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COUNTING S_5-FIELDS WITH A POWER SAVING ERROR TERM

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Abstract

We show how the Selberg Λ^2-sieve can be used to obtain power saving error terms in a wide class of counting problems which are tackled using the geometry of numbers. Specifically, we give such an error term for the counting function of S_5-quintic fields.

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1. Introduction

Over the past decade there has emerged a large body of work concerned with counting arithmetic objects by parameterizing them as $G_{\mathbb{Z}}$ orbits on $V_{\mathbb{Z}}$, where G is some reductive algebraic group, and V is a representation of G (see [3, 5–9, 11]). In certain applications, particularly relating to low lying zeros–see [12], it is important not only to obtain the asymptotic count, but also to obtain a power saving error term, that is a formula of the type

$$\#\{\text{Objects of interest with height less than } X\} = cX^a \log^b X + O(X^{a-\delta})$$

for some fixed constant $\delta > 0$.

In this note, we show how the Selberg Λ^2-sieve can be used very generally to obtain such power savings. In particular, we demonstrate our claim by obtaining the first known power saving for quintic fields with Galois group S_5 and bounded discriminant:

THEOREM 1. *Define $N_5^{(i)}(X)$ to be the number of quintic fields with Galois group S_5 having discriminant bounded in absolute value by X with i complex places. Then*

$$N_5^{(i)}(X) = d_i \prod_p (1 + p^{-2} - p^{-4} - p^{-5})X + O_\epsilon(X^{\frac{199}{200}+\epsilon})$$

where d_0, d_1, d_2 are $1/240$, $1/24$, and $1/16$, respectively.

The analogous version of Theorem 1 in the case for cubic and quartic fields with Galois groups S_3 and S_4, respectively, was proven in [2]. However, in those cases, the arguments used to obtain power saving error estimates were explicit and do not easily generalize. An advantage to using the Selberg Λ^2-sieve is that it is very general. It yields power saving error estimates when counting the arithmetic objects that arise in, for example, [7, 9, 11].

We begin with a general sketch of the argument.

1.1. Sketch of the argument. Typically, one finds a fundamental domain $F \subset V_{\mathbb{R}}$ for the action of $G_{\mathbb{R}}$, and one wants to count integral points inside F of bounded height. However, it is not all points that one wants to count; one partitions the set $V_{\mathbb{Z}}$ into two sets $V_{\mathbb{Z}}^{\mathrm{deg}}$ and $V_{\mathbb{Z}}^{\mathrm{ndeg}}$ where the former set corresponds to objects which are 'degenerate' in some way, and it is only the points in $V_{\mathbb{Z}}^{\mathrm{ndeg}}$ that need to be counted. For example, in the quintic case the degenerate points correspond to quintic rings R such that $R \otimes_{\mathbb{Z}} \mathbb{Q}$ is not a quintic field with Galois group S_5. F is typically not compact and has 'cusps' which contain primarily degenerate points; the method which one uses to estimate the number of nondegenerate points in the cusp typically yields a power saving. Denoting the 'main ball' of F by F_0, and letting $F_0(X)$ be the set of points in F_0 having height at most X, it then follows that

$$|V_{\mathbb{Z}} \cap F_0(X)| = cX^a \log^b X + O(X^{a-\delta}).$$

It remains to estimate the number of degenerate points inside the main body $F_0 \subset F$, and it is in this last estimate that past results have frequently failed to obtain a power saving.

