

SMOOTHED ANALYSIS FOR THE CONDITION NUMBER OF STRUCTURED REAL POLYNOMIAL SYSTEMS

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ABSTRACT. We consider the sensitivity of real zeros of structured polynomial systems to perturbations of their coefficients. In particular, we provide explicit estimates for condition numbers of structured random real polynomial systems and extend these estimates to the smoothed analysis setting.

1. INTRODUCTION

Efficiently finding real roots of real polynomial systems is one of the main objectives of computational algebraic geometry. There are numerous algorithms for this task, but the core steps of these algorithms are easy to outline: They are some combination of algebraic manipulation, a discrete/polyhedral computation, and a numerical iterative scheme.

From a computational complexity point of view, the cost of numerical iteration is much less transparent than the cost of algebraic or discrete computation. This paper constitutes a step toward understanding the complexity of numerically solving structured real polynomial systems. Our main results are Theorems 1.14, 1.16, and 1.18 but we will first need to give some context for our results.

1.1. How to control accuracy and complexity of numerics in real algebraic geometry? In the numerical linear algebra tradition, going back to von Neumann and Turing, condition numbers play a central role in the measurement of speed and the control of accuracy of algorithms (see, e.g., [2, 3] for further background). Shub and Smale initiated the use of condition numbers for polynomial system solving over the field of complex numbers [26, 27]. Subsequently, condition numbers played a central role in the solution of Smale’s 17th problem [1, 3, 17].

The numerics of solving polynomial systems over the real numbers is more subtle than complex case: small perturbations can cause the solution set to change cardinality. One can even go from having no real zero to many real zeros by an arbitrarily small change in the coefficients. This behaviour doesn’t appear over the complex numbers as one has theorems (such as the Fundamental Theorem of Algebra) proving that root counts are “generically” constant. Luckily, a condition number theory that captures these subtleties was developed by Cucker [6]. Now we set up the notation and present Cucker’s definition.

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Definition 1.1 (Bombieri-Weyl norm). We set $x^\alpha := x_1^{\alpha_1} \cdots x_n^{\alpha_n}$ where $\alpha := (\alpha_1, \dots, \alpha_n)$, and let $P = (p_1, \dots, p_{n-1})$ be a system of homogenous polynomials with degree pattern d_1, \dots, d_{n-1} . Let $c_{i,\alpha}$ denote the coefficient of x^α in a p_i . We define the *Bombieri-Weyl norms* of p_i and P to be, respectively,

$$\|p_i\|_W := \sqrt{\sum_{\alpha_1+\dots+\alpha_n=d_i} \frac{|c_{i,\alpha}|^2}{\binom{d_i}{\alpha}}}$$

and

$$\|P\|_W := \sqrt{\sum_{i=1}^{n-1} \|p_i\|_W^2}. \diamond$$

The following is Cucker's condition number definition [6].

Definition 1.2 (Real condition number). For a system of homogenous polynomials $P = (p_1, \dots, p_{n-1})$ with degree pattern (d_1, \dots, d_{n-1}) , let Δ_{n-1} be the diagonal matrix with entries $\sqrt{d_1}, \dots, \sqrt{d_{n-1}}$ and let

$$DP(x)|_{T_x S^{n-1}} : T_x S^{n-1} \longrightarrow \mathbb{R}^m$$

denote the linear map between tangent spaces induced by the Jacobian matrix of the polynomial system P evaluated at the point $x \in S^{n-1}$.

The local condition number of P at a point $x \in S^{n-1}$ is

$$\tilde{\kappa}(P, x) := \frac{\|P\|_W}{\sqrt{\left\| DP(x)|_{T_x S^{n-1}}^{-1} \Delta_{n-1} \right\|^{-2} + \|P(x)\|_2^2}}$$

and the global condition number is

$$\tilde{\kappa}(P) := \sup_{x \in S^{n-1}} \tilde{\kappa}(P, x). \diamond$$

An important feature of Cucker's real condition number is the following geometric fact [9].

Theorem 1.3 (Real condition number theorem). *We use H_D to denote the vector space of homogenous polynomial systems with degree pattern (d_1, \dots, d_{n-1}) , and equip this space with the metric $\rho(\cdot, \cdot)$ induced by the Bombieri-Weyl norm. We define the set of ill-posed problems to be:*

$$\Sigma := \{P \in H_D : P \text{ has a singular zero in } S^{n-1}\}.$$

Then we have

$$\tilde{\kappa}(P) = \frac{\|P\|_W}{\rho(P, \Sigma)}.$$

Cucker's condition number is used in the design and analysis of a numerical algorithm for real zero counting [8–10], in the series of papers for computing homology groups of semialgebraic sets [4, 5, 11], and more recently in the analysis of a well-known algorithm for meshing curves and surfaces (the Plantinga-Vegter algorithm) [7].

One important observation is that the complexity of a numerical algorithm over the real numbers (imagine using bisection for finding real zeros of a given univariate polynomial) varies depending on the geometry of the input, and not just the bit complexity of its vector representation. Therefore it is more natural to go beyond

worst-case analysis and seek quantitative bounds for “typical” inputs. We now explain the existing attempts toward mathematically modeling the intuitive phrase “typical input”.

Random and adversarial random models. Worst-case complexity theory, spearheaded by the P vs. NP question, has been a driving force behind many algorithmic breakthroughs in the last five decades. However, it has become clear that worst-case complexity theory fails to capture the practical performance of algorithms. The unreasonable effectiveness of everyday statistical methods is a case in point: the Spotify app on cell phones solves instances of an NP-Hard problem all the time!

Two dominant paradigms for going beyond the worst-case analysis of algorithms are as follows: Assume an algorithm T operates on the input $x \in \mathbb{R}^k$, with the cost of output $T(x)$ bounded from above by $C(x)$. One then equips the input space \mathbb{R}^k with a probability measure μ and considers the average cost $\mathbb{E}_{x \sim \mu} C(x)$, or *smoothed analysis of the cost with parameter $\delta > 0$* : $\sup_{x \in \mathbb{R}^k} \mathbb{E}_{y \sim \mu} C(x + \delta \|x\| y)$. Clearly, as $\delta \rightarrow 0$, smoothed complexity recovers worst-case complexity, and when $\delta \rightarrow \infty$ we recover average-case complexity. It is also clear that to have a realistic complexity analysis, one should have a probability measure μ that somehow reflects one’s context, and use theorems that allow a broad class of measures μ . The idea of smoothed analysis originated in work of Spielman and Teng [28].

1.2. Existing results for average and smoothed analysis. Existing results for the average analysis of real condition number from [10] can be roughly summarized as follows.

Theorem 1.4 (Cucker, Krick, Malajovich, Wschebor). *Suppose*

$$p_i(x) := \sum_{\alpha_1 + \dots + \alpha_n = d_i} c_{\alpha}^{(i)} x^{\alpha}, \quad i = 1, \dots, n-1$$

are random polynomials where $c_{\alpha}^{(i)}$ are centered Gaussian random variables with variances $\binom{d_i}{\alpha}$. Then, for the random polynomial system $P = (p_1, \dots, p_{n-1})$ and for all $t \geq 1$, we have

$$\mathbb{P} \left\{ \tilde{\kappa}(P) \geq t 8d^{\frac{n+4}{2}} n^{5/2} N^{1/2} \right\} \leq \frac{(1 + \log(t))^{\frac{1}{2}}}{t},$$

where $d = \max_i d_i$ and $N = \sum_{i=1}^{n-1} \binom{n+d_i-1}{d_i}$.

Recall the following smoothed analysis type result from [9]:

Theorem 1.5 (Cucker, Krick, Malajovich, Wschebor). *Let Q be an arbitrary polynomial system with degree pattern (d_1, \dots, d_{n-1}) , let $P = (p_1, \dots, p_{n-1})$ be a random polynomial system as defined above. Now for a parameter $0 < \delta < 1$ we define a random perturbation of Q with (P, δ) as follows: $G := Q + \delta \|Q\|_W P$. Then we have*

$$\mathbb{P} \left\{ \tilde{\kappa}(G) \geq t \frac{13n^2 d^{2n+2} N}{\delta} \right\} \leq \frac{1}{t}.$$

Remark 1.6. The randomness model considered in these seminal results has the following restriction: the induced probability measure is invariant under the action of the orthogonal group $O(n)$ on the space of polynomials. The proof techniques

used in the papers seem to be only applicable when one has this group invariance property. This creates an obstruction against analysis on spaces of structured polynomials; spaces of structured polynomials are not necessarily closed under the action of $O(n)$, and hence do not support an $O(n)$ -invariant probability measure.

1.3. What about structured polynomials? Let H_{d_i} be the vector space of homogenous polynomials with n variables, and let H_D be the vector space of polynomial systems with degree pattern $D = (d_1, \dots, d_{n-1})$. Let $E_i \subset H_{d_i}$ be linear subspaces for $i = 1, \dots, n-1$, and let $E = (E_1, \dots, E_{n-1})$ be the corresponding vector space of polynomial systems.

For virtually any application of real root finding algorithms, the user has a polynomial system with a particular structure rather than a generic polynomial system with $N = \sum_{i=1}^n \binom{n+d_i-1}{d_i}$ many coefficients. Suppose a user has identified the linear structure E that is present in the target equations, and would like to know about how much precision is expected for round-off errors in the space E . One could induce a probability measure μ on E and use $\mathbb{E}_{P \sim \mu} \log(\tilde{\kappa}(P))$ to determine the expected loss of precision in the numerical solutions. What could go wrong?

Example 1.7. Let $u, v \in S^{n-1}$ be two vectors with $u \perp v$, and define the following subspaces:

$$E_i := \{p \in H_{d_i} : p(u) = \langle \nabla p(u), v \rangle = 0\}, \quad i = 1, \dots, n-1,$$

where $\nabla p(u)$ denotes the gradient of p evaluated at u . E_i are codimension 2 linear subspaces of H_{d_i} . Now consider the space of polynomials $E := (E_1, \dots, E_{n-1})$; any polynomial system in the space E has a singular real zero at u . Hence, for all $P \in E$ the condition number $\tilde{\kappa}(P)$ is infinite.

The preceding example illustrates that, for certain linear spaces E , the probabilistic analysis of condition numbers is meaningless: It is possible for *certain* spaces E that all inhabitants have infinite condition number. We will rule out these degenerate cases as follows.

Definition 1.8 (Non-degenerate linear space). We call a linear space $E_i \subset H_{d_i}$ non-degenerate if for all $v \in S^{n-1}$, there exists an element $p_i \in E_i$ with $p_i(v) \neq 0$. In other words, E_i is non-degenerate if there is no base point $v \in S^{n-1}$ where all the elements of E_i vanish all together. We call a space of polynomial systems $E = (E_1, \dots, E_{n-1})$ non-degenerate if all E_i are non-degenerate for $i = 1, \dots, n-1$. \diamond

An easy corollary of Theorem 1.14 shows that the expected precision is finite for any non-degenerate space E .

Corollary 1.9. *Let $E \subset H_D$ be a non-degenerate linear space of polynomials. Let μ be a probability measure supported on the space E that satisfies the assumptions listed in Section 1.5. Then $\mathbb{E}_{P \sim \mu} \log(\tilde{\kappa}(P))$ is finite.*

This is clearly not the end of the story: a non-degenerate linear structure E may still be close to being degenerate, and this would make every element in the space E ill-conditioned. So we need to somehow quantify the numerical conditioning of a linear structure E . Next, we introduce the notion of *dispersion* as a rough measure of conditioning of a linear structure.

