

A Trace Bound for the Hereditary Discrepancy*

BERNARD CHAZELLE[†]
ALEXEY LVOV[‡]

Abstract

Let A be the incidence matrix of an m -by- n set system, and let $t = \text{tr } M$, where $M = A^T A$. Finally, let $\sigma = \text{tr } M^2$ be the sum of squares of the elements of M . We prove that the hereditary discrepancy of the set system is at least $\frac{1}{4} c^{n\sigma/t^2} \sqrt{t/n}$, with $c = 1/324$. This general *trace bound* allows us to resolve discrepancy-type questions for which spectral methods had previously failed. Also, by using this result in conjunction with the “spectral lemma” for linear circuits, we derive new complexity bounds for range searching.

- We show that the (red-blue) discrepancy of the set system formed by n points and n lines in the plane is $\Omega(n^{1/6})$ in the worst case and always¹ $\tilde{O}(n^{1/6})$.
- We give a simple *explicit* construction of n points and n halfplanes with hereditary discrepancy $\tilde{\Omega}(n^{1/4})$.
- We provide a construction of n points and n axis-parallel boxes in dimension $O(\log n / \log \log n)$ with discrepancy $n^{\Omega(1/\log \log n)}$.
- Applying these discrepancy results together with a new variation of the spectral lemma, we derive a lower bound of $\Omega(n \log n)$ on the arithmetic complexity of off-line range searching for points and lines (for non-monotone circuits). We also prove a lower bound of $\Omega(n \log n / \log \log n)$ on the complexity of orthogonal range searching in dimension no larger than $O(\log n / \log \log n)$.

*A preliminary version of this paper appeared in Proc. 16th Annual ACM Symp. Comput. Geom. (2000), 64–69.

[†]NEC Research Institute and Department of Computer Science, Princeton University

[‡]Program in Applied and Computational Mathematics, Princeton University

¹We use the notation $\tilde{O}(m)$ and $\tilde{\Omega}(m)$ as shorthand for $O(m \log^c m)$ and $\Omega(m / \log^c m)$, respectively, for some constant $c > 0$.

1 Introduction

The red-blue discrepancy of a set system is the minimum value of $\|Ax\|_\infty$ over all $x \in \{-1, 1\}^n$, where A is the m -by- n incidence matrix of the set system. In a geometric context, the columns are points in \mathbf{R}^d and the rows are the characteristic vectors of certain regions of space. The discrepancy is not necessarily a robust notion: it might be very small but shoot up as soon as we remove a few points. To avoid this type of pathology, Lovász, Spencer, and Vesztergombi [9] introduced the hereditary discrepancy, which they defined as the maximum discrepancy of any set system derived from A by removing any number of columns. It is important to observe that in geometric set systems, this is just like removing points. To remove a point from a range space gives another range space, and so in that case the hereditary discrepancy in fact coincides with the regular notion of discrepancy. It is simply a more convenient tool, but not a restrictive one. Lovász et al. proved the classical bound, stated here for the case $m = n$,

$$\text{herdisc}(A) \geq \frac{1}{2} |\det A|^{1/n}.$$

A similar lower bound by Lovász and Vesztergombi [10] relates the hereditary discrepancy to the volume of the convex hull of the $2n$ row vectors of A and $-A$.

Lower bounds of this type suffer from two weaknesses: one is that the determinant can be very small for the “wrong” reasons. In other words, the discrepancy could be very high even though $\det A$ is very small or even null. The other problem is that to derive a decent estimate on the determinant might be very difficult. Harmonic analysis is the standard vehicle for estimating the singular values of A , and hence, $\det A$. This works well when the set systems consist of full-dimensional regions with smooth parameterizations (eg, points in balls, boxes, or simplices) [1, 6, 11, 12]. The approach seems to fail, however, when the regions are curves or surfaces.

Our strategy to overcome this difficulty is to relate the discrepancy directly to combinatorial (as opposed to spectral) features of the set system. In particular, we focus on the traces of $M = A^T A$ and M^2 , and prove the following, general *trace bound*:

Lemma 1.1 *If A is an m -by- n incidence matrix and $M = A^T A$, then*

$$\text{herdisc}(A) \geq \frac{1}{4} c^{n \text{tr} M^2 / \text{tr}^2 M} \sqrt{\frac{\text{tr} M}{n}},$$

where $c = \frac{1}{324}$.

