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KUMMER THEORY FOR NUMBER FIELDS AND THE REDUCTIONS OF ALGEBRAIC NUMBERS II

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ABSTRACT. Let K be a number field, and let G be a finitely generated and torsion-free subgroup of $K^\times$. For almost all primes $\mathfrak{p}$ of K, we consider the order of the cyclic group $(G \bmod \mathfrak{p})$, and ask whether this number lies in a given arithmetic progression. We prove that the density of primes for which the condition holds is, under some general assumptions, a computable rational number which is strictly positive. We have also discovered the following equidistribution property: if ℓ^e is a prime power and a is a multiple of ℓ (and a is a multiple of 4 if $\ell = 2$), then the density of primes $\mathfrak{p}$ of K such that the order of $(G \bmod \mathfrak{p})$ is congruent to a modulo ℓ^e only depends on a through its ℓ-adic valuation.

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1. Introduction

If we reduce the number 2 modulo every odd prime number p, then we have the sequence of natural numbers given by the multiplicative order of $(2 \bmod p)$. This sequence is very mysterious, and for example it is not known unconditionally whether the order of $(2 \bmod p)$ equals $p-1$ for infinitely many primes p, see [3]. Now consider a non-zero integer z: the density of primes p for which the multiplicative order of $(z \bmod p)$ lies in a given arithmetic progression has been studied in various papers by Chinen and Murata, and by Moree, see, e.g. [1, 4].

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More generally, consider a number field K and a multiplicative subgroup G of $K^\times$ which is finitely generated. For positive integers x, y with $y \mid x$ we denote by $K_x := K(\zeta_x)$ the xth cyclotomic extension of K, and by $K_{x,y} := K_x(\sqrt[y]{G})$ the yth Kummer extension of G over K_x. If $\mathfrak{p}$ is a prime of K, then we write $\mathrm{ord}_{\mathfrak{p}}(G)$ for the multiplicative order of $(G \bmod \mathfrak{p})$, which we tacitly assume to be well--defined. As customary, given two integers x, y we write (x, y) for their greatest common divisor and $[x, y]$ for their least common multiple. Finally, if we assume (GRH) we mean the extended Riemann hypothesis for the Dedekind zeta function of number fields.

In [8] we have generalised results by Ziegler [10] to higher rank and have proven in particular the following statement.

Theorem 1 ([8, Theorem 1.3])**.** *Let K be a number field, and let G be a finitely generated and torsion-free subgroup of $K^\times$ of positive rank. Fix an integer $d \geqslant 2$, fix an integer a, and consider the following set of primes of K:*

$$\mathcal{P} := \{\mathfrak{p} : \mathrm{ord}_{\mathfrak{p}}(G) \equiv a \bmod d\}\,.$$

Let $\mathcal{P}(x)$ be the number of primes $\mathfrak{p}$ in $\mathcal{P}$ with norm up to x.

Assuming (GRH), for every $x \geqslant 1$ we have

$$\mathcal{P}(x) = \frac{x}{\log x} \sum_{n,t \geqslant 1} \frac{\mu(n) c(n,a,d,t)}{[K_{[d,n]t,nt} : K]} + O\left(\frac{x}{\log^{3/2} x}\right), \tag{1}$$

where $c(n,a,d,t) \in \{0,1\}$, and where $c(n,a,d,t) = 1$ if and only if the following conditions hold:

(i) $(1 + at, d) = 1$;

(ii) $(d, n) \mid a$;

(iii) *the element of* $\mathrm{Gal}\big(\mathbb{Q}(\zeta_{dt})/\mathbb{Q}\big)$ *mapping* ζ_{dt} *to* ζ_{dt}^{1+at} *is the identity on* $\mathbb{Q}(\zeta_{dt}) \cap K_{nt,nt}$.

From this result it is not clear whether the natural density $\mathrm{dens}_K(G, a \bmod d)$ of the set $\mathcal{P}$ is a rational number, if it is strictly positive, or if it is possible to evaluate it. The main results of this paper are the following, where K, G, a, and d are as in Theorem 1:

Theorem 2. *Assume (GRH). Let $d = \ell^e$ for some prime number ℓ and for some $e \geqslant 1$. Suppose that $K = K_\ell$ if ℓ is odd, or that $K = K_4$ if $\ell = 2$. Then the density* $\mathrm{dens}_K(G, a \bmod \ell^e)$ *depends on a only through its ℓ-adic valuation, and it is a computable strictly positive rational number. In particular, it is the same for all a coprime to ℓ.*

Although the previous result has an assumption on the base field, we do not need that assumption in the following corollary.