1.4. The dispersion constant of a linear space. Suppose a linear subspace $F \subset H_d$ is given for some $d > 1$ together with an orthonormal basis $u_j(x)$, $j = 1, \dots, m$ with respect to Bombieri-Weyl norm. Now suppose for a particular point $v_0 \in S^{n-1}$ all the basis elements satisfy $|u_j(v_0)| < \varepsilon$ where $\varepsilon > 0$ is small. What kind of behavior one would expect from elements of F at the point v_0 ? This point v_0 would behave like a base point (like if all elements of F vanishes at v_0) unless one employs rather high precision. This motivates Definition 1.10.

Definition 1.10 (Dispersion constant of a linear space of polynomials). Let $F \subset H_d$ is given for some $d > 1$, and let $u_j(x)$, $j = 1, \dots, m$ be an orthonormal basis of F with respect to Bombieri-Weyl norm. We define the following two quantities

$$\sigma_{\min}(F) := \min_{v \in S^{n-1}} \left(\sum_j u_j(v)^2 \right)^{\frac{1}{2}}, \quad \sigma_{\max}(F) := \max_{v \in S^{n-1}} \left(\sum_j u_j(v)^2 \right)^{\frac{1}{2}}$$

and the dispersion constant $\sigma(F)$ is their ratio:

$$\sigma(F) := \frac{\sigma_{\max}(F)}{\sigma_{\min}(F)}. \diamond$$

The quantity σ_{\max} is introduced to make things scale invariant. We generalize the definition to polynomial systems in a straight-forward manner.

Definition 1.11 (Dispersion constant of a linear space of polynomial systems). Let $E_i \subset H_{d_i}$ be linear spaces for $i = 1, \dots, n-1$, and let $E = (E_1, \dots, E_{n-1})$. We define the dispersion constant $\sigma(E)$ as follows: $\sigma(E) := \max_i \sigma(E_i)$. \diamond

Our estimates replace the dimension N in earlier results with the (potentially much smaller) dimension of E , at the expense of involving the new quantity $\sigma(E)$. So if a user has a fixed structure E with small dimension and tame dispersion constant, then the expected conditioning on E admits a much better bound than what earlier results suggest. On the other hand, if one has a sparse but highly sensitive structure, the resulting average-case conditioning could be a lot worse than the average over the entire space H_D .

How big is the dispersion constant? To better understand the dispersion constant, let us consider two examples at opposite extremes.

Example 1.12 (A subspace with minimal dispersion constant). Consider subspaces of polynomials $F_i \subset P_{n,2d_i}$ defined as the span of

$$u_{kl}^{(i)} = (x_1^2 + \dots + x_n^2)^{d_i-1} x_k x_l \text{ for } 1 \leq k, l \leq n$$

and let $F = (F_1, \dots, F_n)$. It is easy to show that $\sigma(F) = 1$.

Example 1.13 (A sparse but highly sensitive structure). Let $E \subset P_{n,d}$ be the subspace of polynomials spanned by the monomials x_1^d, \dots, x_n^d . Then, we have $\sigma(E) = n^{\frac{d-1}{2}}$.

One may wonder how big the dispersion constant for a “typical” linear space E is, for say, E of dimension around $n^2 \log d$. Would a typical low-dimensional space look like the second example or the first example? We address this question in the Appendix. For our main theorems, we will allow E to be arbitrary and give bounds depending explicitly on the the dispersion constant $\sigma(E)$.

1.5. A general model of randomness for structured polynomial systems. In our precursor paper [13] we obtained probabilistic condition number estimates for general measures (without any group invariance assumption). In this paper we present probabilistic results for the same general family of measures, but this time supported on a structured space E instead of H_D . Note that here the structured space E will be fixed by the user, and our results will give estimates for a random element from E . First, we introduce our general model of randomness.

We say a random vector $X \in \mathbb{R}^n$ satisfies the *Centering*, *sub-Gaussian*, and *Small Ball* properties, with constants K and c_0 , if the following hold true:

1. (Centering) For any $\theta \in S^{n-1}$ we have $\mathbb{E}\langle X, \theta \rangle = 0$.¹
2. (Sub-Gaussian) There is a $K > 0$ such that for every $\theta \in S^{n-1}$ we have

$$\text{Prob}(|\langle X, \theta \rangle| \geq t) \leq 2e^{-t^2/K^2} \text{ for all } t > 0.$$

3. (Small Ball) There is a $c_0 > 0$ such that for every vector $a \in \mathbb{R}^n$ we have

$$\text{Prob}(|\langle a, X \rangle| \leq \varepsilon \|a\|_2) \leq c_0 \varepsilon \text{ for all } \varepsilon > 0.$$

We note that these three assumptions directly yield a relation between K and c_0 : We in fact have $Kc_0 \geq \frac{1}{4}$ (see [13] just before Section 3.2). Moreover, for a random variable X that satisfies above assumptions with constants K and c_0 , and a scalar $\lambda > 0$, the random variable λX satisfies the above assumptions with constants λK and $\lambda^{-1}c_0$. In other words Kc_0 is invariant under scaling, hence one can hope for a universal lower bound of $\frac{1}{4}$.

Random vectors that satisfy these three properties form a large family of distributions, including standard Gaussian vectors and uniform measures on a large family of convex bodies called Ψ_2 -bodies (such as uniform measures on l_p -balls for all $p \geq 2$). We refer the reader to the book of Vershynin [30] for more details. Discrete sub-Gaussian distributions, such as the Bernoulli distribution, also satisfy an inequality similar to the Small Ball inequality in our assumptions. However, the Small Ball type inequality satisfied by such discrete distributions depends not only on the norm of the deterministic vector a but also on the arithmetic structure of a . It is possible that our methods, combined with the work of Rudelson and Vershynin on the Littlewood-Offord problem [22], can extend our main results to discrete distributions such as the Bernoulli distribution. In this work, we will content ourselves with continuous distributions.

The preceding examples of random vectors do not necessarily have independent coordinates. This provides important extra flexibility. There are also interesting examples of random vectors with independent coordinates. In particular, if X_1, \dots, X_m are independent centered random variables that each satisfy both the sub-Gaussian inequality with constant K and the Small Ball condition with c_0 , then the random vector $X = (X_1, \dots, X_m)$ also satisfies the sub-Gaussian and Small Ball inequalities with constants C_1K and C_2c_0 , where C_1 and C_2 are universal constants. This is a relatively new result of Rudelson and Vershynin [24]. The best possible universal constant C_2 is discussed in [19, 21]. To create a random variable satisfying the Small Ball and sub-Gaussian properties one can, for instance, start by fixing any $p \geq 2$ and then considering a random variable with density function $f(t) := c_p e^{-|t|^p}$, for suitably chosen positive c_p .

¹Equivalently, $\mathbb{E}X = \mathbf{0}$.

1.6. Our results. We present estimates for random structured polynomial systems, where the randomness model is the one introduced in the preceding section.

Average-case condition number estimates for structured polynomial systems.

Theorem 1.14. *Let $E_i \subseteq H_{d_i}$ be non-degenerate linear subspaces, and let $E = (E_1, \dots, E_{n-1})$. Assume $\dim(E) \geq n \log(ed)$ and $n \geq 3$. Let $p_i \in E_i$ be independent random elements of E_i that satisfy the Centering Property, the sub-Gaussian Property with constant K , and the Small Ball Property with constant c_0 , each with respect to the Bombieri-Weyl inner product. We set $d := \max_i d_i$ and $M := nK\sqrt{\dim(E)}(c_0CKd^2 \log(ed)\sigma(E))^{2n-2}$, where $C \geq 4$ is a universal constant. Then for the random polynomial system $P = (p_1, \dots, p_{n-1})$, we have*

$$\text{Prob}(\tilde{\kappa}(P) \geq tM) \leq \begin{cases} 3t^{-\frac{1}{2}} & ; \text{ if } 1 \leq t \leq e^{2n \log(ed)} \\ (e^2 + 1)t^{-\frac{1}{2} + \frac{1}{4 \log(ed)}} & ; \text{ if } e^{2n \log(ed)} \leq t. \end{cases}$$

Moreover, for $0 < q < \frac{1}{2} - \frac{1}{2 \log(ed)}$, we have $\mathbb{E}(\tilde{\kappa}(P)^q) \leq M^q(1 + 4q \log(ed))$. In particular, $\mathbb{E} \log(\tilde{\kappa}(P)) \leq 1 + \log M$.

Smoothed analysis for structured polynomial systems. For smoothed analysis we need to introduce a slightly stronger assumption on the random input. This slightly stronger property is called the *Anti-Concentration Property* and it replaces the Small Ball assumption in our model of randomness. We will need a bit of terminology to define anti-concentration.

Definition 1.15 (Anti-Concentration Property). For any real-valued random variable Z and $t \geq 0$, the *concentration function*, $F(Z, t)$, is defined as $F(Z, t) := \max_{u \in \mathbb{R}} \text{Prob}\{|Z - u| \leq t\}$. Let $\langle \cdot, \cdot \rangle$ denote the standard inner product on \mathbb{R}^n . We then say a random vector $X \in \mathbb{R}^n$ satisfies the *Anti-Concentration Property with constant c_0* if we have $F(\langle X, \theta \rangle, \varepsilon) \leq c_0 \varepsilon$ for all $\theta \in S^{n-1}$. \diamond

It is easy to check that if the random variable Z has bounded density f then $F(Z, t) \leq \|f\|_\infty t$. Moreover, the Lebesgue Differentiation theorem states that upper bounds for the function $t^{-1}F(Z, t)$ for all t imply upper bounds for $\|f\|_\infty$. See [23] for the details.

Theorem 1.16. *Let $E \subseteq H_D$ be a non-degenerate linear subspace for $D = (d_1, \dots, d_{n-1})$. Assume $\dim(E) \geq n \log^2(ed)$ and $n \geq 3$. Let $Q \in E$ be a fixed (deterministic) polynomial system let $G \in E$ be a random polynomial system given by the same model of randomness as in Theorem 1.14, but with the Small Ball Property replaced by the Anti-Concentration Property. Set $d := \max_i d_i$, and*

$$M := nK\sqrt{\dim(E)}(c_0d^2CK \log(ed)\sigma(E))^{2n-2} \left(1 + \frac{\|Q\|_W}{\sqrt{n}K \log(ed)}\right)^{2n-1},$$

where $C \geq 4$ is a universal constant. Then for the randomly perturbed polynomial system $P = Q + G$, we have

$$\text{Prob}(\tilde{\kappa}(P) \geq tM) \leq \begin{cases} 3t^{-\frac{1}{2}} & ; \text{ if } 1 \leq t \leq e^{2n \log(ed)} \\ (e^2 + 1)t^{-\frac{1}{2} + \frac{1}{4 \log(ed)}} & ; \text{ if } e^{2n \log(ed)} \leq t. \end{cases}$$

Moreover, for $0 < q < \frac{1}{2} - \frac{1}{2\log(ed)}$, we have

$$\mathbb{E}(\tilde{\kappa}(P)^q) \leq M^q(1 + 4q\log(ed)).$$

In particular, $\mathbb{E}\log(\tilde{\kappa}(P)) \leq 1 + \log M$.