Note that $\text{tr} A^T A = \text{tr} A A^T$ and $\text{tr} (A^T A)^2 = \text{tr} (A A^T)^2$, and so the trace bound is self-dual for square matrices. In particular, we can always replace $M = A^T A$ by $M = A A^T$ if this makes calculations easier. What makes this lower bound particularly useful is that the traces of M and M^2 have natural interpretations:

- Algebraically, $\text{tr} M$ is the sum of the eigenvalues. Combinatorially, it is the number of ones in A . Geometrically, it is the count of point/region incidences.
- Algebraically, $\text{tr} M^2$ is the sum of the squares of the eigenvalues. Combinatorially, it is the number of rectangles of ones in A (or, equivalently, the number of closed paths of length 4 in the bipartite graph corresponding to A). Geometrically, it counts the pairs of points in all the pairwise intersections of regions.

These characterizations give us the combinatorial tools needed to resolve a few open questions: some have to do with discrepancy theory proper, others with the complexity of off-line range searching in a non-monotone model (the standard model of linear circuits with bounded coefficients). A problem instance is specified by a set system of n weighted points and m regions. The output consists of the sums of the weights in each region. This is equivalent to multiplying the incidence matrix A by the weight vector x . The *spectral lemma* [3] states that the complexity of the problem is lower-bounded by $\Omega(\max_k k \log \lambda_k)$, where λ_k is the k -th largest eigenvalue of $A^T A$. By appealing to Lemma 1.1 we are able to bypass eigenvalues altogether to give a lower bound based solely on traces.²

Lemma 1.2 *The complexity of range searching with incidence matrix A is*

$$\Omega_\varepsilon \left(n \log \left(\text{tr} M / n - \varepsilon \sqrt{\text{tr} M^2 / n} \right) \right),$$

where $M = A^T A$ and $\varepsilon > 0$ is an arbitrarily small constant.

²The spectral lemma allows the presence of help gates. So can Lemma 1.2, but we ignore this technical point for the purpose of this abstract.

This paper follows the principle of the discrepancy method [5], which is to derive complexity bounds from discrepancy results. We specialize the two lemmas above to two classical set systems which had resisted previous investigations: points in lines and points in higher dimensional boxes. We show that the (red-blue) discrepancy of the set system formed by n points and n lines in the plane is $\Omega(n^{1/6})$. Using the entropy method of discrepancy theory we give a nearly matching upper bound of $O(n^{1/6} \log^{2/3} n)$. We also prove that the corresponding off-line range searching problem has complexity $\Omega(n \log n)$.

The exponent of $1/6$ stands in contrast with that of $1/4$ associated with points and triangles. Triangle range searching does not seem harder than line range searching (think of Hopcroft's problem), and the best algorithms for both run in time $\tilde{O}(n^{4/3})$, so it is intriguing that their discrepancies should differ by so much. Of incidental interest, our techniques allow a very elementary derivation of an $\tilde{\Omega}(n^{1/4})$ bound for points and triangles. As shown in [4], $\Omega(n^{1/4})$ is the exact bound on the discrepancy. There are two reasons why our bound is interesting nevertheless: (i) it is purely combinatorial and, in particular, it requires no harmonic analysis; (ii) the construction is *explicit* whereas the previous one was existential. Also, we provide an explicit construction for n points and n axis-parallel boxes in dimension $O(\log n / \log \log n)$ with hereditary discrepancy $n^{\Omega(1/\log \log n)}$. Of course, this implies the same lower bound on the standard discrepancy (but the construction is no longer explicit). This quasi-linear discrepancy stands in sharp contrast with the polylogarithmic bound for the fixed-dimensional case.