Corollary 3 (Equidistribution property)**.** *Assume (GRH). Let K be any number field, and let $d = \ell^e$ for a prime number ℓ and $e \geqslant 1$. Suppose that $\ell \mid a$ if ℓ is odd, or that $4 \mid a$ and $e \geqslant 2$ if $\ell = 2$. Then the density $\mathrm{dens}_K(G, a \bmod \ell^e)$ depends on a only through its ℓ-adic valuation, and it is a computable strictly positive rational number.*

The following result concerns the case of composite modulus.

Theorem 4. *Assume (GRH). Let $d \geqslant 2$ and set $r := \prod_{\ell \mid d} \ell$ to be its radical. Suppose that $K = K_r$ if d is odd, or that $K = K_{2r}$ if d is even. Then, for a coprime to d, the density $\mathrm{dens}_K(G, a \bmod d)$ is a computable strictly positive rational number which does not depend on a.*

The following result generalises the positivity assertion of Corollary 3.

Theorem 5. *Assume (GRH). The density $\mathrm{dens}_K(G, a \bmod d)$ is strictly positive for any number field K if d is a prime power or if a is coprime to d.*

Theorem 2 is proven in Section 3.1 for ℓ odd, and in Section 3.2 for $\ell = 2$, respectively. We prove Corollary 3 in Section 3.3. Theorem 4 is proven in Section 3.4, while Theorem 5 is proven in Section 3.5. Section 4 is devoted to removing from Theorem 1 the assumption that the group G is torsion-free. Finally, Section 5 contains examples of applications of the above theorems and some numerical data.

Notice that in this paper we rely on Theorem 1 and hence most of our results assume (GRH): if the density in Theorem 1 is known unconditionally, then our results would also be unconditional.

2. Preliminaries

Let K be a number field, and let G be a finitely generated and torsion-free subgroup of $K^\times$. In the whole paper we tacitly assume that the primes $\mathfrak{p}$ of K that we consider are such that the reduction of G modulo $\mathfrak{p}$ is a well-defined subgroup of the multiplicative group of the residue field at $\mathfrak{p}$. Notice that the results of this section are unconditional.

2.1. Prescribing valuations for the order

Theorem 6. *Let $\ell_1, \dots, \ell_n$ be distinct prime numbers and $x_1, \dots, x_n$ nonnegative integers. Then the density of primes $\mathfrak{p}$ of K such that $v_{\ell_i}\big(\mathrm{ord}_{\mathfrak{p}}(G)\big) = x_i$ for all i is a strictly positive computable rational number.*

P r o o f. The rationality of the density can be seen by neglecting the condition on the Frobenius in [5, Theorem 18]. For the positivity, apply [6, Proposition 12] to a basis $g_1, \dots, g_r$ of G consisting of $\mathbb{Z}$-independent points of the multiplicative group $K^\times$. □

Corollary 7. *Given an integer $d \geqslant 2$ and a positive divisor g of d, the sum of densities*

$$\sum_{\substack{0 \leqslant a < d \\ (a,d)=g}} \mathrm{dens}_K(G, a \bmod d) \tag{2}$$

is a strictly positive computable rational number.

P r o o f. We will express the sum (2) as a rational combination of densities as in Theorem 6. Write $g = \prod_{i=1}^n \ell_i^{f_i}$, and partition the index set as $\{1, \dots, n\} = I \sqcup J$ such that $f_i < v_{\ell_i}(d)$ for $i \in I$, and $f_i = v_{\ell_i}(d)$ for $i \in J$. Then it is easy to check that

$$\sum_{\substack{0 \leqslant a < d \\ (a,d)=g}} \mathrm{dens}_K(G, a \bmod d) = \mathrm{dens}_K\left(\left\{\mathfrak{p} : \begin{array}{l} v_{\ell_i}\big(\mathrm{ord}_{\mathfrak{p}}(G)\big) = f_i\,, \forall i \in I, \\ v_{\ell_i}\big(\mathrm{ord}_{\mathfrak{p}}(G)\big) \geqslant f_i\,, \forall i \in J \end{array}\right\}\right). \tag{3}$$