We would like to consider a corollary to make the result easier to parse.

Corollary 1.17. *Let $E \subseteq H_D$ be a non-degenerate linear subspace for $D = (d_1, \dots, d_{n-1})$. Assume $\dim(E) \geq n\log(ed)^2$ and $n \geq 3$. Let $Q \in E$ be a fixed (deterministic) polynomial system, and let $G \in E$ be a random polynomial system given by the model of randomness as in Theorem 1.16, but with fixed $K = 1$. Now let $0 < \delta < 1$ be a parameter and consider the polynomial system*

$$P := Q + \delta \|Q\|_W G.$$

We set $d := \max_i d_i$, and

$$M := n\sqrt{\dim(E)} (c_0 C d^2 \log(ed) \sigma(E))^{2n-2} \delta \|Q\|_W \left(1 + \frac{1}{\delta \sqrt{n} \log(ed)}\right)^{2n-1},$$

where $C \geq 4$ is a universal constant. Then, we have

$$\text{Prob}(\tilde{\kappa}(P) \geq tM) \leq \begin{cases} 3t^{-\frac{1}{2}} & ; \text{ if } 1 \leq t \leq e^{2n\log(ed)} \\ (e^2 + 1)t^{-\frac{1}{2} + \frac{1}{4\log(ed)}} & ; \text{ if } e^{2n\log(ed)} \leq t. \end{cases}$$

An interesting consequence. As a corollary of the smoothed analysis estimate in Theorem 1.16, we derive the following structural result.

Theorem 1.18. *Let $E_i \subseteq H_{d_i}$ be non-degenerate linear subspaces, let $E = (E_1, \dots, E_{n-1})$, and let $Q \in E$. Then, for every $0 < \varepsilon < 1$, there is a polynomial system $P_\varepsilon \in E$ with the following properties:*

$$\|P_\varepsilon - Q\|_W \leq \varepsilon \|Q\|_W \left(\frac{\sqrt{\dim(E)}}{\log(ed)\sqrt{n}} \right)$$

and

$$\tilde{\kappa}(P_\varepsilon) \leq \sqrt{n}\sqrt{\dim(E)} \left(\frac{d^2 C \log(ed) \sigma(E)}{\varepsilon} \right)^{2n-2}$$

for a universal constant C .

One can view this result as a metric entropy statement as follows: Suppose we are given a bounded set $\mathbb{T} \subset E$ with $\sup_{P \in T} \|P\|_W \leq 1$, and we would like to cover \mathbb{T} with balls of radius δ , i.e., $\mathbb{T} = \bigcup_i B(p_i, \delta)$. Moreover, suppose we want the ball-centers p_i to have a controlled condition number. We can start with an arbitrary $\frac{\delta}{2}$ covering $\mathbb{T} = \bigcup_i B(p_i, \frac{\delta}{2})$, and use Theorem 1.18 with $\varepsilon = \frac{\delta\sqrt{n}}{2\sqrt{\dim(E)}}$ to find a p_i with controlled condition number in each one of the balls $B(p_i, \frac{\delta}{2})$. Then $\mathbb{T} = \bigcup_i B(p_i, \delta)$ gives a δ -covering of \mathbb{T} where p_i has controlled condition number.

2. BACKGROUND AND BASIC ESTIMATES

We first present a simple lemma for a single random polynomial.

Lemma 2.1. *Let $F \subset H_d$ be non-degenerate linear subspace of degree d homogenous polynomials. We equip F with Bombieri-Weyl norm. Suppose $p \in F$ is a random element that satisfies Centering Property, sub-Gaussian Property with constant K , and small probability with constant c_0 each with respect to Bombieri inner product. Then for all $w \in S^{n-1}$ the following estimates hold:*

$$\text{Prob}(|p(w)| \geq t\sigma_{\max}(F)) \leq \exp\left(1 - \frac{t^2}{K^2}\right)$$

$$\text{Prob}(|p(w)| \leq \varepsilon\sigma_{\min}(F)) \leq c_0\varepsilon.$$

Proof. Suppose u_1, \dots, u_m is an orthonormal basis of F with respect to Bombieri-Weyl inner product. Let $f \in F$ be a polynomial with $f(x) = \sum_i f_i u_i(x)$, then for any $v \in S^{n-1}$, clearly $f(v) = \sum_i a_i u_i(v)$. In other words, if we set $q_v := \sum_i u_i(v) u_i(x)$ then we have $f(v) = \langle f, q_v \rangle_W$. Also note since u_i is an orthonormal basis with respect to Bombieri norm, we have $\|q_v\|_W = (\sum_i u_i(v)^2)^{\frac{1}{2}}$.

Now let $p \in E'$ be the random element described above. The reasoning in the preceding paragraph gives us the following estimates for any fixed point $v \in S^{n-1}$:

$$\text{Prob}(|p(v)| \geq t\|q_v\|_W) \leq \exp\left(1 - \frac{t^2}{K^2}\right)$$

$$\text{Prob}(|p(v)| \leq \varepsilon\|q_v\|_W) \leq c_0\varepsilon.$$

By the definition of $\sigma_{\max}(F)$ and $\sigma_{\min}(F)$ these pointwise estimates yield the desired result. \blacksquare

The following is the generalization of Lemma 2.1 to systems of polynomials.

Lemma 2.2. *Let $D = (d_1, \dots, d_{n-1}) \in \mathbb{N}^{n-1}$. For all $i \in \{1, \dots, n-1\}$ let $E_i \subseteq H_{d_i}$ be non-degenerate linear subspaces, and let $E := (E_1, \dots, E_{n-1})$. For each i , let p_i be chosen from E_i via a distribution satisfying the Centering Property, the Sub-Gaussian Property with constant K , and the Small Ball Property with constant c_0 (each with respect to the Bombieri-Weyl inner product). Then, for the random polynomial system $P = (p_1, \dots, p_{n-1})$, and all $v \in S^{n-1}$, the following estimates hold:*

$$\text{Prob}(\|P(v)\|_2 \geq t\sigma_{\max}(E)\sqrt{n-1}) \leq \exp\left(1 - \frac{a_1 t^2(n-1)}{K^2}\right)$$

$$\text{and} \quad \text{Prob}(\|P(v)\|_2 \leq \varepsilon\sigma_{\min}(E)\sqrt{n-1}) \leq (a_2 c_0 \varepsilon)^{n-1},$$

where a_1 and a_2 are absolute constants.

For the proof of Lemma 2.2 we need to recall some theorems from probability theory and some basic tools developed in our earlier work [13]. These basic lemmata will also be used throughout the paper. We start with a theorem which is reminiscent of Hoeffding's classical inequality [14].

Theorem 2.3 ([32, Prop. 5.10]). *There is an absolute constant $\tilde{c}_1 > 0$ with the following property: If X_1, \dots, X_n are centered, sub-Gaussian random variables with constant K , $a = (a_1, \dots, a_n) \in \mathbb{R}^n$ and $t \geq 0$, then*

$$\text{Prob}\left(\left|\sum_i a_i X_i\right| \geq t\right) \leq 2 \exp\left(\frac{-\tilde{c}_1 t^2}{K^2 \|a\|_2^2}\right). \quad \blacksquare$$

We will also need the following standard lemma (see, e.g., [22, Lemma 2.2]).

Lemma 2.4. *Assume Z_1, \dots, Z_n are independent random variables that have the property that $F(Z_i, t) \leq c_0 t$ for all $t > 0$. Then for $t > 0$ we have $F(W, t\sqrt{n}) \leq (cc_0 t)^n$, where $W := \|(Z_1, \dots, Z_n)\|_2$. Moreover, if ξ_1, \dots, ξ_k are independent random variables such that, for every $\varepsilon > 0$, we have $\text{Prob}(|\xi_i| \leq \varepsilon) \leq c_0 \varepsilon$. Then there is a universal constant $\tilde{c} > 0$ such that for every $\varepsilon > 0$ we have*

$$\text{Prob} \left(\sqrt{\xi_1^2 + \dots + \xi_k^2} \leq \varepsilon \sqrt{k} \right) \leq (\tilde{c} c_0 \varepsilon)^k. \quad \blacksquare$$

Now that we have our basic probabilistic tools we proceed to deriving some deterministic inequalities.

Lemma 2.5 was proved in our earlier paper [13], generalizing a classical Theorem of Kellogg [15]. To state the lemma we need a bit of terminology: For any system of homogenous polynomials $P := (p_1, \dots, p_{n-1}) \in (\mathbb{R}[x_1, \dots, x_n])^{n-1}$ define $\|P\|_\infty := \sup_{x \in S^{n-1}} \sqrt{\sum_{i=1}^{n-1} p_i(x)^2}$. Let $DP(x)$ denote the Jacobian matrix of the polynomial system at point x , let $DP(x)(u)$ denote the image of the vector u under the linear operator $DP(x)$, and set $\|D^{(1)}P\|_\infty := \sup_{x, u \in S^{n-1}} \|DP(x)(u)\|_2$. (Alternatively, the last quantity can be written $\sup_{x, u \in S^{n-1}} \sqrt{\sum_{i=1}^{n-1} \langle \nabla p_i(x), u \rangle^2}$.)

Lemma 2.5. *Let $P := (p_1, \dots, p_{n-1}) \in (\mathbb{R}[x_1, \dots, x_n])^{n-1}$ be a polynomial system with p_i homogenous of degree d_i for each i and set $d := \max_i d_i$. Then:*

- (1) *We have $\|D^{(1)}P\|_\infty \leq d^2 \|P\|_\infty$ and, for any mutually orthogonal $x, y \in S^{n-1}$, we also have $\|DP(x)(y)\|_2 \leq d \|P\|_\infty$.*
- (2) *If $\deg(p_i) = d$ for all $i \in \{1, \dots, n-1\}$ then we also have $\|D^{(1)}P\|_\infty \leq d \|P\|_\infty$. \blacksquare*

The final lemma we need is a discretization tool for homogenous polynomial systems that was developed in [13] based on Lemma 2.5. We need a bit of terminology to state the lemma.

Definition 2.6. Let K be a compact set in a metric space (X, d) , then a set $A \subseteq K$ with finitely many elements is called a δ -net if for every $x \in K$ there exists $y \in A$ with $d(x, y) \leq \delta$. \diamond

For the unit sphere in \mathbb{R}^n , equipped with the standard Euclidean metric, there are known bounds for the size of a δ -net. We recall one such bound below.

Lemma 2.7. *Let S^{n-1} be the unit sphere in \mathbb{R}^n with respect to standard Euclidean metric. Then for every $\delta > 0$, there exist a δ -net $\mathcal{N} \subset S^{n-1}$ with size at most $2n(1 + \frac{2}{\delta})^{n-1}$.*

Lemma 2.7 is almost folklore: a proof appears in Proposition 2.1 of [23].