We establish a lower bound of $\Omega(n \log n)$ on the complexity of off-line line range searching. The only previous result was $\Omega(n^{4/3})$ for monotone circuits [5]. We also prove a lower bound of $\Omega(n \log n / \log \log n)$ on the complexity of orthogonal range searching in dimension $O(\log n / \log \log n)$. In fixed dimension, the lower bound is $\Omega(n \log \log n)$ [2]. It is intriguing to observe that when the dimension becomes as big as roughly $\log n$, orthogonal range searching essentially rises to the (known) complexity level of triangle range searching in two dimensions.

2 The Trace Bound

The linear discrepancy of an m -by- n 0/1 matrix A is defined as

$$\text{lindisc}(A) = \max_{c \in [-1, 1]^n} \min_{x \in \{-1, 1\}^n} \|A(x - c)\|_\infty.$$

The main advantage of the linear discrepancy over the hereditary variety is that the continuous parameter c brings linear algebra into the picture. Lovász, Spencer, and Vesztergombi [9] proved that

$$\text{herdisc}(A) \geq \frac{1}{2} \text{lindisc}(A). \quad (1)$$

By definition, for any $c \in [-1, 1]^n$, there exists some $x \in \{-1, 1\}^n$ such that $Ac = Ax + y$, where $y \in [-\text{lindisc}(A), \text{lindisc}(A)]^n$. The image of the cube $[-1, 1]^n$ via A is a polyhedron in \mathbf{R}^m whose vertices belong to $A\{-1, 1\}^n$. We conclude:

Lemma 2.1 *The polyhedron $A[-1, 1]^n$ is covered by the $\leq 2^n$ m -dimensional cubes of side length $2\text{lindisc}(A)$ centered at the vertices of $A[-1, 1]^n$.*

The trace bound does not involve eigenvalues explicitly but its proof does. Let $\lambda_1 \geq \dots \geq \lambda_n \geq 0$ be the eigenvalues of $A^T A$; ties are broken arbitrarily.

Lemma 2.2 *For any $1 \leq k \leq n$,*

$$\text{lindisc}(A) \geq 18^{-n/k} \sqrt{\lambda_k}.$$

Proof: The singular-value decomposition of a matrix allows us to express A as UDV^T , where U (resp. V) is the orthogonal matrix whose columns are the eigenvectors of AA^T (resp. $A^T A$) and D is the m -by- n diagonal matrix whose only nonzero entries are $\sqrt{\lambda_1}, \dots, \sqrt{\lambda_n}$ (the singular values of A). Let L be the subspace spanned by the k eigenvectors of $A^T A$ corresponding to $\lambda_1, \dots, \lambda_k$. Consider the projection of $[-1, 1]^n$ on L . We omit the proof that projecting a cube from \mathbf{R}^n to \mathbf{R}^k creates a volume distortion factor which lies (conservatively) between 3^{-n} and 3^n . It follows that

$$\begin{aligned} \text{vol}(A \text{proj}_L[-1, 1]^n) &= \\ \sqrt{\lambda_1 \cdots \lambda_k} \text{vol}(\text{proj}_L[-1, 1]^n) &\geq \\ 2^k 3^{-n} \lambda_k^{k/2}. & \end{aligned} \quad (2)$$

Given any $x \in L$ and $y \in L^\perp$, $A^T Ax$ lies in L and so $(Ax)^T(Ay) = (A^T Ax)^T y = 0$. In fact, not only are AL and $A(L^\perp)$ orthogonal, but they span all \mathbf{R}^n and therefore $(AL)^\perp = A(L^\perp)$. It easily follows that

$$A \text{proj}_L[-1, 1]^n = \text{proj}_{AL} A[-1, 1]^n$$

and by (2)

$$\text{vol}(\text{proj}_{AL} A[-1, 1]^n) \geq 2^k 3^{-n} \lambda_k^{k/2}.$$

By Lemma 2.1, the projection of $A[-1, 1]^n$ on AL is covered by the projections of 2^n cubes of side length $2 \text{lindisc}(A)$. Accounting for the dilation factor of 3^n , we find that

$$\text{vol}(\text{proj}_{AL} A[-1, 1]^n) \leq 2^n 3^m (2 \text{lindisc}(A))^k,$$

which, together with $m \leq n$, proves the lemma. \square

We prove the trace bound by a probabilistic argument. Let λ be the random variable λ_i , where i is chosen at random uniformly in $\{1, \dots, n\}$.