From this expression and Theorem 6 we deduce that (2) is strictly positive. The density on the right-hand side of (3) is given by (applying the inclusion--exclusion principle for the primes up to x and then taking the limit to make the densities)

$$\sum_{s=0}^{|J|}(-1)^s \sum_{\substack{S \subseteq J \\ |S|=s}} \mathrm{dens}_K\left(\left\{\mathfrak{p} : \begin{array}{ll} v_{\ell_i}\big(\mathrm{ord}_{\mathfrak{p}}(G)\big) = f_i\,, & \forall i \in I, \\ v_{\ell_i}\big(\mathrm{ord}_{\mathfrak{p}}(G)\big) \leqslant f_i - 1\,, & \forall i \in S \end{array}\right\}\right), \tag{4}$$

and each of the densities in (4) exists and equals

$$\mathrm{dens}_K\left(\left\{\mathfrak{p} : \begin{array}{l} v_{\ell_i}\big(\mathrm{ord}_{\mathfrak{p}}(G^h)\big) = f_i\,, \forall i \in I, \\ v_{\ell_i}\big(\mathrm{ord}_{\mathfrak{p}}(G^h)\big) = 0\,, \ \forall i \in S \end{array}\right\}\right),$$

where $h = \prod_{i \in S} \ell_i^{f_i - 1}$.

Such densities are computable rational numbers by Theorem 6. Hence the statement is proven. □

Remark 8. Corollary 7 implies that the density $\mathrm{dens}_K(G, 0 \bmod d)$ is known unconditionally to be a strictly positive computable rational number.

2.2. Simplifications by changing the modulus

We keep the notation of Theorem 1. By Remark 8 we may suppose that $0 < a < d$. The following lemma allows us to reduce to residue classes coprime to d if d is a prime power.

Lemma 9. *Let $d = \ell^e$, where ℓ is a prime number and $e \geqslant 1$. Suppose that $a = \ell^x \cdot w$, where w is coprime to ℓ and $0 < x < e$. Set $w_j := w + j\ell^{e-x}$ for $0 \leqslant j < \ell$ (notice that w_j is also coprime to ℓ). Then the primes $\mathfrak{p}$ of K such that $\mathrm{ord}_{\mathfrak{p}}(G) \equiv a \bmod d$ are exactly those such that*

$$\mathrm{ord}_{\mathfrak{p}}\big(G^{\ell^x}\big) \equiv w \bmod \ell^{e-x} \tag{5}$$

minus those such that

$$\mathrm{ord}_{\mathfrak{p}}\big(G^{\ell^{x-1}}\big) \equiv w_j \bmod \ell^{e-x+1} \tag{6}$$

for some $0 \leqslant j < \ell$. In particular, we have

$$\mathrm{dens}_K\,(G,\ a \bmod \ell^e) = \mathrm{dens}_K\left(G^{\ell^x},\ w \bmod \ell^{e-x}\right) - \sum_{j=0}^{\ell-1} \mathrm{dens}_K\left(G^{\ell^{x-1}},\ w_j \bmod \ell^{e-x+1}\right).$$

Proof. Notice that condition (6) for any j implies condition (5) because w_j is coprime to ℓ and hence we must have $\mathrm{ord}_{\mathfrak{p}}\big(G^{\ell^x}\big) = \mathrm{ord}_{\mathfrak{p}}\big(G^{\ell^{x-1}}\big)$.

Let $\mathfrak{p}$ be a prime of K such that $\mathrm{ord}_{\mathfrak{p}}(G) \equiv a \bmod d$. In particular, ℓ^x divides $\mathrm{ord}_{\mathfrak{p}}(G)$. Thus we have

$$\mathrm{ord}_{\mathfrak{p}}\left(G^{\ell^x}\right) = \frac{\mathrm{ord}_{\mathfrak{p}}(G)}{\ell^x} \quad \text{and} \quad \mathrm{ord}_{\mathfrak{p}}\left(G^{\ell^{x-1}}\right) = \frac{\mathrm{ord}_{\mathfrak{p}}(G)}{\ell^{x-1}}.$$

Dividing the congruence $\mathrm{ord}_{\mathfrak{p}}(G) \equiv a \bmod \ell^e$ by ℓ^x and ℓ^{x-1}, respectively, we obtain

$$\mathrm{ord}_{\mathfrak{p}}\left(G^{\ell^x}\right) \equiv w \bmod \ell^{e-x} \quad \text{and} \quad \mathrm{ord}_{\mathfrak{p}}\left(G^{\ell^{x-1}}\right) \equiv w\ell \bmod \ell^{e-x+1}.$$

We have proven one containment because $w\ell$ is not congruent to any of the w_j modulo ℓ.