Lemma 2.8. *Let $P = (p_1, \dots, p_{n-1})$ be a system of homogenous polynomials p_i with n variables and $\deg(p_i) = d_i$. Let \mathcal{N} be a δ -net on S^{n-1} . Let $\max_{\mathcal{N}}(P) = \sup_{y \in \mathcal{N}} \|P(y)\|_2$ and $\|P\|_\infty = \sup_{x \in S^{n-1}} \|P(x)\|_2$. Similarly let us define,*

$$\max_{\mathcal{N}^{k+1}}(D^{(k)}P) = \sup_{x, u_1, \dots, u_k \in \mathcal{N}} \left\| D^{(k)}P(x)(u_1, \dots, u_k) \right\|_2$$

$$\text{and} \quad \|D^{(k)}P\|_\infty = \sup_{x, u_1, \dots, u_k \in S^{n-1}} \left\| D^{(k)}P(x)(u_1, \dots, u_k) \right\|_2.$$

Then

- (1) When $\deg(p_i) = d$ for all $i \in \{1, \dots, m\}$ we have $\|P\|_\infty \leq \frac{\max_{\mathcal{N}}(P)}{1-d\delta}$ and $\|D^{(k)}P\|_\infty \leq \frac{\max_{\mathcal{N}^{k+1}}(D^{(k)}P)}{1-\delta d\sqrt{k+1}}$.
- (2) When $\max_i\{\deg(p_i)\} \leq d$ we have $\|P\|_\infty \leq \frac{\max_{\mathcal{N}}(P)}{1-d^2\delta}$ and $\|D^{(k)}P\|_\infty \leq \frac{\max_{\mathcal{N}^{k+1}}(D^{(k)}P)}{1-\delta d^2\sqrt{k+1}}$. ■

Proof of Lemma 2.2. We begin with the first claim. Using Lemma 2.1 and the fact that $\sigma_{\max}(E) \geq \sigma_{\max}(E_i)$ for all i , we get the following estimate for any $p_i \in E_i$ and $w \in S^{n-1}$:

$$\text{Prob}(|p_i(w)| \geq s\sigma_{\max}(E)) \leq \exp\left(1 - \frac{s^2}{K^2}\right).$$

Now let $a = (a_1, \dots, a_{n-1}) \in \mathbb{R}^{n-1}$ with $\|a\|_2 = 1$, and apply Lemma 2.3 to the sub-Gaussian random variables $\frac{p_i(w)}{\sigma_{\max}(E)}$ and the vector a . We then get

$$\text{Prob}\left(\left|\sum_i a_i p_i(w)\right| \geq s\sigma_{\max}(E)\right) \leq \exp\left(1 - \frac{\tilde{c}_1 s^2}{K^2}\right).$$

Observe that $\|P(w)\|_2 = \max_{a \in S^{n-2}} |\langle a, P(w) \rangle|$. For any fixed point $w \in S^{n-1}$ and a free variable $a \in \mathbb{R}^n$, we have that $\langle a, P(w) \rangle$ is a linear polynomial on a . We then use Lemma 2.8 on this linear polynomial, which gives us the following estimate:

$$\text{Prob}\left(\|P(w)\|_2 \geq \frac{s\sigma_{\max}(E)}{1-\delta}\right) \leq |\mathcal{N}| \exp\left(1 - \frac{\tilde{c}_1 s^2}{K^2}\right).$$

We then use Lemma 2.7 to control the cardinality of the δ -net and get

$$|\mathcal{N}| \leq 2n(1 + \frac{2}{\delta})^{n-1} \leq e^{(n-1)\tilde{c} \log(\frac{1}{\delta})},$$

for some absolute constant \tilde{c} . So we set $t = 2s\sqrt{n-1}$, $\delta = \frac{1}{2}$, and obtain the following estimate for some universal constant a_1 :

$$\text{Prob}\left(\|P(w)\|_2 \geq t\sigma_{\max}(E)\sqrt{n-1}\right) \leq \exp\left(1 - \frac{a_1 t^2 (n-1)}{K^2}\right).$$

We continue with the proof of the second claim. Using Lemma 2.1 and the fact that $\sigma_{\min}(E) \leq \sigma_{\min}(E_i)$ for all i , we deduce the following estimate for all p_i and for any $\varepsilon > 0$:

$$\text{Prob}\left(\left|\frac{p_i(w)}{\sigma_{\min}(E)}\right| \leq \varepsilon\right) \leq c_0 \varepsilon.$$

Using Lemma 2.4 on the random variables $\left|\frac{p_i(w)}{\sigma_{\min}(E)}\right|$ gives the following estimate:

$$\text{Prob}\left(\|P(w)\|_2 \leq \varepsilon\sigma_{\min}(E)\sqrt{n-1}\right) \leq (\tilde{c}_2 c_0 \varepsilon)^{n-1}. ■$$

3. OPERATOR NORM TYPE ESTIMATES

In this section we will estimate the absolute maximum norm of a random polynomial system on the sphere. Recall that for a homogenous polynomial system $P = (p_1, \dots, p_{n-1})$ the sup-norm is defined as $\|P\|_\infty = \sup_{x \in S^{n-1}} \|P(x)\|_2$. Lemma 3.1 is our sup-norm estimate for a random polynomial system P .

Lemma 3.1. *Let $D = (d_1, \dots, d_{n-1})$ be a vector with positive integer coordinates, let $E_i \subseteq H_{d_i}$ be full linear subspaces, and let $E = (E_1, \dots, E_{n-1})$. Let $p_i \in E_i$ be independent random elements of E_i that satisfy the Centering Property, the Sub-Gaussian Property with constant K , and the Small Ball Property with constant c_0 , each with respect to Bombieri-Weyl inner product. Let \mathcal{N} be a δ -net on S^{n-1} . Then for $P = (p_1, \dots, p_{n-1})$ we have*

$$\text{Prob} \left(\max_{x \in \mathcal{N}} \|P(x)\|_2 \geq t \sigma_{\max}(E) \sqrt{n} \right) \leq |\mathcal{N}| \exp \left(1 - \frac{a_1 t^2 n}{K^2} \right),$$

where a_1 is a universal constant. In particular, for $d = \max_i \deg(p_i)$, $\delta = \frac{1}{3d^2}$, and $t = s \log(ed)$ with $s \geq 1$ this gives us the following estimate

$$\text{Prob} \left(\|P\|_\infty \geq s \sigma_{\max}(E) \sqrt{n} \log(ed) \right) \leq \exp \left(1 - \frac{a_3 s^2 n \log(ed)^2}{K^2} \right),$$

where a_3 is a universal constant.

Proof. The first statement is proven by just taking a union bound over \mathcal{N} and using Lemma 2.2. The second part of the statement immediately follows by using the first part and Lemma 2.8. \blacksquare

4. SMALL BALL TYPE ESTIMATES

We define the following quantity for later convenience.

$$\mathcal{L}(x, y) := \sqrt{\|\Delta_m^{-1} D^{(1)} P(x)(y)\|_2^2 + \|P(x)\|_2^2}.$$

It follows directly that

$$\frac{\|P\|_W}{\tilde{\kappa}(P, x)} = \sqrt{\|P\|_W^2 \tilde{\mu}_{\text{norm}}(P, x)^{-2} + \|P(x)\|_2^2} = \inf_{\substack{y \perp x \\ y \in S^{n-1}}} \mathcal{L}(x, y).$$

So we set $L(P, x) = \frac{\|P\|_W}{\tilde{\kappa}(P, x)}$ and $L(P) = \min_{x \in S^{n-1}} L(P, x)$. We then have the following equalities:

$$L(P, x) = \inf_{\substack{y \perp x \\ y \in S^{n-1}}} \mathcal{L}(x, y), \quad \tilde{\kappa}(P, x) = \frac{\|P\|_W}{L(P, x)}$$

and, finally

$$\tilde{\kappa}(P) = \frac{\|P\|_W}{L(P)}.$$

In this section, we prove a Small Ball type estimate to control behavior of the denominator $L(p)$. We first need to recall a technical lemma from our earlier paper [13], which builds on an idea of Nguyen [20].

Lemma 4.1. *Let $n \geq 2$, let $P := (p_1, \dots, p_{n-1})$ be a system of n -variate homogenous polynomials, and assume $\|P\|_\infty \leq \gamma$. Let $x, y \in S^{n-1}$ be mutually orthogonal vectors with $\mathcal{L}(x, y) \leq \alpha$, and let $r \in [-1, 1]$. Then for every w with $w = x + \beta ry + \beta^2 z$ for some $z \in B_2^n$, we have the following inequalities:*

- (1) *If $d := \max_i d_i$ and $0 < \beta \leq d^{-4}$ then $\|P(w)\|_2^2 \leq 8(\alpha^2 + (2 + e^4)\beta^4 d^4 \gamma^2)$.*
- (2) *If $\deg(p_i) = d$ for all $i \in [n-1]$ and $0 < \beta \leq d^{-2}$ then*

$$\|P(w)\|_2^2 \leq 8(\alpha^2 + (2 + e^4)\beta^4 d^4 \gamma^2).$$

\blacksquare

We also need to state and prove the following simple Lemma for the clarity of succeeding proofs.

Lemma 4.2. *Let $n \geq 1$ be an integer. Then for $0 \leq x \leq \frac{1}{n}$ we have $(1+x)^n \leq 1 + 3nx$.*

Proof. For every $0 \leq y \leq 1$ we have $1 + 3y \geq e^y$. This can be seen by setting $f(y) = 1 + 3y - e^y$, observing $f'(y) > 0$ for all $0 \leq y \leq 1$ and $f(1) > 0$, $f(0) = 0$. With a similar reasoning one can prove $e^x \geq 1 + x$, and hence $e^{nx} \geq (1+x)^n$ for all $0 \leq x \leq 1$. Using $y = nx$ completes the proof. \blacksquare

Theorem 4.3. *Let $D = (d_1, \dots, d_{n-1})$ be a vector with positive integer coordinates, let $E_i \subseteq H_{d_i}$ be full linear subspaces, and let $E = (E_1, \dots, E_{n-1})$. Let $p_i \in E_i$ be independent random elements of E_i that satisfy the Centering Property, the Sub-Gaussian Property with constant K , and the Small Ball Property with constant c_0 , each with respect to Bombieri-Weyl inner product. Let $\gamma \geq 1$, $d := \max_i d_i$, and assume $\alpha \leq \min\{d^{-8}, n^{-1}\}$. Then for $P = (p_1, \dots, p_{n-1})$ we have*

$$\text{Prob}(L(P) \leq \alpha) \leq \text{Prob}(\|P\|_\infty \geq \gamma) + c\alpha^{\frac{1}{2}}\sqrt{n} \left(\frac{c_0 d^2 \gamma C}{\sigma_{\min}(E)\sqrt{n}} \right)^{n-1},$$

where C is a universal constant.

The proof of Theorem 4.3 is similar to a proof in our earlier paper [13]. We reproduce the proof here due to the importance of Theorem 4.3 in the flow of our current paper.

Proof. We assume the hypotheses of Assertion (1) in Lemma 4.1: Let $\alpha, \gamma > 0$ and $\beta \leq d^{-4}$. Let $\mathbf{B} := \{P \mid \|P\|_\infty \leq \gamma\}$ and let

$$\mathbf{L} := \{P \mid L(P) \leq \alpha\} = \{P \mid \text{There exist } x, y \in S^{n-1} \text{ with } x \perp y \text{ and } \mathcal{L}(x, y) \leq \alpha\}.$$

Let $\Gamma := 8(\alpha^2 + (2 + e^4)\beta^4 d^4 \gamma^2)$ and let B_2^n denote the unit ℓ_2 -ball in \mathbb{R}^n .