Lemma 2.3 *If $n/k \geq 2 \text{var} \lambda / \mathbf{E}^2 \lambda + 1$, then $\lambda_k \geq \mathbf{E} \lambda / 4$.*

Proof: We use a second-moment argument based on a one-way Chebyshev inequality.³ For $x \geq 0$, let G_x be the event, $\lambda \geq \mathbf{E} \lambda - x$, and let p be its probability.

$$\begin{aligned} 0 &= \mathbf{E}[\lambda | G_x] p + \mathbf{E}[\lambda | \overline{G_x}] (1 - p) - \mathbf{E} \lambda \\ &= (\mathbf{E}[\lambda | G_x] - \mathbf{E} \lambda) p + (\mathbf{E}[\lambda | \overline{G_x}] - \mathbf{E} \lambda) (1 - p) \\ &\leq (\mathbf{E}[\lambda | G_x] - \mathbf{E} \lambda) p - x(1 - p), \end{aligned}$$

and hence,

$$\mathbf{E}[\lambda | G_x] \geq \mathbf{E} \lambda + x(1/p - 1).$$

Consider the random variable $\mathbf{E}[\lambda | Y]$, where Y is the σ -algebra generated by G_x and $\overline{G_x}$. The conditional variance $\text{var}[\lambda | Y]$, defined as the variance of $\mathbf{E}[\lambda | Y]$, can never exceed the (unconditional) variance (see [8], pp. 195-196), and so

$$\begin{aligned} \text{var} \lambda &\geq \text{var} \mathbf{E}[\lambda | Y] \\ &\geq (\mathbf{E}[\lambda | G_x] - \mathbf{E} \lambda)^2 p (\mathbf{E}[\lambda | \overline{G_x}] - \mathbf{E} \lambda)^2 (1 - p) \\ &\geq x^2 (1/p - 1)^2 p + x^2 (1 - p) \geq x^2 (1/p - 1). \end{aligned}$$

³Interestingly, this cannot be derived directly from Chebyshev's inequality.

It follows that

$$p \geq \frac{1}{1 + x^{-2} \mathbf{var} \lambda}. \quad (3)$$

Setting $x = 3\mathbf{E}\lambda/4$, we find that the number of eigenvalues greater than or equal to $\mathbf{E}\lambda/4$ is at least

$$\frac{n}{1 + (16/9\mathbf{E}^2\lambda) \mathbf{var} \lambda},$$

which completes the proof. \square

We can now prove Lemma 1.1. If we write $M = A^T A$, $t = \text{tr } M$ and $\sigma = \text{tr } M^2$, then $\mathbf{E}\lambda = t/n$ and $\mathbf{var} \lambda = \sigma/n - t^2/n^2$. Therefore, by setting n/k to about $2(\mathbf{var} \lambda / \mathbf{E}^2 \lambda + 1) = 2n\sigma/t^2$, we derive from (1) and Lemmas 2.2 and 2.3:

$$\begin{aligned} \text{herdisc}(A) &\geq \frac{1}{2} \text{lindisc}(A) \geq \\ \frac{1}{2} 18^{-n/k} \sqrt{\lambda_k} &\geq \frac{1}{4} 18^{-2n\sigma/t^2} \sqrt{\frac{t}{n}}, \end{aligned}$$

which proves Lemma 1.1. \square

We now prove Lemma 1.2. By the *spectral lemma* [3], the circuit size (or, equivalently, the straight-line complexity) of $x \mapsto Ax$ is at least $\Omega(k \log \lambda_k)$, where λ_k is the k -th largest eigenvalue of $A^T A$. This result holds under the assumption that gates compute functions of the form $(u, v) \mapsto \alpha u + \beta v$, with $|\alpha|, |\beta| = O(1)$. Set $x = \varepsilon \sqrt{\text{tr } M^2/n}$ in (3). Then,

