
- If $E \cap W^\perp = \langle a \rangle$, again ab vanishes on W , and the condition is $c = 0$ and $e \in W^\perp \setminus \{0, a\}$, giving six functions. There are seven choices of $\langle a \rangle \leq W^\perp$, and then $2^{d-1} - 4$ planes through a not contained in $W^\perp$, so there are $28(2^{d-3} - 1)$ such spaces E .
- If $E \cap W^\perp = 0$, then a and b are independent on W , so ab is not affine on W and no function vanishes on W .

In total $M_2(d) = 28 + 6 \cdot 28(2^{d-3} - 1)$.

Step 2: the recurrence. Let $h \geq 3$ and $r = t_{h-1}$. There are $2^{h+1} - 1$ nonzero functionals s vanishing on W . In $\ker s$, which has dimension $d - 1$, the space W has codimension h , so there are $M_{h-1}(d - 1)$ choices of a W -avoiding child. Let L_0 be its essential dual space. The r -spaces $L_1 \leq (\ker s)^*$ with $L_0 \cap L_1 = 0$ number $2^{r^2} \left[\begin{smallmatrix} d-1-r \\ r \end{smallmatrix} \right]_2$: choose the image of L_1 in $(\ker s)^*/L_0$, then a linear map from it to L_0 . Such a space exists because $d \geq 2r + 1$. Finally there are C_{h-1} children on the other slice with essential dual space L_1 . By Lemma 6.5, different choices give different functions.

Step 3: the order of growth. For fixed h , the Gaussian coefficient has order 2^{dr} and the other new factors are constants. The exponent e_h of 2^d therefore satisfies $e_2 = 1$ and $e_h = e_{h-1} + 2^{h-1} - 1$, so $e_h = 2^h - h - 1$. $\square$

At height three, which gives agreement 9/16 below, and with $w = 2^d/16$,

$$M_3(d) = 71680(6w - 5)(w - 1)(w - 2)(w - 4) \sim (105/16) 2^{4d}.$$

Theorem 6.10 (Decision-tree construction at rate 1/2). Let $D \subseteq \mathbb{F}$ be binary additive of size $N = 2^d$, let $q = |\mathbb{F}| > N$, and fix $h \geq 3$ with $d \geq 2^h - 1$. Put $K = N/2$ and $w = N/2^{h+1}$, let $M = M_h(d)$ be the count of Lemma 6.9, and set

$$F = \frac{1}{2} \left[\left(K - w - \frac{K^2}{N - w} \right) M^2 + wM \right].$$

There is one received pair with

$$\text{CA}_K(f, g) = \text{agr}_K(g) = K, \quad \text{agr}_K(f) \leq K + w - 1,$$

and at least $Z(M, F)$ distinct nonzero exceptional challenges at agreement $K + w$, with Z as in (6.2). This number is $\Omega_h(\min\{N^{2^h-h-1}, q/N\})$, and the exceptional probability is at least

$$\Omega_h \left(\min \left\{ \frac{N^{2^h-h-1}}{q}, \frac{1}{N} \right\} \right),$$

with implied constants depending only on h . The fractional common-agreement gap is $w/N = 2^{-h-1}$.

Proof. Fix a subspace $W \leq D$ of size w , and apply Lemma 6.1 to the supports A of the W -avoiding height- h tree functions on D , with $T_0 = K$. By Lemmas 6.4 and 6.9, these are M distinct subsets of $D \setminus W$, each a union of flats of size $N/2^h = 2w$. Since $\sum_{x \notin W} I_x = KM$, Cauchy–Schwarz over the $N - w$ points outside W gives

$$\sum_{x \notin W} \binom{I_x}{2} \geq \frac{1}{2} \left(\frac{K^2 M^2}{N - w} - KM \right),$$

so

$$(K - w) \binom{M}{2} - \sum_{x \notin W} \binom{I_x}{2} \leq F,$$

which is (6.1). This gives the pair and the bound $Z(M, F)$. Since $K - K^2/(N - w) < N/4$ and $M \geq 1$, we have $F \leq NM^2/8$, so $Z(M, F) \geq \min\{M/2, q/N\}$, and $M = \Theta_h(N^{2^h-h-1})$. $\square$

Heights $h = 3, 4, 5$ give agreement fractions 9/16, 17/32, and 33/64, with $M_h(d)$ of order N^4, N^{11} , and N^{26} , for d at least 7, 15, and 31. The counted supports give $\Theta_h(M_h(d))$ distinct challenges once $q \geq NM_h(d)$, and for every $h \geq 3$ the guaranteed count grows faster than N^2 whenever $q/N^3 \rightarrow \infty$. The same proof applies at height two, at agreement 5/8, where $M_2(d) = \Theta(N)$ gives only $\Omega(\min\{N, q/N\})$ challenges.

Suppose D lies in a proper subfield $\mathbb{B}$ of $\mathbb{F}$ with $|\mathbb{B}| > N$. Then the theorem over $\mathbb{B}$, followed by Lemma 3.12, gives a pair over $\mathbb{F}$ at the same agreement $K + w$ whose two individual agreements both equal the common agreement K . The count is that of the theorem with $|\mathbb{B}|$ in place of q , since the conversion preserves every counted nonzero challenge.