Lemma 4.1 implies that if the event $\mathbf{B} \cap \mathbf{L}$ occurs then there exists a non-empty set

$$V_{x,y} := \{w \in \mathbb{R}^n : w = x + \beta ry + \beta^2 z, x \perp y, |r| \leq 1, z \perp y, z \in B_2^n\} \setminus B_2^n$$

such that $\|P(w)\|_2^2 \leq \Gamma$ for every w in this set. Let $V := \text{Vol}(V_{x,y})$. Note that for $w \in V_{x,y}$ we have $\|w\|_2^2 = \|x + \beta^2 z\|_2^2 + \|\beta y\|_2^2 \leq 1 + 4\beta^2$. Hence we have $\|w\|_2 \leq 1 + 2\beta^2$. Since $V_{x,y} \subseteq (1 + 2\beta^2)B_2^n \setminus B_2^n$, we have showed that

$$\mathbf{B} \cap \mathbf{L} \subseteq \{P \mid \text{Vol}(\{x \in (1 + 2\beta^2)B_2^n \setminus B_2^n \mid \|P(x)\|_2^2 \leq \Gamma\}) \geq V\}.$$

Using Markov's Inequality, Fubini's Theorem, and Lemma 2.2, we can estimate the probability of this event. Indeed,

$$\text{Prob}(\text{Vol}(\{x \in (1 + 2\beta^2)B_2^n \setminus B_2^n : \|P(x)\|_2^2 \leq \Gamma\}) \geq V)$$

$$\begin{aligned} &\leq \frac{1}{V} \mathbb{E} \text{Vol}(\{x \in (1 + 2\beta^2)B_2^n \setminus B_2^n : \|P(x)\|_2^2 \leq \Gamma\}) \\ &\leq \frac{1}{V} \int_{(1+2\beta^2)B_2^n \setminus B_2^n} \text{Prob}(\|P(x)\|_2^2 \leq \Gamma) dx \\ &\leq \frac{\text{Vol}((1 + 2\beta^2)B_2^n \setminus B_2^n)}{V} \max_{x \in (1+2\beta^2)B_2^n \setminus B_2^n} \text{Prob}(\|P(x)\|_2^2 \leq \Gamma). \end{aligned}$$

Now recall that $\text{Vol}(B_2^n) = \frac{\pi^{n/2}}{\Gamma(\frac{n}{2}+1)}$. Then $\frac{\text{Vol}(B_2^n)}{\text{Vol}(B_2^{n-1})} \leq \frac{c'}{\sqrt{n}}$ for some constant $c' > 0$. If we assume that $\beta^2 \leq \frac{1}{2n}$, then Lemma 4.2 implies $(1+2\beta^2)^n \leq 1+6n\beta^2$, and we obtain

$$\frac{\text{Vol}((1+2\beta^2)B_2^n \setminus B_2^n)}{V} \leq \frac{\text{Vol}(B_2^n)((1+2\beta^2)^n - 1)}{\beta(\beta^2)^{n-1}\text{Vol}(B_2^{n-1})} \leq c\sqrt{n}\beta\beta^{2-2n},$$

for some absolute constant $c > 0$. Note that here, for a lower bound on V , we used the fact that $V_{x,y}$ contains more than half of a cylinder with base having radius β^2 and height 2β .

Writing $\tilde{x} := \frac{x}{\|x\|_2}$ for any $x \neq 0$ we then obtain, for $z \notin B_2^n$, that

$$\|P(z)\|_2^2 = \sum_{j=1}^m |p_j(z)|^2 = \sum_{j=1}^m |p_j(\tilde{z})|^2 \|z\|_2^{2d_j} \geq \sum_{j=1}^m |p_j(\tilde{z})|^2 = \|P(\tilde{z})\|_2^2.$$

This implies, via Lemma 2.2, that for every $w \in (1+2\beta^2)B_2^n \setminus B_2^n$ we have

$$\text{Prob}(\|P(w)\|_2^2 \leq \Gamma) \leq \text{Prob}(\|P(\tilde{w})\|_2^2 \leq \Gamma) \leq \left(c c_0 \sqrt{\frac{\Gamma}{n\sigma_{\min}(E)^2}} \right)^{n-1}.$$

So we conclude that $\text{Prob}(\mathbf{B} \cap \mathbf{L}) \leq c\sqrt{n}\beta^{3-2n} \left(c c_0 \sqrt{\frac{\Gamma}{n\sigma_{\min}(E)^2}} \right)^{n-1}$. Since $\text{Prob}(L(P) \leq \alpha) \leq \text{Prob}(\|P\|_\infty \geq \gamma) + \text{Prob}(\mathbf{B} \cap \mathbf{L})$ we then have

$$\text{Prob}(L(P) \leq \alpha) \leq \text{Prob}(\|P\|_\infty \geq \gamma) + c\sqrt{n}\beta^{3-2n} \left(c c_0 \sqrt{\frac{\Gamma}{n\sigma_{\min}(E)^2}} \right)^{n-1}.$$

Recall that $\Gamma = 8(\alpha^2 + (5+e^4)\beta^4 d^4 \gamma^2)$. We set $\beta^2 := \alpha$. Our choice of β and the assumption that $\gamma \geq 1$ then imply that $\Gamma \leq C\alpha^2\gamma^2 d^4$ for some constant C . So we obtain

$$\text{Prob}(L(P) \leq \alpha) \leq \text{Prob}(\|P\|_\infty \geq \gamma) + c\sqrt{n}(\alpha)^{\frac{3}{2}-n} \left(\frac{c_0 C \alpha d^2 \gamma}{\sigma_{\min}(E) \sqrt{n}} \right)^{n-1}$$

$$\text{Prob}(L(P) \leq \alpha) \leq \text{Prob}(\|P\|_\infty \geq \gamma) + c\sqrt{n}(\alpha)^{\frac{1}{2}} \left(\frac{c_0 d^2 \gamma C}{\sigma_{\min}(E) \sqrt{n}} \right)^{n-1}$$

and our proof is complete. ■

5. PROOF OF THEOREM 1.14

We first need to estimate Bombieri norm of a random polynomial system. Lemma 5.1 is more or less standard, and it follows from Lemma 2.3.

Lemma 5.1. *Let $D = (d_1, \dots, d_{n-1})$ be a vector with positive integer coordinates, let $E_i \subseteq H_{d_i}$ be full linear subspaces, and let $E = (E_1, \dots, E_{n-1})$. Let $p_i \in E_i$ be random elements of E_i that satisfy the Centering Property and the Sub-Gaussian Property with constant K , each with respect to Bombieri-Weyl inner product. Then for all $t \geq 1$, we have*

$$\text{Prob} \left(\|p_i\|_W \geq t\sqrt{\dim(E_i)} \right) \leq \exp \left(1 - \frac{t^2 \dim(E_i)}{K^2} \right)$$

and for the random polynomial system $P = (p_1, \dots, p_{n-1})$ we have

$$\text{Prob} \left(\|P\|_W \geq t\sqrt{\dim(E)} \right) \leq \exp \left(1 - \frac{t^2 \dim(E)}{K^2} \right). \quad \blacksquare$$

Now we have all the necessary tools to prove our probabilistic condition number theorem. We will prove the following statement:

Theorem 5.2. *Let $D = (d_1, \dots, d_{n-1})$ be a vector with positive integer coordinates, let $E_i \subseteq H_{d_i}$ be non-degenerate linear subspaces, and let $E = (E_1, \dots, E_{n-1})$. We assume that $\dim(E) \geq n \log(ed)$ and $n \geq 3$. Let $p_i \in E_i$ be independent random elements of E_i that satisfy the Centering Property, the Sub-Gaussian Property with constant K , and the Small Ball Property with constant c_0 , each with respect to the Bombieri-Weyl inner product. We set $d := \max_i d_i$, and*

$$M := nK\sqrt{\dim(E)}(c_0d^2CK\log(ed)^2\sigma(E))^{2n-2},$$

where $C \geq 4$ is a universal constant. Then for $P = (p_1, \dots, p_{n-1})$, we have

$$\text{Prob}(\tilde{\kappa}(P) \geq tM) \leq \begin{cases} \frac{3}{\sqrt{t}} & ; \text{if } 1 \leq t \leq e^{2n \log(ed)} \\ \frac{e^2+1}{\sqrt{t}} \left(\frac{\log t}{2n \log(ed)} \right)^{\frac{n}{2}} & ; \text{if } e^{2n \log(ed)} \leq t. \end{cases}$$

For notational simplicty we set $m = \dim(E)$. To start the proof we observe the following:

$$\text{Prob}(\tilde{\kappa}(P) \geq tM) \leq \text{Prob}(\|P\|_W \geq sK\sqrt{m}) + \text{Prob}\left(L(P) \leq \frac{sK\sqrt{m}}{tM}\right).$$

The first probability on the right hand side will be controlled by Lemma 5.1, and the second will be controlled by Theorem 4.3. Theorem 4.3 states that for any $\gamma \geq 1$ and for $\frac{sK\sqrt{m}}{tM} \leq \min\{d^{-8}, n^{-1}\}$, we have

$$\text{Prob}\left(L(P) \leq \frac{sK\sqrt{m}}{tM}\right) \leq \text{Prob}(\|P\|_\infty \geq \gamma) + \left(\frac{sK\sqrt{m}}{tM}\right)^{\frac{1}{2}} \sqrt{n} \left(\frac{c_0C\gamma d^2}{\sigma_{\min}(E)\sqrt{n}}\right)^{n-1}.$$

To have $\frac{sK\sqrt{m}}{tM} \leq \min\{d^{-8}, n^{-1}\}$ is equivalent to $tM \min\{d^{-8}, n^{-1}\} \geq sK\sqrt{m}$. We will check this condition at the end of the proof. Now, for $\gamma = u\sigma_{\max}(E)\sqrt{n}\log(ed)K$ with $u \geq 1$, from Lemma 3.1 we have $\text{Prob}(\|P\|_\infty \geq u\sigma_{\max}(E)\sqrt{n}\log(ed)K) \leq \exp(1 - a_3u^2n\log(ed)^2)$. That is, for $\gamma = u\sigma_{\max}(E)\sqrt{n}\log(ed)K$, we have the following estimate:

$$\begin{aligned} \text{Prob}\left(L(P) \leq \frac{sK\sqrt{m}}{tM}\right) &\leq \exp(1 - a_3u^2n\log(ed)^2) \\ &\quad + \left(\frac{sK\sqrt{m}}{tM}\right)^{\frac{1}{2}} \sqrt{n} \left(\frac{c_0Cu\sigma_{\max}(E)\log(ed)d^2K}{\sigma_{\min}(E)}\right)^{n-1}. \end{aligned}$$

Since $\sigma(E) = \frac{\sigma_{\max}(E)}{\sigma_{\min}(E)}$ and $M = n\sqrt{n}K(c_0C\log(ed)d^2K\sigma(E))^{2n-2}$, we have

$$\text{Prob}\left(L(P) \leq \frac{sK\sqrt{m}}{tM}\right) \leq \exp(1 - a_3u^2n\log(ed)) + \left(\frac{s}{t}\right)^{\frac{1}{2}} u^{n-1}.$$