Now suppose that (5) holds, and that (6) does not hold for any j. In particular we must have $\mathrm{ord}_{\mathfrak{p}}\big(G^{\ell^{x-1}}\big) \neq \mathrm{ord}_{\mathfrak{p}}\big(G^{\ell^x}\big)$. We deduce $\mathrm{ord}_{\mathfrak{p}}\big(G^{\ell^{x-1}}\big) = \ell \cdot \mathrm{ord}_{\mathfrak{p}}\big(G^{\ell^x}\big)$, and therefore $\mathrm{ord}_{\mathfrak{p}}(G) = \ell^x \cdot \mathrm{ord}_{\mathfrak{p}}\big(G^{\ell^x}\big)$. We may conclude because multiplying (5) by ℓ^x gives

$$\ell^x \cdot \mathrm{ord}_{\mathfrak{p}}\left(G^{\ell^x}\right) \equiv a \bmod d. \qquad \square$$

Remark 10. Consider the condition $\mathrm{ord}_{\mathfrak{p}}(G) \equiv a \bmod d$. Decompose $(a,d) = sh$ where $s = \prod_{\ell \mid (a,d)} \ell$ is its radical, and write $a' = \frac{a}{h}$, $d' = \frac{d}{h}$. Notice that $(a', d') = s$ is squarefree. We claim that the following equivalence holds:

$$\mathrm{ord}_{\mathfrak{p}}(G) \equiv a \bmod d \qquad \Longleftrightarrow \qquad \mathrm{ord}_{\mathfrak{p}}\left(G^h\right) \equiv a' \bmod d' .$$

If the first congruence is satisfied, then (a,d) divides $\mathrm{ord}_{\mathfrak{p}}(G)$, so in particular we have

$$\frac{\mathrm{ord}_{\mathfrak{p}}(G)}{h} \equiv a' \bmod d' .$$

Since h divides $\mathrm{ord}_{\mathfrak{p}}(G)$, we have $\frac{\mathrm{ord}_{\mathfrak{p}}(G)}{h} = \mathrm{ord}_{\mathfrak{p}}(G^h)$ and the second congruence holds. Conversely, if the second congruence is satisfied, then $s = (a', d')$ divides $\mathrm{ord}_{\mathfrak{p}}(G^h)$. Since h introduces no new prime factors, we have

$$\mathrm{ord}_{\mathfrak{p}}\left(G^h\right) \cdot h = \mathrm{ord}_{\mathfrak{p}}(G)$$

and hence the congruence $\mathrm{ord}_{\mathfrak{p}}(G) \equiv a \bmod d$ holds.

2.3. A general result

We keep the notation from Theorem 1, and we denote by $\mathrm{Dens}_K(G,d)$ the density of primes $\mathfrak{p}$ of K such that $\mathrm{ord}_{\mathfrak{p}}(G)$ is coprime to d.

Remark 11. From the results in [2] and [7], under the assumptions of Theorems 2 and 4, the density $\mathrm{Dens}_K(G,d)$ depends on G only through the d--parameters for the ℓ-divisibility of G for each $\ell \mid d$. As a consequence of the results of this paper, the same holds for the density $\mathrm{dens}_K(G, a \bmod d)$ considered in Theorems 2 and 4 and in Corollary 3.

Theorem 12. *Let ℓ be a prime number. Suppose that for every G and for every $e \geqslant 1$ we have*

$$\mathrm{dens}_K\left(G, w \bmod \ell^e\right) = \mathrm{dens}_K\left(G, w' \bmod \ell^e\right)$$

as long as w, w' are coprime to ℓ. Then for every G and for every $e \geqslant 1$ the density

$$\mathrm{dens}_K(G, a \bmod \ell^e)$$

depends on a only through its ℓ-adic valuation, and it is a computable rational number.