6.4 Concrete bounds for the parameters of LeanVM and Flock

LeanVM and Flock both have configurations at rate $1/2$ on additive domains of length $N = 2^{22}$, spanned by the first 22 powers of a generator of $\mathbb{F}_{2^{64}}$ and of $\mathbb{F}_{2^{128}}$ respectively (Section 5). LeanVM draws its challenges from $\mathbb{F}_{2^{192}}$ and Flock from $\mathbb{F}_{2^{256}}$ [23, 38]. These domains are too sparse for the Gold construction, but Theorem 6.10 applies to every additive domain of this length. The received words of our pairs take values in the challenge field $\mathbb{F}$.

Take $\mathbb{F} = \mathbb{F}_{2^{192}}$ and $N = 2^{22}$. At height three, Theorem 6.10 gives more than 2.0309×10^{27} distinct nonzero challenges at rate $1/2$ and agreement $9/16$. The exceptional probability is greater than $2^{-101.286}$.

At height four the same theorem gives a much larger exceptional set at agreement $17/32$ (Table 1). For $N = 2^{22}$ and $\mathbb{F} = \mathbb{F}_{2^{192}}$, the finite collision bound gives $Z(M, F) > 2^{172}$, so the exceptional probability is at least 2^{-20} . For $\mathbb{F} = \mathbb{F}_{2^{256}}$ and the same N , there are more than 2^{229} nonzero exceptional challenges, hence probability greater than 2^{-27} . Indeed, with $M = M_4(22)$ and F as in the theorem, direct substitution gives $(2^{256} - N)(M - 2^{229} - 1) > F$, so the first term of $Z(M, F)$ suffices.

The two fields are in different regimes of the collision bound. At $d = 22$ the support count is $M_4(22) \approx 2^{229.5}$, well below its asymptotic order $N^{11} = 2^{242}$. Over $\mathbb{F}_{2^{192}}$ the supports far outnumber the distinct challenges that the collision bound can guarantee: the second term of $Z(M, F)$ is approximately $q/(0.21N)$, so the probability bound is about $4.7/N$ and does not improve as the challenge field shrinks. Over $\mathbb{F}_{2^{256}}$ nearly all M supports give distinct challenges, and the probability is about M/q .

7 Discussion and open questions

The main open questions are whether larger exceptional sets can reach Johnson on sparse domains and whether near-Johnson counterexamples exist at additional rates.

Sparse domains near Johnson. On prescribed sparse domains, such as spans of the first few powers of a fixed field element, Theorem 4.1 gives $\Omega(N^2)$ exceptional challenges at rate $1/16$, within a constant number of agreement coordinates of Johnson and with $N/8$ positions between combination and common agreement. Can the count grow faster than N^2 at such thresholds, with a fixed positive fractional common-agreement gap? The classification in Theorem 4.1 shows that this requires a different pair f, g : the pair constructed there has no further challenges with more than $N/8$ agreements. The Gold moment equations still define valid candidates on sparse domains, but Lemma 5.13 does not guarantee any solutions of the required rank. At rate $1/4$ even a quadratic count near Johnson is open on these domains: Theorem 4.7 gives $2N - 2$ challenges at agreement $1/2$.

Rates other than $1/b^2$. Even on dense domains, our counterexamples approach Johnson only at rates $1/b^2$. Removing the linear term of an $\mathbb{F}_b$ -subspace locator leaves a b th power, which gives agreement b times the degree, and this equals Johnson only at rate $1/b^2$. We reach the other rates by padding, which raises the degree bound faster than the agreement. At rate $1/2$, for instance, Corollary 5.15 gives superpolynomial counts at agreement approaching $5/8 = 0.625$, while Johnson is $1/\sqrt{2} \approx 0.707$. Whether a proximity gap, or a polynomial list-size bound, holds between these two thresholds is open, as it is at every rate covered only by Corollary 5.16, 5.17, or 5.24.

Explicit domains in binary fields. Every construction in this paper uses the vanishing polynomial of a subspace. Over a binary field, however, randomly chosen evaluation points satisfy guarantees up to capacity with high probability [29]. The bounds proved beyond Johnson for prescribed domains require the

characteristic to exceed the degree bound [18, Theorem 5.13], so they do not apply in characteristic two. Is there an explicit family of domains in binary fields on which proximity gaps hold beyond Johnson?

Protocols. Our counterexamples are pairs of received words with values in the challenge field. We do not claim that such pairs arise in an execution of any of the systems discussed here, and none of these systems is configured beyond Johnson. Can such pairs arise in a proof system that is? A prover must also satisfy the protocol’s constraints on the received words and its other verification checks, and such constraints can restore a bound. For example, if both words take values in a subfield $\mathbb{B}$ containing the domain, then by (3.1) every challenge that is exceptional at an agreement above $\text{CA}_K(f, g)$ lies in $\mathbb{B}$, so the exceptional probability is at most $|\mathbb{B}|/|\mathbb{F}|$.

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