Using Lemma 5.1 and the assumption that $m \geq n \log(ed)$ we then obtain

$$\text{Prob}(\tilde{\kappa}(P) \geq tM) \leq \exp(1 - s^2n\log(ed)^2) + \exp(1 - a_3u^2n\log(ed)) + \left(\frac{s}{t}\right)^{\frac{1}{2}} u^{n-1}.$$

If $t \leq e^{2n \log(ed)}$ then setting $s = u = 1$ gives the desired inequality. If $t \geq e^{2n \log(ed)}$ then we set $s = u^2 = \frac{\log(t)}{2\tilde{a}n \log(ed)}$, where $\tilde{a} > a_3 > 0$ is a constant greater than 1. We then obtain

$$\text{Prob}(\tilde{\kappa}(P) \geq tM) \leq \exp\left(2 - \frac{1}{2} \log(t)\right) + \left(\frac{\log(t)}{2n \log(ed)}\right)^{\frac{n}{2}} \frac{1}{\sqrt{t}}.$$

Observe that $\exp(2 - \frac{1}{2} \log t) = \frac{e^2}{\sqrt{t}}$. So we have

$$\text{Prob}(\tilde{\kappa}(P) \geq tM) \leq \left(\frac{\log(t)}{2n \log(ed)}\right)^{\frac{n}{2}} \frac{e^2 + 1}{\sqrt{t}}.$$

To finalize our proof we need to check if $tM \min\{d^{-8}, n^{-1}\} \geq sK\sqrt{m}$. So we check the following:

$$tKn\sqrt{m}(c_0C \log(ed)d^2K\sigma(E))^{2n-2} \min\{d^{-8}, n^{-1}\} \stackrel{?}{\geq} \frac{\log(t)}{2n \log(ed)}K\sqrt{m}.$$

For $n \geq 3$ we have $(d^2 \log(ed))^{2n-2} > d^8$. Since $Kc_0 \geq \frac{1}{4}$, $C \geq 4$, and $\sigma(E) \geq 1$, we have

$$(c_0C \log(ed)d^2K\sigma(E))^{2n-2} > d^8.$$

Hence, it suffices to check if $t \geq \frac{\log(t)}{2n \log(ed)}$, which is clear.

We would like to complete the proof of Theorem 1.14 as it was stated in the introduction, for which the following easy observation suffices.

Lemma 5.3. *For $t \geq e^{2n \log(ed)}$, we have $\left(\frac{\log(t)}{2n \log(ed)}\right)^{\frac{n}{2}} \leq t^{\frac{1}{4 \log(ed)}}$.*

Proof. Let $t = xe^{2n \log(ed)}$ where $x \geq 1$. Then

$$\left(\frac{\log(t)}{2n \log(ed)}\right)^{\frac{n}{2}} = \left(1 + \frac{\log(x)}{2n \log(ed)}\right)^{\frac{n}{2}} \leq e^{\frac{\log(x)}{4 \log(ed)}} = x^{\frac{1}{4 \log(ed)}}.$$

Since $x \leq t$, we are done. ■

We now state the resulting bounds on the expectation of the condition number.

Corollary 5.4. *Under the assumptions of Theorem 5.2, $0 < q < \frac{1}{2} - \frac{1}{2 \log(ed)}$ implies that $\mathbb{E}(\tilde{\kappa}(P)^q) \leq M^q(1 + 4q \log(ed))$. In particular, $\mathbb{E} \log(\tilde{\kappa}(P)) \leq 1 + \log M$.*

Proof. Observe that

$$\mathbb{E}(\tilde{\kappa}(P)^q) = M^q + qM^q \int_{t=1}^{\infty} \mathbb{P}\{\tilde{\kappa}(P) \geq tM\} t^{q-1} dt.$$

For $t \geq e^{2n \log(ed)}$, we have

$$\mathbb{P}\{\tilde{\kappa}(P) \geq tM\} t^{q-1} \leq t^{q + \frac{1}{4 \log(ed)} - \frac{3}{2}} \leq t^{-1 - \frac{1}{4 \log(ed)}}.$$

For $t \leq e^{2n \log(ed)}$ we have even stronger tail bounds:

$$\mathbb{E}(\tilde{\kappa}(P)^q) \leq M^q \left(1 + q \int_{t=1}^{\infty} t^{-1 - \frac{1}{4 \log(ed)}} dt\right).$$

This proves the first claim. The second claim follows by sending $q \rightarrow 0$ and using Jensen's inequality. ■

6. PROOF OF THEOREM 1.16

Let $E_i \subseteq H_{d_i}$ be non-degenerate linear spaces, and let $E = (E_1, \dots, E_{n-1})$. Suppose $Q \in E$ is a fixed polynomial system. Let $g_i \in E_i$ be independent random elements of E_i that satisfy the Centering Property, the Sub-Gaussian Property with constant K , and the Anti-Concentration Property with constant c_0 , each with respect to the Bombieri-Weyl inner product. Let $G := (g_1, \dots, g_{n-1})$ be the corresponding polynomial system. We define random perturbation of Q as follows: $P := Q + G$. We will use this notation for P , Q and G for the rest of this section.

Lemma 6.1. *Let $Q \in E$ be a polynomial system, let G be a random polynomial system in E that satisfies the Centering, sub-Gaussian, and Anti-Concentration hypotheses, and let $P = Q + G$. Then we have*

$$\text{Prob}(\|P\|_\infty \geq s\sigma_{\max}(E)\sqrt{n}\log(ed) + \|Q\|_\infty) \leq \exp\left(1 - \frac{a_3 s^2 n \log(ed)}{K^2}\right),$$

where a_3 is an absolute constant.

Proof. The triangle inequality implies $\|P\|_\infty \leq \|Q\|_\infty + \|G\|_\infty$. We complete the proof by using Lemma 3.1 for the random system G . \blacksquare

Lemma 6.2. *Let $Q \in E$ be a polynomial system, let G be a random polynomial system in E that satisfies the Centering, sub-Gaussian, and Anti-Concentration hypotheses, and let $P = Q + G$. Then, for all $\varepsilon > 0$, and for any $w \in S^{n-1}$ we have*

$$\text{Prob}(\|P(w)\|_2 \leq \varepsilon\sigma_{\min}(E)\sqrt{n-1}) \leq (a_2 c_0 \varepsilon)^{n-1},$$

where a_2 is an absolute constant.

Proof. By the Anti-Concentration Property, for all $1 \leq i \leq n-1$, we have

$$\text{Prob}\{|g_i(w) + q_i(w)| \leq c_0 \varepsilon \sigma_{\min}(E_i)\} \leq c_0 \varepsilon.$$

We then use Lemma 2.4 with the random variables $g_i(w) + q_i(w)$. \blacksquare

Lemma 6.3. *Let $Q \in E$ be a polynomial system, let G be a random polynomial system in E that satisfies the Centering, sub-Gaussian, and Anti-Concentration hypotheses, and let $P = Q + G$. Then for all $t \geq 1$, we have*

$$\text{Prob}(\|P\|_W \geq tK\sqrt{\dim(E)} + \|Q\|_W) \leq \exp(1 - t^2 m).$$

Proof. For all $1 \leq i \leq n-1$, by triangle inequality $\|p_i\|_W \leq \|q_i\|_W + \|g_{C_i}\|_W$. So using the first claim of Lemma 5.1 gives

$$\text{Prob}(\|p_i\|_W \geq t\sqrt{\dim(E_i)} + \|q_i\|_W) \leq \exp\left(1 - \frac{t^2 \dim(E_i)}{K^2}\right).$$

Note that $\|P\|_W = \max_{\|w\|_2=1} \text{abs}(w, (p_1, \dots, p_{n-1}))$. So proceeding as in the proof of Lemma 2.2 completes the proof. \blacksquare

Theorem 6.4. *Let $Q \in E$ be a polynomial system, let G be a random polynomial system in E that satisfies the Centering, sub-Gaussian, and Anti-Concentration hypotheses, and let $P = Q + G$. Now let $\gamma \geq 1$, $d := \max_i d_i$, and assume $\alpha \leq \min\{d^{-8}, n^{-1}\}$. Then*

$$\text{Prob}(L(P) \leq \alpha) \leq \text{Prob}(\|P\|_\infty \geq \gamma) + c\alpha^{\frac{1}{2}}\sqrt{n} \left(\frac{c_0 d^2 \gamma C}{\sigma_{\min}(E)\sqrt{n}}\right)^{n-1},$$

where C is a universal constant.

The proof of Theorem 6.4 is identical to Theorem 4.3, so we skip it. Now we are ready to state main theorem of this section.

Theorem 6.5. *Let $Q \in E$ be a polynomial system, let G be a random polynomial system in E that satisfies the Centering, sub-Gaussian, and Anti-Concentration hypotheses, and let $P = Q + G$. Also let $d := \max_i d_i$, and set*

$$M = nK\sqrt{\dim(E)} (c_0 d^2 C K \log(ed) \sigma(E))^{2n-2} \left(1 + \frac{\|Q\|_W}{\sqrt{nK \log(ed)}}\right)^{2n-1},$$

where $C \geq 4$ is a universal constant. Assume also that $\dim(E) \geq n \log(ed)^2$ and $n \geq 3$. Then

$$\text{Prob}(\tilde{\kappa}(P) \geq tM) \leq \begin{cases} \frac{3}{\sqrt{t}} & ; \text{if } 1 \leq t \leq e^{2n \log(ed)} \\ \frac{e^2 + 1}{\sqrt{t}} \left(\frac{\log t}{2n \log(ed)}\right)^{\frac{n}{2}} & ; \text{if } e^{2n \log(ed)} \leq t. \end{cases}$$

Proof. We need a quick observation before we start our proof: For any $Q \in E$ and $w \in S^{n-1}$, we have $\|Q(w)\|_2^2 \leq \sum_{i=1}^{n-1} \|q_i\|_W^2 \sigma_{\max}(E_i)^2 \leq \|Q\|_W^2 \sigma_{\max}(E)^2$. So we have

$$\|Q\|_\infty \leq \|Q\|_W \sigma_{\max}(E).$$

Using this upper bound on $\|Q\|_\infty$ and the assumption that $\dim(E) \geq n \log(ed)^2$, we deduce

$$\begin{aligned} M &\geq nK\sqrt{\dim(E)} (c_0 d^2 C K \log(ed) \sigma(E))^{2n-2} \\ &\times \left(1 + \frac{\|Q\|_W}{nK\sqrt{\dim(E)}}\right) \left(1 + \frac{\|Q\|_\infty}{\sqrt{n} \log(ed) K \sigma_{\max}(E)}\right)^{2n-2}. \end{aligned}$$

We will use this lower bound on M later in our proof. Now let $m = \dim(E)$. We start our proof with the following observation:

$$\begin{aligned} \text{Prob}(\tilde{\kappa}(P) \geq tM) &\leq \text{Prob}(\|P\|_W \geq sK\sqrt{m} + \|Q\|_W) \\ &+ \text{Prob}\left(L(P) \leq \frac{sK\sqrt{m} + \|Q\|_W}{tM}\right). \end{aligned}$$