The typical argument runs as follows. The reduction modulo a prime p of $V_{\mathbb{Z}}^{\mathrm{deg}}$ is shown to lie in a subset $B_p \subset V_{\mathbb{F}_p}$ of density μ_p, which approaches a constant c between 0 and 1 as $p \to \infty$. Set $\widetilde{B}_p$ to be the set of elements of $V_{\mathbb{Z}}$ reducing to B_p. For any finite fixed set S of primes, one has the estimate

$$|V_{\mathbb{Z}}^{\mathrm{deg}} \cap F_0(X)| \leqslant \left| \bigcap_{p \in S} \widetilde{B}_p \cap F_0(X) \right| \sim \prod_{p \in S} \mu_p \cdot cX^a \log^b X.$$

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This is true for every fixed S. Since $\prod_{p \in S} \mu_p$ can be made arbitrarily small by picking S to be a large set, one obtains

$$|V_{\mathbb{Z}}^{\deg} \cap F_0(X)| = o(X^a \log^b X).$$

However it is possible to do much better by estimating $|\bigcap_{p \in S} \widetilde{B}_p|$ with the Selberg sieve [10, Theorem 6.4]. To apply this sieve, we need the following uniform statement. Let $L \subset V_{\mathbb{Z}}$ be defined by congruence conditions modulo m. Then

$$|L \cap F_0(X)| = \mu(L) c X^a \log^b X + O(X^{a-\delta} m^A),$$

where $\mu(L)$ denotes the density of L in $V_{\mathbb{Z}}$, and A is a fixed constant independent of L. The application of the Selberg sieve immediately yields a power saving error term:

$$|V_{\mathbb{Z}}^{\deg} \cap F_0(X)| = O_\epsilon(X^{a - \frac{\delta}{2A+3} + \epsilon}).$$

We remark that for arithmetic applications one usually needs a further sieve (for example, a sieve from quintic rings to maximal quintic rings). This can be done with a power saving error term following [2].

1.2. Outline of the paper. In Section 2, we collect the arguments used by Bhargava in [5] to parameterize and count the number of quintic rings of a bounded discriminant. In Section 3 we use the Selberg sieve to obtain a power saving estimate for the number of non-S_5-orders having bounded discriminant. We try to adhere to the notation of [10, Theorem 6.4] for the convenience to the reader. In Section 4 we prove our main theorem by sieving down from S_5-orders to S_5-fields.

2. S_5-quintic orders

In this section, we recall results from [5] that allow us to obtain asymptotics for the number of S_5-quintic orders having bounded discriminant. All the results and the notation in this section directly follow [5].

2.1. Parameterizing quintic rings. Let $V_{\mathbb{Z}}$ denote the space of quadruples of 5×5 skew-symmetric matrices with integer coefficients. The group $G_{\mathbb{Z}} := \mathrm{GL}_4(\mathbb{Z}) \times \mathrm{SL}_5(\mathbb{Z})$ acts on $V_{\mathbb{Z}}$ via $(g_4, g_5) \cdot (A, B, C, D)^t = g_4(g_5 A g_5^t, g_5 B g_5^t, g_5 C g_5^t, g_5 D g_5^t)^t$. The ring of invariants for this action is generated by one element, denoted as the discriminant. In [4], Bhargava shows that quintic rings are parameterized by $G_{\mathbb{Z}}$-orbits on $V_{\mathbb{Z}}$:

THEOREM 2 (Bhargava [4]). *There is a canonical bijection between the set of $G_{\mathbb{Z}}$-orbits on elements $(A, B, C, D) \in V_{\mathbb{Z}}$ and the set of isomorphism classes of pairs (R, R'), where R is a quintic ring and R' is a sextic resolvent of R. Under this bijection, we have* $\mathrm{Disc}(A, B, C, D) = \mathrm{Disc}(R) = (1/16)\mathrm{Disc}(R')^{1/3}$.

2.2. Counting quintic rings. Following [5], we say that an element $v \in V_{\mathbb{Z}}$ is *irreducible* if it corresponds to a pair of rings (R, R') such that R is an integral domain. For a $G_{\mathbb{Z}}$-invariant subset S of $V_{\mathbb{Z}}$, let $N(S, X)$ denote the number of irreducible $G_{\mathbb{Z}}$-orbits on S having discriminant bounded by X.