Proof. We know from [2, Theorem 3] that the quantity

$$\mathrm{Dens}_K(G,\ell) = 1 - \mathrm{dens}_K(G, 0 \bmod \ell)$$

is a computable rational number. Then for every a coprime to ℓ, by the assumption on the equidistribution, we have

$$\mathrm{dens}_K(G, a \bmod \ell^e) = \frac{1}{\varphi(\ell^e)} \cdot \mathrm{Dens}_K(G,\ell) ,$$

so that $\mathrm{dens}_K(G, a \bmod \ell^n)$ is a computable rational number which does not depend on a.

For $0 < a < \ell^e$ not coprime to ℓ we apply Lemma 9, which allows us to compute the density $\mathrm{dens}_K(G, a \bmod \ell^e)$ as the difference of densities which we know to be computable rational numbers. More precisely, by the equidistribution condition the formula given in Lemma 9 becomes

$$\mathrm{dens}_K(G, a \bmod \ell^e) = \mathrm{dens}_K\left(G^{\ell^x},\, w \bmod \ell^{e-x}\right) - \ell \cdot \mathrm{dens}_K\left(G^{\ell^{x-1}},\, w \bmod \ell^{e-x+1}\right),$$

where $a = w\ell^x$ and $x = v_\ell(a)$. In particular, this formula shows that what matters about a is only its ℓ-adic valuation.

Finally, the density for $a = 0$ is given as the complementary density of all the considered cases, and hence it is also a computable rational number. □

Remark 13. Notice that for $0 < a < \ell^e$ with some fixed valuation $v_\ell(a) = x$ where $0 \leqslant x < e$, the previous theorem says that we have the following density

$$\mathrm{dens}_K(G, a \bmod \ell^e) = \frac{1}{\varphi(\ell^{e-x})} \cdot \mathrm{dens}_K\Big(\{\mathfrak{p} : v_\ell\big(\mathrm{ord}_{\mathfrak{p}}(G)\big) = x\}\Big). \tag{7}$$

Proposition 14. *With the assumptions of Theorem 12, we have that the density* $\mathrm{dens}_K(G, a \bmod \ell^e)$ *is strictly positive for every* a.

Proof. For $a = 0$ we know this unconditionally by Remark 8. For $0 < a < \ell^e$, by Theorem 6 the densities (7) in Remark 13 are strictly positive. □

We say that a prime $\mathfrak{p}$ of K is of degree 1 if both its ramification index and its residue class degree over $\mathbb{Q}$ are equal to 1.

Lemma 15. *Let K be a number field, and let G be a finitely generated and torsion-free subgroup of $K^\times$. Let a, d be integers with $d \geqslant 2$ and let $r := \prod_{\ell \mid d} \ell$ be the radical of d. Let $m = r$ if d is odd, and $m = 2r$ otherwise. Consider the following set of primes $\mathfrak{p}$ of K:*

$$\mathcal{S} := \{\mathfrak{p} : \mathrm{ord}_{\mathfrak{p}}(G) \equiv a \bmod d,\, \mathrm{N}\,\mathfrak{p} \equiv 1 \bmod m\}.$$

Then the density of the set $\mathcal{S}$ exists and it is equal to

$$\frac{1}{[K_m : K]} \cdot \mathrm{dens}_{K_m}(G, a \bmod d). \tag{8}$$

Remark 16. Notice that, assuming (GRH), a formula for the density of the set $\mathcal{S}$ is given in [8, Corollary 5.2]. By Theorems 2 and 4 it follows that the density (8) is a computable strictly positive rational number if d is a prime power or if a is coprime to d. Moreover, if $d = \ell^e$ for a prime ℓ, then the density of $\mathcal{S}$ depends on a only through its ℓ-adic valuation, while if d is composite and $(a, d) = 1$, then it does not depend on a.

P r o o f o f L e m m a 15. We may assume that the primes $\mathfrak{p}$ of $\mathcal{S}$ are of degree 1 and unramified in K_m. Hence for a prime $\mathfrak{p}$ in $\mathcal{S}$ we have $\mathrm{N}\,\mathfrak{p} \equiv 1 \bmod m$ if and only if $\mathfrak{p}$ splits completely in K_m. Therefore, the set of primes of K_m lying above the primes of $\mathcal{S}$ is the set

$$\{\mathfrak{P} \subseteq K_m \text{ of degree } 1 : \mathrm{ord}_{\mathfrak{P}}(G) \equiv a \bmod d\}\,,$$

which has density $\mathrm{dens}_{K_m}(G, a \bmod d)$. Thus we obtain that the density of the set $\mathcal{S}$ exists and it is equal to $1/[K_m : K]$ times $\mathrm{dens}_{K_m}(G, a \bmod d)$ (see, for instance, [7, Proposition 1]). □

3. Proof of the results in the Introduction

We keep the notation of Theorem 1.