Lemma 6.3 states that

$$\text{Prob}(\|P\|_W \geq sK\sqrt{m} + \|Q\|_W) \leq \exp(1 - s^2 m).$$

Theorem 6.4 states that for $\frac{sK\sqrt{m} + \|Q\|_W}{tM} \leq \min\{d^{-8}, n^{-1}\}$ we have

$$\begin{aligned} \text{Prob}\left(L(P) \leq \frac{sK\sqrt{m} + \|Q\|_W}{tM}\right) \\ \leq \text{Prob}(\|P\|_\infty \geq \gamma) + c\left(\frac{sK\sqrt{m} + \|Q\|_W}{tM}\right)^{\frac{1}{2}} \sqrt{n} \left(\frac{c_0 d^2 \gamma C}{\sigma_{\min}(E) \sqrt{n}}\right)^{n-1}. \end{aligned}$$

We set $\gamma = u\sigma_{\max}(E)\sqrt{n} \log(ed)K + \|Q\|_\infty$. From Lemma 6.1, we have

$$\text{Prob}(\|P\|_\infty \geq u\sigma_{\max}(E)\sqrt{n} \log(ed)K + \|Q\|_\infty) \leq \exp(1 - a_3 u^2 n \log(ed)).$$

We also have

$$\left(\frac{c_0 d^2 \gamma C}{\sigma_{\min}(E) \sqrt{n}}\right)^{n-1} = (c_0 u d^2 C K \log(ed) \sigma(E))^{n-1} \left(1 + \frac{\|Q\|_\infty}{u \sqrt{n} \log(ed) K \sigma_{\max}(E)}\right)^{n-1}.$$

Using $u \geq 1$, $s \geq 1$, $m \geq n \log(ed)^2$, and the lower obtained on M , we obtain

$$\text{Prob}(\tilde{\kappa}(P) \geq tM) \leq \exp(1 - s^2 n \log(ed)) + \exp(1 - a_3 u^2 n \log(ed)) + \left(\frac{s}{t}\right)^{\frac{1}{2}} u^{n-1}.$$

The rest of the proof is identical to the proof of Theorem 5.2. \blacksquare

7. PROOF OF THEOREM 1.18

Define a random polynomial system $F_\varepsilon = Q + G$ where G is Gaussian random polynomial system with $K = \frac{\varepsilon \|Q\|_W}{\sqrt{n \log(ed)}}$ and $c_0 K = \frac{1}{\sqrt{2\pi}}$. Using Lemma 5.1 with $t = 1$, we have with probability at least $1 - \exp(1 - \dim(E))$ that

$$\|F_\varepsilon - Q\|_W = \|G\|_W \leq \frac{\varepsilon \|Q\|_W \sqrt{\dim(E)}}{\sqrt{n \log(ed)}}.$$

For the condition estimate we will use Theorem 6.5: First note that with $K = \frac{\varepsilon \|Q\|_W}{\sqrt{n \log(ed)}}$ and $c_0 K = \frac{1}{\sqrt{2\pi}}$, the quantity M in Theorem 6.5 is the following:

$$M = \frac{\varepsilon \sqrt{n} \sqrt{\dim(E)}}{\log(ed)} \left(\frac{d^2 C \log(ed) \sigma(E)}{\sqrt{2\pi}} \right)^{2n-2} \left(1 + \frac{1}{\varepsilon} \right)^{2n-1}.$$

So we have $M \leq 2\sqrt{n} \sqrt{\dim(E)} \left(\frac{2}{\varepsilon} \right)^{2n-2} \left(\frac{d^2 C \log(ed) \sigma(E)}{\sqrt{2\pi}} \right)^{2n-2}$. Using Theorem 6.5 with $t = 36$ we deduce that with probability greater than $\frac{1}{2}$ we have

$$\tilde{\kappa}(F_\varepsilon) \leq 2\sqrt{n} \sqrt{\dim(E)} \left(\frac{d^2 C \log(ed) \sigma(E)}{\varepsilon} \right)^{2n-2}.$$

Since the union of the complement of these two events has measure less than $\frac{1}{2} + \exp(1 - \dim(E))$, their intersection has positive measure, and the proof is completed. \blacksquare

Remark 7.1. The proof of Theorem 6.4 actually works for

$$\begin{aligned} M &= nK \sqrt{\dim(E)} (c_0 d^2 C K \log(ed) \sigma(E))^{2n-2} \\ &\quad \times (1 + \|Q\|_W) \left(1 + \frac{\|Q\|_\infty}{\sqrt{n \log(ed) K \sigma_{\max}(E)}} \right)^{2n-2}, \end{aligned}$$

which is often much more smaller than the M used in the theorem statement. \diamond

8. APPENDIX: THE DISPERSION CONSTANTS OF RANDOM SUBSPACES OF POLYNOMIAL SYSTEMS

Here we address the question how big the dispersion constant is for a “typical” low-dimensional linear space. Imagine we have fixed a dimension $m \sim n \log d$ and wish to consider subspaces of dimension m inside H_d (the vector space homogenous polynomials of degree d). How does the dispersion constant vary among these subspaces? We know that some of these subspaces will be degenerate and have infinite dispersion constant. Can we argue that high dispersion constants are rare?

To address this problem, we represent the space of m -dimensional linear subspaces of H_d by the *Grassmannian variety*, $\text{Gr}(m, \dim(H_d))$, which comes equipped with a Haar measure. We will analyze the Haar measure of the set of subspaces in $\text{Gr}(m, \dim(H_d))$ that yield high dispersion constant (see Corollary 8.4).

We will first need to introduce the following notion from high-dimensional probability.

Definition 8.1 (Gaussian complexity). Let $X \subseteq \mathbb{R}^n$ be a set, then the *Gaussian complexity* of X denoted by $\gamma(X)$ is defined as follows:

$$\gamma(X) := \mathbb{E} \sup_{x \in X} |\langle G, x \rangle|,$$

where G is distributed according to standard normal distribution $\mathcal{N}(0, \mathbb{I})$ on \mathbb{R}^n . \diamond

The use of the term *complexity* in Definition 8.1 might look unorthodox to readers with a computational complexity theory background. The rationale behind this standard terminology in high-dimensional probability is that the Gaussian complexity of a set X is known to control the complexity of stochastic processes indexed on the set X (see, e.g., [30]).

A corollary of Lemma 2.1 and Lemma 2.8 is the following.

Corollary 8.2 (Gaussian complexity of the Veronese embedding). *Let H_d be the vector space of degree d homogenous polynomials in n variables. Let u_i $i = 1, \dots, \binom{n+d-1}{d}$ be an orthonormal basis for the vector space H_d with respect to the Bombieri-Weyl norm. For every $v \in S^{n-1}$, we define the following polynomial q_v :*

$$q_v(x) := \sum_i u_i(v) u_i(x)$$

and the following set created out of q_v :

$$B_d := \{q_v : v \in S^{n-1}\}.$$

Then we have $\gamma(B_d) \leq c\sqrt{n} \log(ed)$ for a universal constant c .

Proof of Corollary 8.2. We need to consider a Gaussian element G in the vector space H_d . Note that for $G \sim \mathcal{N}(0, \mathbb{I})$ in H_d we have $\left\langle G, \sqrt{\binom{d}{\alpha}} x^\alpha \right\rangle_W \sim \mathcal{N}(0, 1)$ since $\sqrt{\binom{d}{\alpha}} x^\alpha$ is an orthonormal basis with respect to the Bombieri-Weyl inner product. This means Gaussian elements of H_d are included in our model of randomness for the special case $K = 1$. Since $\sigma_{\max}(H_d) = 1$, Lemma 2.1 gives us the following estimate for pointwise evaluations of the Gaussian element $G \sim \mathcal{N}(0, \mathbb{I})$ in H_d :

$$\text{Prob}\{|G(v)| \geq t\} \leq \exp\left(1 - \frac{t^2}{2}\right).$$

Note that $\|G\|_\infty = \max_{v \in S^{n-1}} |G(v)| = \max_{q_v \in B_d} |\langle G, q_v \rangle|$. So to estimate Gaussian complexity of the Veronese embedding B_d , we need to estimate $\mathbb{E} \|G\|_\infty$. Let \mathcal{N} be a δ -net on the sphere S^{n-1} . Using a union bound, we then have

$$\text{Prob}\{\max_{v \in \mathcal{N}} |G(v)| \geq t\} \leq |\mathcal{N}| \exp\left(1 - \frac{t^2}{2}\right).$$

Setting $\delta = \frac{1}{d}$ and using Lemma 2.8 for $t \geq a_1 \sqrt{n} \log(ed)$ then gives the following:

$$\text{Prob}\{\|G\|_\infty \geq a_1 t \sqrt{n} \log(ed)\} \leq |\mathcal{N}| \exp\left(1 - \frac{a_1^2 t^2 n \log(ed)}{2}\right).$$

It is known that $|\mathcal{N}| \leq \exp(a_0 n \log d)$. So we have

$$|\mathcal{N}| \exp\left(1 - \frac{a_1^2 t^2 n \log(ed)}{2}\right) \leq \exp(1 - a_2 t^2 n \log(ed))$$

for some constant a_2 . So $\text{Prob}\{\|G\|_\infty \geq a_1 t \sqrt{n} \log(ed)\} \leq \exp(1 - a_2 t^2 n \log(ed))$. Using this inequality one can routinely derive the estimate for $\mathbb{E} \|G\|_\infty$. \blacksquare

Since Talagrand proved his celebrated “majorizing measure theorem” (see [29]) it has been observed that for a set X and a random $k \times n$ sub-Gaussian matrix A , the deviation $\sup_{x \in X} |\|Ax\|_2 - \mathbb{E}\|Ax\|_2|$ is controlled by the Gaussian complexity $\gamma(X)$. We will use a variant established in [16] but not stated explicitly:

Theorem 8.3. *Let F be a random m dimensional subspace of \mathbb{R}^n drawn from Haar measure on $\text{Gr}(m, n)$, and let P_F be orthogonal projection map on F . Let $X \subseteq \mathbb{R}^n$ be a set. Then there is a universal constant C such that*

$$\sup_{x \in X} \left| \sqrt{n} \|P_F(x)\| - \sqrt{m} \|x\| \right| \leq Ct\gamma(X), \quad t \geq 1$$

with probability greater than $1 - e^{-t^2}$.

There is a series of papers that established several variants of the preceding two deviation bounds—mainly in [16, 25] and, more recently in [12, 18]. Vershynin devoted the 9th chapter of his recent book [30] on these results and their applications. Theorem 8.3 follows easily upon combining some statements and exercises from [30, Ch. 9]. We include a sketch of the proof below for the interested reader.