The quantity $N(V_{\mathbb{Z}}; X)$ is estimated in the following way: the action of $G_{\mathbb{R}}$ on $V_{\mathbb{R}}$ has three open orbits denoted as $V_{\mathbb{R}}^{(0)}$, $V_{\mathbb{R}}^{(1)}$, and $V_{\mathbb{R}}^{(2)}$. Let $\mathcal{F}$ be a fundamental domain for the action of $G_{\mathbb{Z}}$ on $G_{\mathbb{R}}$ and let H be an open bounded set in $V_{\mathbb{R}}^{(i)}$. Denote $V_{\mathbb{Z}} \cap V_{\mathbb{R}}^{(i)}$ by $V_{\mathbb{Z}}^{(i)}$, and let $S \subset V_{\mathbb{Z}}^{(i)}$ be a $G_{\mathbb{Z}}$-invariant subset. Then by [5, Equations (9) and (10)], we have

$$\begin{aligned} N(S, X) &= \frac{\displaystyle\int_{v \in H} \#\{x \in \mathcal{F}v \cap S^{\mathrm{irr}} : |\mathrm{Disc}(x)| < X\} |\mathrm{Disc}(v)|^{-1} dv}{\displaystyle n_i \int_{v \in H} |\mathrm{Disc}(v)|^{-1} dv} \\ &= C_i \int_{g \in \mathcal{F}} \#\{x \in gH \cap S^{\mathrm{irr}} : |\mathrm{Disc}(x)| < X\} dg, \end{aligned} \tag{1}$$

where dg is the Haar measure on $G_{\mathbb{R}}$ and S^{irr} denotes the set of irreducible elements in S. Note that n_i depends only on i and C_i is independent of S. In what follows, we pick $\mathcal{F}$ and dg as in [5, Section 2.1]. Once they are picked, we let (1) define $N(S, X)$ even for sets S that are not $G_{\mathbb{Z}}$-invariant. Define also the related quantity $N^*(S, X)$ via

$$N^*(S, X) := C_i \int_{g \in \mathcal{F}} \#\{x \in gH \cap S : |\mathrm{Disc}(x)| < X\} dg.$$

For $G_{\mathbb{Z}}$-invariant sets S, the quantity $N^*(S, X)$ is the number of (not necessarily irreducible) $G_{\mathbb{Z}}$-orbits on S having discriminant bounded by X.

Let a_{12} denote the 12-coordinate of A. In [5], the set of elements in gH is partitioned into two sets: the set where $|a_{12}| \geqslant 1$ or the 'main ball' and the set where $|a_{12}| < 1$ or the 'cusp'. Then [5, Lemma 11] states that we have

$$N(\{x \in V_{\mathbb{Z}}^{(i)} : a_{12} = 0\}, X) = O(X^{\frac{39}{40}}). \tag{2}$$

Proposition 12 combined with the last equation in Section 2.6 of [5] implies that

$$N^*(\{x \in V_{\mathbb{Z}}^{(i)} : a_{12} \neq 0\}, X) = c_i X + O(X^{\frac{39}{40}}), \tag{3}$$

where
$$c_i := \frac{\zeta(2)^2\zeta(3)^2\zeta(4)^2\zeta(5)}{2n_i}.$$

To sieve down to fields, we will need analogous equations where $V_{\mathbb{Z}}^{(i)}$ is replaced by a set defined by finitely many congruence conditions on $V_{\mathbb{Z}}$. Specifically, if L is a translate of $mV_{\mathbb{Z}}$, then from [5, Equation 28] we have

$$N^*(\{x \in L \cap V_{\mathbb{Z}}^{(i)} : a_{12} \neq 0\}, X) = c_i m^{-40} X + O(m^{-39} X^{\frac{39}{40}}). \tag{4}$$