3.1. Proof of Theorem 2 for ℓ odd

Lemma 17. *Let ℓ be an odd prime number. Suppose that $K = K_\ell$. For every G and for every $e \geqslant 1$ we have*

$$c(n, x, \ell^e, t) = c(n, x', \ell^e, t)$$

as long as x, x' are coprime to ℓ.

P r o o f. Let $d = \ell^e$. Let a vary among the integers strictly between 0 and d and coprime to ℓ. Since a is coprime to ℓ and $d = \ell^e$, the condition $(d, n) \mid a$ means $\ell \nmid n$ and it is independent of a. If $c(n, a, d, t)$ is non-zero, then the integer t must be divisible by ℓ because $\zeta_\ell \in K$ and hence it must be fixed if raised to the power $1 + at$ (recall that a is coprime to ℓ). In particular, the condition $(1 + at, d) = 1$ holds independently of a.

We are left to check that Condition (iii) of Theorem 1 does not depend on a, provided that Conditions (i) and (ii) hold. Write $F := K_{nt,nt}$ and define $\tau := v_\ell(t)$. We thus have to show that the following is independent of a: the Galois group of $F_{\ell^{e+\tau}}/F$ contains the automorphism σ_{1+ta} satisfying $\zeta_{\ell^{e+\tau}} \mapsto \zeta_{\ell^{e+\tau}}^{1+at}$. Since $K = K_\ell$, we have some largest integer $x \geqslant \tau \geqslant 1$ such that F contains $\mathbb{Q}_{\ell^x}$, and this integer determines the Galois group of $F_{\ell^{e+\tau}}/F$, which is a finite cyclic ℓ-group.

If $x \geqslant e+\tau$, then the field extension $F_{\ell^{e+\tau}}/F$ is trivial and the coefficient $c(n,a,\ell^e,t)$ is 0 independently of a. Now suppose that $\tau \leqslant x < e+\tau$. The exponents for the action on $\zeta_{\ell^{e+\tau}}$ are those corresponding to the automorphisms of order dividing $\ell^{e+\tau-x}$. Since $v_\ell(at)$ does not depend on a, we have that

$$v_\ell\big((1+at)^{\ell^n}-1\big) = \tau+n$$

independently of a and we conclude. □

Proof of Theorem 2 for ℓ odd. Lemma 17 implies that the conditions of Theorem 12 are satisfied if $K = K_\ell$ (compare with formula (1)). Thus the density $\mathrm{dens}_K(G, a \bmod d)$ depends on a only through its ℓ-adic valuation, and it is a computable rational number. By Proposition 14 this rational number must be strictly positive. □

3.2. Proof of Theorem 2 for $\ell = 2$

Lemma 18. *Suppose $K = K_4$. For every G and for every $e \geqslant 1$ we have*

$$c(n,x,2^e,t) = c(n,x',2^e,t)$$

as long as x, x' are odd.

Proof. Let $d = 2^e$. Notice that the claim is clear for $e = 1$, so suppose $e \geqslant 2$. Let a vary in the odd integers strictly between 0 and d. Similarly to the proof of Lemma 17, the condition $(n,d) \mid a$ means that $2 \nmid n$ and is independent of a. Moreover, t must be an even integer and hence the condition $(1+at,d) = 1$ is satisfied independently of a. Now suppose that the above conditions are satisfied, and let us focus on Condition (iii) of Theorem 1.

Set $\tau := v_2(t)$, and call F the field $K_{nt,nt}$. Similarly to the proof of Lemma 17, we check that the following condition is independent of a: the Galois group of $F_{2^{e+\tau}}/F$ contains the automorphism σ_{1+ta} satisfying $\zeta_{2^{e+\tau}} \mapsto \zeta_{2^{e+\tau}}^{1+at}$.

Recall that $K = K_4$, and call $x \geqslant 2$ the largest integer such that F contains $\mathbb{Q}_{2^x}$ (we clearly have $x \geqslant \tau$). We then need to investigate the cyclic group $\mathrm{Gal}(\mathbb{Q}_{2^{e+\tau}}/\mathbb{Q}_{2^x})$.