$$\begin{aligned} \text{Prob}\left\{\lambda \geq \text{tr } M/n - \varepsilon \sqrt{\text{tr } M^2/n}\right\} &\geq \\ \frac{1}{1 + n\varepsilon^{-2} \mathbf{var} \lambda / \text{tr } M^2} &\geq \frac{1}{1 + \varepsilon^{-2}}, \end{aligned}$$

which is independent of n . Setting $k = \lceil n/(1 + \varepsilon^{-2}) \rceil$, the spectral lemma yields an asymptotic circuit complexity lower bound of

$$\frac{n}{1 + \varepsilon^{-2}} \log \left(\text{tr } M/n - \varepsilon \sqrt{\text{tr } M^2/n} \right),$$

which proves Lemma 1.2. \square

Remark: The spectral lemma allows the use of help gates, which take two arguments and output any function of them. In the presence of h help gates, Lemma 1.2 still holds if we replace $n \log(\dots)$ by $(n - ch) \log(\dots)$, for some constant $c > 0$ depending on ε .

3 Lines and Halfplanes

We consider the discrepancy of an n -by- n set system formed by points and lines in \mathbf{R}^2 . We prove a tight bound of $n^{1/6}$ (up to a polylogarithmic factor). This is a surprising result because it differs so noticeably from the $\Theta(n^{1/4})$ bound for points and triangles.

Theorem 3.1 *For any $n > 0$, there exists an n -by- n set system of points and lines in the plane with discrepancy $\Omega(n^{1/6})$. This is optimal up to a factor of $(\log n)^{2/3}$.*

Proof: We begin with the lower bound, whose one-paragraph proof illustrates the surprising power of the trace bound. A classical construction of Erdős (see [13]), whose description we omit here, produces an n -by- n set system of points and lines whose incidence matrix A has $\Theta(n^{1/3})$ ones per row (ie, points per line) and $\Theta(n^{1/3})$ ones per column: (i) each diagonal element of $M = A^T A$ is $\Theta(n^{1/3})$, so the trace of M is $\Omega(n^{4/3})$, while the squares of the elements along the diagonal sum up to $O(n^{5/3})$; (ii) each nondiagonal element is 0/1 (at most one of the n lines passes through two distinct points), and the number of ones among them coincides with the number of pairs of points on any of the n lines, ie, $O(n^{5/3})$. It follows that the trace of M^2 is $O(n^{5/3})$. By Lemma 1.1, it follows that

$$\text{herdisc}(A) \geq \frac{1}{4} c^{n^{1+5/3}/(n^{4/3})^2} \sqrt{\frac{n^{4/3}}{n}} = \Omega(n^{1/6}),$$

hence the lower bound.

We now establish an upper bound of $O(n^{1/6})(\log n)^{2/3}$ on the discrepancy of any n -by- n set system of points and lines. Our argument builds on two known facts. One is the Szemerédi-Trotter bound of $O(m^{2/3}n^{2/3} + m + n)$ on the number of incidences between n points and m lines in the plane [13, 14, 15]. The other is Beck's partial coloring lemma of discrepancy theory [1, 5, 11]: Let (X, \mathcal{R}_0) and (X, \mathcal{R}_1) be two set systems, and assume that

$$\prod_{R \in \mathcal{R}_0} (|R| + 1) \leq 2^{(n-1)/5},$$

where $n = |X|$, and that $|R| \leq r$ for any $R \in \mathcal{R}_1$. Then, there exists a partial coloring $\chi : X \mapsto \{-1, 0, 1\}$, such that χ is nonzero over at least one tenth of X , $\chi(R) = 0$, for each $R \in \mathcal{R}_0$, and $|\chi(R)| \leq \sqrt{2r \ln(4|\mathcal{R}_1|)}$, for each $R \in \mathcal{R}_1$.