2.3. Congruence conditions for $V_{\mathbb{Z}}^{\mathrm{NS5}}$. Let $V_{\mathbb{Z}}^{\mathrm{S5}}$ denote the set of elements in $V_{\mathbb{Z}}$ that correspond to quintic orders whose field of fractions is an S_5-number field, and let $V_{\mathbb{Z}}^{\mathrm{NS5}}$ denote the complement of $V_{\mathbb{Z}}^{\mathrm{S5}}$ in $V_{\mathbb{Z}}$. As explained in [5, Section 3.2], there exist disjoint subsets $T_p(1112)$ and $T_p(5)$ of $V_{\mathbb{Z}}$, that are defined by congruence conditions modulo p, such that for any two distinct primes p and q, the set $V_{\mathbb{Z}}^{\mathrm{NS5}}$ is disjoint from $T_p(1112) \cap T_q(5)$. Furthermore, the densities $g_p(1112)$ of $T_p(1112)$ and $g_p(5)$ of $T_p(5)$ approach $1/12$ and $1/5$, respectively, as $p \to \infty$. We set $S_p(1112)$ and $S_p(5)$ as the complements of $T_p(1112)$ and $T_p(5)$ respectively.

3. Applying the Selberg sieve

Define
$$N_{12}^*(S, X) = N^*(\{x \in S : a_{12} \neq 0\}, X).$$
In this section we give a power saving estimate for $N_{12}^*(V_{\mathbb{Z}}^{\mathrm{NS5},(i)}, X)$. By Section 2.3, we know that

$$N_{12}^*(V_{\mathbb{Z}}^{\mathrm{NS5},(i)}, X) \leqslant N_{12}^*(\cap_p S_p(5), X) + N_{12}^*(\cap_p S_p(1112), X). \tag{5}$$

Our goal is to bound each of the two terms on the RHS of (5) using the Selberg sieve. We turn to the details. We begin by fixing a number $z < X$. Set $P(z) = \prod_{p<z} p$. For each square-free number $d \mid P(z)$, set $g_d(5) = \prod_{p\mid d} g_p(5)$ and

$$a_d = N_{12}^*\left(\bigcap_{p\mid d} T_p(5) \bigcap_{p\mid \frac{P(z)}{d}} S_p(5), X\right).$$

We define a_d to be 0 for $d \nmid P(z)$. This is a sequence of nonnegative integers, and by (4) we have that for all $d \mid P(z)$,

$$\sum_{n \equiv 0 \bmod d} a_n = N_{12}^*(\cap_{p\mid d} T_p(5), X) = c_i g_d(5) X + r_d \tag{6}$$

where $r_d = O(dg_d(5)X^{39/40})$. Fix $D > 1$ and define

$$h_d(5) = \prod_{p|d} \frac{g_p(5)}{1 - g_p(5)}, \quad H = \sum_{\substack{d<\sqrt{D}\\ d|P(z)}} h_d(5).$$

A direct application of [10, Theorem 6.4] yields

$$a_1 = \sum_{(n,P(z))=1} a_n \leqslant c_i X H^{-1} + O\left(\sum_{d<D, d|P(z)} \tau_3(d) r_d\right). \tag{7}$$

To use (7) we take $z = \sqrt{X}$. Note that since $g_p(5) \to \frac{1}{5}$, we have

$$d^{-\epsilon} \ll_\epsilon g_d(5), h_d(5) \ll_\epsilon d^\epsilon.$$

It follows that $H = D^{\frac{1}{2}+o(1)}$ while

$$\left| \sum_{d<D, d|P(z)} \tau_3(d) r_d \right| \ll_\epsilon X^{\frac{39}{40}} D^\epsilon \sum_{d<D} d \leqslant X^{\frac{39}{40}} D^{2+\epsilon}.$$

We deduce that $a_1 \ll_\epsilon X D^{-1/2+\epsilon} + X^{39/40} D^{2+\epsilon}$. Optimizing, we take $D = X^{1/100}$ to deduce that $a_1 \ll_\epsilon X^{199/200+\epsilon}$.