Proof of Theorem 8.3. Let $x \in X$ and consider the random process $W_x := \sqrt{n}\|Px\| - \sqrt{m}\|x\|$. By [[16], Lemma 4.2, [25]] we have that W_x is a subgaussian process in X , i.e.,

$$\mathbb{P}(\|Px\| - \|Py\| \geq s\|x - y\|) \leq 2e^{-cs^2}, \quad s > 0,$$

where $c > 0$ is an absolute constant and $x, y \in X$, or equivalently

$$\|Px\| - \|Py\| \leq c\|x - y\|.$$

In [[16], Lemma 4.2], the above inequality is stated for $x, y \in S^{n-1}$. To extend it for every x, y is straightforward, and we explain the idea below (see e.g. proof of Lemma 9.1.4 in [30] or [18] for details). By scaling, without loss of generality we may assume that $\|x\| = 1, \|y\| \geq 1$. Set $\tilde{y} = \frac{y}{\|y\|}$. Note that

$$\|W_y - W_{\tilde{y}}\| = \|y - \tilde{y}\| \|W_{\tilde{y}}\|_{\psi_2} \leq C\|y - \tilde{y}\|$$

for a universal constant C . Using all the above and the triangle inequality we get that

$$\|W_x - W_y\|_{\psi_2} \leq C(\|x - \tilde{y}\| + \|y - \tilde{y}\|) \leq \sqrt{2}C\|x - y\|.$$

Now that we have established that W_x for $x \in X$ is a subgaussian process we may apply [[12] Theorem 3.2] or [[29] Theorem 2.2.27] to conclude the proof. For example the latter states that

$$\mathbb{P} \left(\sup_{x, y \in X} |W_x - W_y| \geq C(\gamma_2(X, \|\cdot\|) + s\text{diam}(X)) \right) \leq 2e^{-s^2}.$$

Here $\text{diam}(X) := \max_{x, y \in X} \|x - y\|_2$ and γ_2 is Talagrand’s functional (see [30], Definition of 8.5.1 for details). By Talagrand’s majorizing measure theorem (see e.g. [30], Theorem 8.6.1) it is known that $\gamma_2(X, \|\cdot\|) \simeq \gamma(X)$. Using the triangle inequality and the fact that $\text{diam}(X) \leq 2\gamma(X)$, we conclude that

$$\mathbb{P} \left(\sup_{x \in X} |W_x| \geq cs\gamma(X) \right) \leq 2e^{-s^2}, \quad s \geq 1.$$

■

A simple consequence of Theorem 8.3 is the following estimate on the dispersion constant of a random subspace of polynomial systems:

Corollary 8.4. *Let F be a random m dimensional subspace of H_d drawn from the Haar measure on $\text{Gr}(m, \dim(H_d))$, where $m \geq 16Cn \log(ed)^2$. Then*

$$\sigma(F) \leq \frac{\sqrt{m} + Ct\sqrt{n} \log(ed)}{\sqrt{m} - Ct\sqrt{n} \log(ed)}$$

with probability greater than $1 - e^{-t^2}$, where C is the absolute constant from Theorem 8.3.

Proof of Corollary 8.4. Since $\|q_v\|_W = 1$ for all $v \in S^{n-1}$, applying Theorem 8.3 to the set B_d implies that

$$\sup_{x \in B_d} \left| \binom{n+d-1}{d}^{\frac{1}{2}} \|\Pi_F(x)\| - \sqrt{m} \right| \leq Ct\sqrt{n} \log(ed)$$

with probability greater than $1 - e^{-t^2}$ for all $t \geq 1$. Since $\sigma_{\min}(F) = \min_{x \in B_d} \|\Pi_F(x)\|$ and $\sigma_{\max}(F) = \max_{x \in B_d} \|\Pi_F(x)\|$, we have

$$\frac{\sqrt{m} - Ct\sqrt{n} \log(ed)}{\binom{n+d-1}{d}^{\frac{1}{2}}} \leq \sigma_{\min}(F) \leq \sigma_{\max}(F) \leq \frac{\sqrt{m} + Ct\sqrt{n} \log(ed)}{\binom{n+d-1}{d}^{\frac{1}{2}}}$$

with probability greater than $1 - e^{-t^2}$. ■

REFERENCES

- [1] C. Beltrán and L. M. Pardo, *Smale's 17th problem: average polynomial time to compute affine and projective solutions*, J. Amer. Math. Soc. **22** (2009), no. 2, 363–385, DOI 10.1090/S0894-0347-08-00630-9. MR2476778
- [2] L. Blum, F. Cucker, M. Shub, and S. Smale, *Complexity and real computation*, Springer-Verlag, New York, 1998. With a foreword by Richard M. Karp, DOI 10.1007/978-1-4612-0701-6. MR1479636
- [3] P. Bürgisser and F. Cucker, *Condition*, Grundlehren der Mathematischen Wissenschaften [Fundamental Principles of Mathematical Sciences], vol. 349, Springer, Heidelberg, 2013. The geometry of numerical algorithms, DOI 10.1007/978-3-642-38896-5. MR3098452
- [4] P. Bürgisser, F. Cucker, and P. Lairez, *Computing the homology of basic semialgebraic sets in weak exponential time*, J. ACM **66** (2019), no. 1, Art. 5, 30, DOI 10.1145/3275242. [Publication date initially given as 2018]. MR3892564
- [5] P. Bürgisser, F. Cucker, and J. Tonelli-Cueto, *Computing the homology of semialgebraic sets. I: Lax formulas*, Found. Comput. Math. **20** (2020), no. 1, 71–118, DOI 10.1007/s10208-019-09418-y. MR4056926
- [6] F. Cucker, *Approximate zeros and condition numbers*, J. Complexity **15** (1999), no. 2, 214–226, DOI 10.1006/jcom.1999.0503. MR1693884
- [7] F. Cucker, A. A. Ergür, and J. Tonelli-Cueto, *Plantinga-Vegter algorithm takes average polynomial time*, ISSAC'19—Proceedings of the 2019 ACM International Symposium on Symbolic and Algebraic Computation, ACM, New York, 2019, pp. 114–121. MR4007450
- [8] F. Cucker, T. Krick, G. Malajovich, and M. Wschebor, *A numerical algorithm for zero counting. I. Complexity and accuracy*, J. Complexity **24** (2008), no. 5–6, 582–605, DOI 10.1016/j.jco.2008.03.001. MR2467589
- [9] F. Cucker, T. Krick, G. Malajovich, and M. Wschebor, *A numerical algorithm for zero counting. II. Distance to ill-posedness and smoothed analysis*, J. Fixed Point Theory Appl. **6** (2009), no. 2, 285–294, DOI 10.1007/s11784-009-0127-4. MR2580979
- [10] F. Cucker, T. Krick, G. Malajovich, and M. Wschebor, *A numerical algorithm for zero counting. III: Randomization and condition*, Adv. in Appl. Math. **48** (2012), no. 1, 215–248, DOI 10.1016/j.aam.2011.07.001. MR2845516

- [11] F. Cucker, T. Krick, and M. Shub, *Computing the homology of real projective sets*, Found. Comput. Math. **18** (2018), no. 4, 929–970, DOI 10.1007/s10208-017-9358-8. MR3833646
- [12] S. Dirksen, *Tail bounds via generic chaining*, Electron. J. Probab. **20** (2015), no. 53, 29, DOI 10.1214/EJP.v20-3760. MR3354613
- [13] A. A. Ergür, G. Paouris, and J. M. Rojas, *Probabilistic condition number estimates for real polynomial systems I: A broader family of distributions*, Found. Comput. Math. **19** (2019), no. 1, 131–157, DOI 10.1007/s10208-018-9380-5. MR3913875
- [14] W. Hoeffding, *Probability inequalities for sums of bounded random variables*, J. Amer. Statist. Assoc. **58** (1963), 13–30. MR144363
- [15] O. D. Kellogg, *On bounded polynomials in several variables*, Math. Z. **27** (1928), no. 1, 55–64, DOI 10.1007/BF01171085. MR1544896
- [16] B. Klartag and S. Mendelson, *Empirical processes and random projections*, J. Funct. Anal. **225** (2005), no. 1, 229–245, DOI 10.1016/j.jfa.2004.10.009. MR2149924
- [17] P. Lairez, *A deterministic algorithm to compute approximate roots of polynomial systems in polynomial average time*, Found. Comput. Math. **17** (2017), no. 5, 1265–1292, DOI 10.1007/s10208-016-9319-7. MR3709332
- [18] C. Liaw, A. Mehrabian, Y. Plan, and R. Vershynin, *A simple tool for bounding the deviation of random matrices on geometric sets*, Geometric aspects of functional analysis, Lecture Notes in Math., vol. 2169, Springer, Cham, 2017, pp. 277–299. MR3645128
- [19] G. Livshyts, G. Paouris, and P. Pivovarov, *On sharp bounds for marginal densities of product measures*, Israel J. Math. **216** (2016), no. 2, 877–889, DOI 10.1007/s11856-016-1431-5. MR3557469
- [20] H. H. Nguyen, *On a condition number of general random polynomial systems*, Math. Comp. **85** (2016), no. 298, 737–757, DOI 10.1090/mcom/2993. MR3434879
- [21] G. Paouris and P. Pivovarov, *Randomized isoperimetric inequalities*, Convexity and concentration, IMA Vol. Math. Appl., vol. 161, Springer, New York, 2017, pp. 391–425. MR3837278
- [22] M. Rudelson and R. Vershynin, *The Littlewood-Offord problem and invertibility of random matrices*, Adv. Math. **218** (2008), no. 2, 600–633, DOI 10.1016/j.aim.2008.01.010. MR2407948
- [23] M. Rudelson and R. Vershynin, *Smallest singular value of a random rectangular matrix*, Comm. Pure Appl. Math. **62** (2009), no. 12, 1707–1739, DOI 10.1002/cpa.20294. MR2569075
- [24] M. Rudelson and R. Vershynin, *Small ball probabilities for linear images of high-dimensional distributions*, Int. Math. Res. Not. IMRN **19** (2015), 9594–9617, DOI 10.1093/imrn/rnu243. MR3431603
- [25] G. Schechtman, *Two observations regarding embedding subsets of Euclidean spaces in normed spaces*, Adv. Math. **200** (2006), no. 1, 125–135, DOI 10.1016/j.aim.2004.11.003. MR2199631
- [26] M. Shub and S. Smale, *Complexity of Bézout’s theorem. I. Geometric aspects*, J. Amer. Math. Soc. **6** (1993), no. 2, 459–501, DOI 10.2307/2152805. MR1175980
- [27] S. Smale, *Mathematical problems for the next century*, Math. Intelligencer **20** (1998), no. 2, 7–15, DOI 10.1007/BF03025291. MR1631413
- [28] D. A. Spielman and S.-H. Teng, *Smoothed analysis of algorithms*, Proceedings of the International Congress of Mathematicians, Vol. I (Beijing, 2002), Higher Ed. Press, Beijing, 2002, pp. 597–606. MR1989210
- [29] M. Talagrand, *The generic chaining*, Springer Monographs in Mathematics, Springer-Verlag, Berlin, 2005. Upper and lower bounds of stochastic processes. MR2133757
- [30] R. Vershynin, *High-dimensional probability*, Cambridge Series in Statistical and Probabilistic Mathematics, vol. 47, Cambridge University Press, Cambridge, 2018. An introduction with applications in data science; With a foreword by Sara van de Geer, DOI 10.1017/9781108231596. MR3837109
- [31] R. Vershynin, *Four lectures on probabilistic methods for data science*, The mathematics of data, IAS/Park City Math. Ser., vol. 25, Amer. Math. Soc., Providence, RI, 2018, pp. 231–271, DOI 10.1090/pcms/025. MR3839170
- [32] R. Vershynin, *Introduction to the non-asymptotic analysis of random matrices*, Compressed sensing, Cambridge Univ. Press, Cambridge, 2012, pp. 210–268. MR2963170

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