If $x \geqslant e+\tau$, then this field extension is trivial and we have $c(n,a,2^e,t) = 0$ independently of a (where a is odd). If $x = \tau$, then $\mathrm{Gal}(\mathbb{Q}_{2^{e+\tau}}/\mathbb{Q}_{2^x})$ contains 2^e automorphisms acting distinctly on $\zeta_{2^{e+\tau}}$ and fixing ζ_{2^τ}: we deduce that $c(n,a,2^e,t) = 1$ independently of a (where a is odd).

From now on, suppose $\tau < x < e+\tau$. We see $\mathrm{Gal}(\mathbb{Q}_{2^{e+\tau}}/\mathbb{Q}_{2^x})$ as a subgroup of the cyclic Galois group $\mathrm{Gal}(\mathbb{Q}_{2^{e+\tau}}/\mathbb{Q}_4)$. That subgroup contains the elements of order dividing $2^{e+\tau-x}$. The Galois automorphisms are determined by the image of $\zeta_{2^{e+\tau}}$, and they are determined by the exponent to which they raise this element.

If $\tau = 1$, then we do not have the automorphism σ_{1+ta} in $\mathrm{Gal}(\mathbb{Q}_{2^{e+\tau}}/\mathbb{Q}_4)$ (independently of a) because a is odd and hence $\zeta_4^{1+ta} \neq \zeta_4$. This means that in this case $c(n, a, 2^e, t) = 0$ independently of a (for a odd).

Finally, suppose $1 < \tau < x < e + \tau$. Since $\tau > 1$, the automorphism $\sigma_{1+ta} \in \mathrm{Gal}(\mathbb{Q}_{2^{e+\tau}}/\mathbb{Q}_4)$ is well-defined. We have to check whether σ_{1+ta} also belongs to $\mathrm{Gal}(\mathbb{Q}_{2^{e+\tau}}/\mathbb{Q}_{2^x})$ or not independently of a. It is then sufficient to show that the order of σ_{1+ta} does not depend on a. This order is a power of 2, namely the smallest power 2^n such that $v\big((1+at)^{2^n} - 1\big) \geqslant e + \tau$. Since $v_2(at) \geqslant 2$, then for every $n \geqslant 1$ we have $v_2\big((1+at)^{2^n} - 1\big) = \tau + n$ independently of a and hence the order of the automorphism σ_{1+ta} does not depend on a. □

Proof of Theorem 2 for $\ell = 2$. Analogously to the proof for the odd case, it suffices to combine Lemma 18 with Theorem 12 and Proposition 14. □

3.3. Proof of Corollary 3

Proof of Corollary 3. Let $m = \ell$ if ℓ is odd, and $m = 4$ if $\ell = 2$. Let $\mathfrak{p}$ be a prime of K of degree 1, and which does not ramify in K_m. In view of our hypothesis on a, we have that if $\mathfrak{p}$ is such that $\mathrm{ord}_{\mathfrak{p}}(G) \equiv a \bmod \ell^e$, then $\mathrm{N}\mathfrak{p} \equiv 1 \bmod m$. We deduce from Lemma 15 that

$$\mathrm{dens}_K(G, a \bmod \ell^e) = \frac{1}{[K_m : K]} \cdot \mathrm{dens}_{K_m}(G, a \bmod \ell^e)\,.$$

By Theorem 2 we conclude that $\mathrm{dens}_K(G, a \bmod \ell^e)$ depends on a only through its ℓ-adic valuation and that it is a computable strictly positive rational number. □

3.4. Proof of Theorem 4

Lemma 19. *Let $d \geqslant 2$ be an integer and write $d = \prod \ell^e$ for its prime decomposition. For the coefficients of Theorem 1, with respect to any fixed group G, we have*