Consider a set system formed by n points and m lines. We partition it into two sub-systems: \mathcal{R}_0 includes the subsets with at least $r = c(n \log n)^{1/3}$ incidences, for some constant $c > 0$ small enough, while \mathcal{R}_1 consists of the others. Clearly, assuming that n is large enough,

$$r|\mathcal{R}_0| = O(n^{2/3}|\mathcal{R}_0|^{2/3} + n + |\mathcal{R}_0|),$$

and so $|\mathcal{R}_0| \leq n/6 \log n$ and, indeed,

$$\prod_{R \in \mathcal{R}_0} (|R| + 1) \leq (n + 1)^{n/6 \log n} < 2^{(n-1)/5}.$$

This implies the existence of a partial coloring with at least $n/10$ nonzeros and discrepancy at most proportional to $n^{1/6}(\log n)^{2/3}$. Next, we extract the points corresponding to the color 0, and we iterate through this partial coloring process. Adding the various discrepancies increases the bound above by only a constant factor. \square

By way of illustration, here is another interesting application of the trace bound. We describe a set system of n points and n halplanes with discrepancy $\tilde{\Omega}(n^{1/4})$. (The best bound [4] has no tilde factor—which in this case is $\sqrt{\log n}$ —but it is purely existential.) The simple construction below illustrates why $1/4$ is the right exponent purely by combinatorial means.

We use strips instead of halfplanes. This is equivalent, up to a constant factor, since a strip is the intersection of two halfplanes. Consider a $\lfloor n^{1/2}/\log n \rfloor \times \lfloor n^{1/2} \log n \rfloor$ square grid. The set of points consists of the centers of all the unit squares, so their number is $\Theta(n)$. Let $S_{u,v}$ denote the strip intersecting the top and bottom sides of the grid in the horizontal intervals $[u, u + 1]$ and $[u + v \log n, u + v \log n + 1]$, respectively. The set of strips consists of all the $S_{u,v}$ cutting the grid's boundary only in the top and bottom sides: their number is clearly $\Theta(n)$. For any fixed v_0 , the strips $\{S_{u,v_0}\}$ are disjoint while, for any two distinct v_0 and v_1 , the intersection of any two S_{*,v_0} and S_{*,v_1} can be covered with a parallelogram of width 1 and height $O(n^{1/2})/|v_0 - v_1| \log^2 n$ and thus contains $O(n^{1/2})/|v_0 - v_1| \log^2 n$ points. Also, S_{*,v_0} cannot intersect more than $O(|v_0 - v_1| \log n)$ strips S_{*,v_1} inside the grid.

We can now bound the traces $t = \text{tr } M$ and $\sigma = \text{tr } M^2$ for this set system. For convenience, we consider $M = AA^T$ instead of $M = A^T A$. Each strip contains $\Theta(n^{1/2}/\log n)$ points, so the total number of incidences is $t = \Omega(n^{3/2}/\log n)$. Let L_{u_0,v_0} be the sum of the squares of the elements

in row (u_0, v_0) of $A^T A$, and let P denote the set of $\Theta(n)$ points:

$$\begin{aligned}
L_{u_0, v_0} &= \\
&= \sum_{u, v} |P \cap S_{u_0, v_0} \cap S_{u, v}|^2 \\
&= O(n/\log^2 n) + \sum_{v \neq v_0} O\left(\frac{n^{1/2}}{|v - v_0| \log^2 n}\right)^2 |v - v_0| \log n \\
&= O(n/\log^2 n) + O(n/\log^3 n) \sum_{i=1}^{n^{1/2}} 1/i = O(n/\log^2 n).
\end{aligned}$$

It follows that $\sigma = O(n/\log n)^2$. By Lemma 1.1,

$$\text{herdisc}(A) \geq \frac{1}{4} c^{n\sigma/t^2} \sqrt{t/n} = \Omega(n^{1/4})/\sqrt{\log n},$$

as claimed. \square

Theorem 3.2 *For any large enough n , there exists an n -by- n set system of points and axis-parallel boxes in $\mathbf{R}^{O(\log n/\log \log n)}$ with discrepancy $n^{\Omega(1/\log \log n)}$.*

Proof: As usual, it suffices to prove the theorem relative to the hereditary discrepancy; indeed, by moving the relevant points outside of the boxes, the hereditary discrepancy becomes the actual (standard) discrepancy. Given an integer p , define $s = \lfloor \sqrt{p}/\log p \rfloor$, $d = \lfloor s/5 \rfloor$, and $k = \lfloor d/2 \log p \rfloor$. To establish the theorem, we may restrict ourselves to n -by- n set systems where n is of the form p^s , for a large prime p . Indeed, given an arbitrary (large) value of n , we can apply the theorem for $n' = p^s$, where p is defined as the largest prime not exceeding $\log^2 n$. The resulting n' -by- n' set system is made n -by- n trivially by adding $n - n'$ empty boxes and far away points. This addition does not change the discrepancy. Furthermore, by the prime distribution law [7], it easily follows that $\sqrt{n} \leq n' \leq n$; therefore, the bounds on the dimension and the discrepancy claimed by the theorem (for n') remain true if we change n' into n .