It follows that

$$N_{12}^*(\cap_p S_p(5), X) \leqslant N_{12}^*(\cap_{p<z} S_p(5), X) = a_1 \ll_\epsilon X^{\frac{199}{200}+\epsilon}.$$

The case of $N^*(\cap_p S_p(1112), X)$ can be treated similarly, and we thus conclude by (5) that

$$N_{12}^*(V_{\mathbb{Z}}^{\mathrm{NS5},(i)}, X) \ll_\epsilon X^{\frac{199}{200}+\epsilon}. \tag{8}$$

4. Sieving to fields

In this section we follow [2] to prove Theorem 1. For d square-free, define $W_d \subset V_{\mathbb{Z}}$ to be the set of elements corresponding to quintic orders that are not maximal at each prime dividing d, and $U_d \subset V_{\mathbb{Z}}$ to be the complement of W_d. Recall from [5] that W_d is defined by congruence conditions modulo d^2.

We need a slight generalization of the uniformity estimate [5, Proposition 19].

LEMMA 3. $N(W_d, X) = O_\epsilon(X/d^{2-\epsilon})$.

Proof. As in [5, Proposition 19], we count rings that are not maximal by counting their over-rings. As in that proof, we use the result of Brakenhoff [1] that the number of orders having index m in a maximal quintic ring R is $\prod_{p^k||m} O(p^{\min(2k-2,20k/11)})$. Moreover, from [4, Proof of Corollary 4], the number of sextic resolvents of a quintic ring of content n is $O(n^6)$. (Recall that the content of a ring is the largest integer n such that $R = \mathbb{Z} + nR'$ for some quintic ring R'.)

Since $\mathrm{Disc}(R) = n^8\mathrm{Disc}(R')$, we have

$$N(W_d, X) \ll_\epsilon d^\epsilon X \sum_{n=1}^{\infty} \frac{n^6}{n^8} \prod_{p|d} \sum_{k=1}^{\infty} \frac{p^{\min(2k-2, \frac{20k}{11})}}{p^{2k}} \ll_\epsilon X/d^{2-\epsilon}$$

as desired. □

Now, a point in $V_\mathbb{Z}$ corresponds to a maximal order in an S_5-field precisely if it is in $\cap_p U_p \cap V_\mathbb{Z}^{\mathrm{S5}}$. Denote the density of W_d by k_d, and recall from [5] that $k_d = O_\epsilon(d^{-2+\epsilon})$. A quintic field is maximal if and only if it is maximal at all primes p, and so we count S_5-quintic fields by estimating the quantity $N(\cap_p U_p \cap V_\mathbb{Z}^{(i)}, X)$ as follows:

$$\begin{aligned} N(\cap_p U_p \cap V_\mathbb{Z}^{(i)}, X) &= \sum_{d\in\mathbb{N}} \mu(d) N(W_d \cap V_\mathbb{Z}^{(i)}, X) \\ &= \sum_{d<T} \Big(c_i \mu(d) k_d X + O(X^{\frac{39}{40}} d^\epsilon)\Big) + \sum_{d>T} O_\epsilon(X/d^{2-\epsilon}) \\ &= \sum_{d\in\mathbb{N}} c_i \mu(d) k_d X + O_\epsilon(X/T^{1-\epsilon} + X^{\frac{39}{40}} T^{1+\epsilon}) \\ &= c_i \prod_p (1-k_p) X + O_\epsilon(X/T^{1-\epsilon} + X^{\frac{39}{40}} T^{1+\epsilon}). \end{aligned}$$

Since W_d is the union of $O_\epsilon(d^{78+\epsilon})$ translates of $d^2 V_\mathbb{Z}$, the second equality follows from (4) and Lemma 3. Optimizing, we pick $T = X^{1/80}$ and, taking this in conjunction with (2) and (8), we obtain Theorem 1.

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