So, from now on, we assume that $n = p^s$, with s, d, k as specified above, and p a large prime. The set of n points is a p -ary Faure set⁴ of p^s points in \mathbf{R}^d . We postpone a review of the properties of such points to the place in the proof where they are needed. To define our set B of n boxes B , we consider all grids $\mathcal{G}_{i_1, \dots, i_d}$ in \mathbf{R}^d consisting of cells of the form

$$\frac{1}{p^{i_1}} \times \frac{1}{p^{i_2}} \times \cdots \times \frac{1}{p^{i_d}}, \quad i_1 + i_2 + \cdots + i_d = s - k.$$

⁴For a detailed description of Faure sets, see, eg, [11] pp. 51–54.

Note that the total number of such grids is $\binom{s-k+d-1}{d-1}$.

Each cell σ of $\mathcal{G}_{i_1, \dots, i_d}$ is a box that contains exactly p^k points. Let B be a set consisting of any p^s of these boxes chosen from (any) p^k grids (we shall prove later that there are at least p^s such boxes). A few words of motivation for the choice of parameters d, k :

- The trace t of $M = A^T A$ is equal to np^k , so k should be as large as possible. However,
- as k grows, $d = d(k)$ should grow to ensure that our set system contains at least p^s boxes. At the same time,
- d should be kept small enough so as to bound by a constant the exponent $n\sigma/t^2$ in Lemma 1.1 (recall that $\sigma = \text{tr } M^2$).

We now prove that the total number of boxes is at least p^s , and so B is well defined. The total number of boxes in all the grids is equal to $\# \text{ grids} \times p^{s-k}$, so it is enough to show that the number of grids is at least p^k . As we observed earlier, this number is

$$\begin{aligned} \binom{s-k+d-1}{d-1} &> \left(\frac{s}{2(d-1)} \right)^{d-1} \\ &> 2^d \geq 2^{\lfloor d/2 \log p \rfloor \log p} = p^k. \end{aligned}$$

Next, we prove that the hereditary discrepancy of the set system is $n^{\Omega(1/\log \log n)}$, as desired. The number of points in each box is p^k and so the trace t satisfies

$$\begin{aligned} \sqrt{\frac{t}{n}} = p^{k/2} &= p^{\frac{1}{2} \lfloor \frac{1}{2 \log p} \lfloor s/5 \rfloor \rfloor} \geq p^{s/21 \log p} = 2^{\Omega(s)} \\ &= n^{\Omega(1/\log \log n)}. \end{aligned} \tag{4}$$

On the other hand, the trace of M^2 satisfies

$$\begin{aligned} \sigma \leq p^s \sum \{ (\# \text{inters.})^2 \mid \\ \text{relative to a fixed box and all boxes in } B \}. \end{aligned} \tag{5}$$

Let boxes b_1 and b_2 belong to grids $\mathcal{G}_{i_1, \dots, i_d}$ and $\mathcal{G}_{j_1, \dots, j_d}$, respectively. Then the number of points in their intersection is at most $\max\{1, p^{k-\text{dist}/2}\}$,

where $dist$ is the L^1 -distance between the vectors (i_1, \dots, i_d) and (j_1, \dots, j_d) . So,

$$\sigma \leq p^s \left(\underbrace{p^{2k}}_{\text{inters. with itself}} + \underbrace{p^{2k-1}d^2 + p^{2k-2}d^4 + \dots}_{\text{inters. with grids at dist } \leq 2k} + \underbrace{p^k \cdot (\# \text{ of grids})}_{\text{inters. with other grids}} \right).$$

The first and the third items are equal to p^{2k} and the second item forms a convergent geometric series (because $d^2/p < 1/2$), so

$$\sigma \leq O(p^{2k+s}) = O(t^2/n).$$

The lower bound follows from (4) and Lemma 1.1. \square

In view of Lemma 1.2, the proof above immediately implies:

Theorem 3.3 *Off-line orthogonal range searching in \mathbf{R}^d has complexity $\Omega(n \log n / \log \log n)$ for any value of $d > c \log n / \log \log n$, for some constant c .*

4 Further Work and Open Problems

The trace bound is a very general tool that can be applied to a host of other problems (finite projective plane, Hadamard set systems, arithmetic progressions, etc.) Being essentially a second-moment result, however, it falls short for problems requiring tighter estimates on the distribution of eigenvalues (eg, halfspace range searching in higher dimension). We are currently attempting to develop an extension of the technique via tensor products, but it is too early to claim tangible progress on this question.

We can prove that the lower bound of $\Omega(n \log n / \log \log n)$ on the complexity of orthogonal range searching in dimension $O(\log n / \log \log n)$ shoots up to $\Omega(n \log n)$ in dimension \sqrt{n} and above. Put differently, in dimension d , the median eigenvalue of $A^T A$ is of the form $n^{\delta(d,n)}$, where $\delta(d,n) = 1/\log \log n$ for $d = \log n / \log \log n$ and $\delta(d,n) = \Omega(1)$, for $d \geq \sqrt{n}$. How does δ grow as a function of d ?

5 Acknowledgment

We wish to thank Jirka Matoušek for reading a draft of this paper and making several useful comments and suggestions.

References

- [1] Beck, J., Chen, W.W.L. *Irregularities of Distribution*, Cambridge Tracts in Mathematics, 89, Cambridge University Press, Cambridge, 1987.
- [2] Chazelle, B. *Lower bounds for off-line range searching*, Disc. Comput. Geom., 17 (1997), 53–65.
- [3] Chazelle, B. *A spectral approach to lower bounds with applications to geometric searching*, SIAM J. Comput., 27 (1998), 545–556.
- [4] Chazelle, B. *Discrepancy bounds for geometric set systems with Square Incidence Matrices*, in “Advances in Discrete and Computational Geometry,” eds. B. Chazelle, J.E. Goodman and R. Pollack, Contemporary Mathematics, 223, AMS (1999), 103–107.
- [5] Chazelle, B. *The Discrepancy Method: Randomness and Complexity*, Cambridge University Press, 2000.
- [6] Drmota, M., Tichy, R.F., *Sequences, Discrepancies and Applications*, Lecture Notes in Mathematics, Vol. 1651, Springer, March 1997.
- [7] Huxley, M., *On the difference between consecutive primes*, Invent. Math. 15 (1972), 164–170.
- [8] Kalbfleisch, J.G., *Probability and Statistical Inference*, Vol. 1, Springer-Verlag (1995), New York Inc.
- [9] Lovász, L., Spencer, J., Vesztergombi, K. *Discrepancy of set systems and matrices*, European Journal of Combinatorics, 7 (1986), 151-160.
- [10] Lovász, L., Vesztergombi, K. *Extremal problems for discrepancy*, In “Irregularities of partitions”, G. Halász, V.T. Sós, eds. (1989), 107–113.
- [11] Matoušek, J. *Geometric Discrepancy: An Illustrated Guide*, Algorithms and Combinatorics, 18, Springer, 1999.

- [12] Montgomery, H.L. *Ten Lectures on the Interface Between Analytic Number Theory and Harmonic Analysis*, CBMS Regional Conference Series in Mathematics, No. 84), Amer. Math. Soc., Providence (1994).
- [13] Pach, J., Agarwal, P.K. *Combinatorial Geometry*, John Wiley & Sons, 1995.
- [14] Sharir, M, Agarwal, P.K. *Davenport-Schinzel sequences and their geometric applications*, Cambridge University Press, 1995.
- [15] Szemerédi, E., Trotter, W. *Extremal problems in discrete geometry*, *Combinatorica*, 3 (1983), 381–392.