$$c(n, a, d, t) = \prod_{\ell \mid d} c(n, a, \ell^e, t)\,.$$

Proof. We prove that $c(n, a, d, t) = 1$ if and only if $c(n, a, \ell^e, t) = 1$ for every prime divisor ℓ of d. It is clear that $(1 + at, d) = 1$ and $(d, n) \mid a$ if and only if $(1 + at, \ell^e) = 1$ and $(\ell^e, n) \mid a$ for every ℓ. Now suppose that these conditions hold. Let σ be the element of $\mathrm{Gal}(\mathbb{Q}(\zeta_{dt})/\mathbb{Q})$ such that $\sigma(\zeta_{dt}) = \zeta_{dt}^{1+at}$, and let σ_ℓ be the element of $\mathrm{Gal}(\mathbb{Q}(\zeta_{\ell^e t})/\mathbb{Q})$ such that $\sigma_\ell(\zeta_{\ell^e t}) = \zeta_{\ell^e t}^{1+at}$. We are left to show that σ is the identity on $\mathbb{Q}(\zeta_{dt}) \cap K_{nt,nt}$ if and only if σ_ℓ is the identity on $\mathbb{Q}(\zeta_{\ell^e t}) \cap K_{nt,nt}$ for every ℓ. This follows from the fact that $\mathbb{Q}(\zeta_{dt})$ is the compositum of the fields $\mathbb{Q}(\zeta_{\ell^e t})$, and σ_ℓ is the restriction of σ to $\mathbb{Q}(\zeta_{\ell^e t})$ for each ℓ. □

Lemma 20. *Let $d \geqslant 2$ be an integer and let $r := \prod_{\ell | d} \ell$ be its radical. Suppose that $K = K_r$ if d is odd, or that $K = K_{2r}$ if d is even. For the coefficients of Theorem 1, with respect to any fixed group G, we then have*

$$c(n, x, d, t) = c(n, x', d, t)$$

as long as x, x' are coprime to d.

Proof. We have to show that, whenever a is coprime to d, the coefficient $c(n, a, d, t)$ is independent of a. By Lemma 19 we may reduce to the case in which d is a prime power, and then we may conclude by Lemma 17 if d is odd, and Lemma 18 if d is even. □

Proof of Theorem 4. By [7, Corollary 12] and [2, Theorem 3] the density $\mathrm{Dens}_K(G, d)$ of primes $\mathfrak{p}$ of K such that $\mathrm{ord}_{\mathfrak{p}}(G)$ is coprime to d is an explicitly computable rational number. This density can be decomposed as the sum over a, with a coprime to d, of the densities $\mathrm{dens}_K(G, a \bmod d)$. Since $K_r = K$ if d is odd, and $K_{2r} = K$ if d is even, by Lemma 20 the above densities have equal value, so that for every a coprime to d we have

$$\mathrm{dens}_K(G, a \bmod d) = \frac{1}{\varphi(d)} \cdot \mathrm{Dens}_K(G, d)\,,$$

which is then a computable rational number. Moreover, this density is also strictly positive because by Theorem 6 the density $\mathrm{Dens}_K(G, d)$ is strictly positive. □

3.5. Proof of Theorem 5

Proof of Theorem 5. Let r be the radical of d, and let $m = r$ if d is odd, and $m = 2r$ otherwise. Consider the following set of primes $\mathfrak{p}$ of K of degree 1, and unramified in K_m

$$\mathcal{S} := \{\mathfrak{p} : \mathrm{ord}_{\mathfrak{p}}(G) \equiv a \bmod d,\ \mathrm{N}\,\mathfrak{p} \equiv 1 \bmod m\}\,.$$

By Lemma 15 the set $\mathcal{S}$ has density equal to

$$\frac{1}{[K_m : K]} \cdot \mathrm{dens}_{K_m}(G, a \bmod d)\,.$$

By Theorems 2 and 4, the density $\mathrm{dens}_{K_m}(G, a \bmod d)$ is strictly positive if d is a prime power or if a is coprime to d, so the same holds for the density of $\mathcal{S}$. Consequently, the density $\mathrm{dens}_K(G, a \bmod d)$ is also strictly positive. □

4. Multiplicative groups with torsion

Stating Theorem 1 for a finite group is trivial (the given density is either 0 or 1). However it is not trivial to remove the assumption that the multiplicative group is torsion-free: this is what we achieve in this section. As a side remark, notice that our strategy also applies to the density considered in [8, Theorem 1.4], i.e. if we introduce a condition on the Frobenius conjugacy class with respect to a fixed finite Galois extension of the base field.

Let K be a number field, and let G' be a finitely generated (and not necessarily torsion-free) multiplicative subgroup of $K^\times$ of positive rank. Then we can write G' as $G' = \langle\zeta\rangle \times G$, where ζ is a root of unity of K generating the torsion part of G' and G is torsion-free. Let us exclude finitely many primes $\mathfrak{p}$ of K so that the reduction of G' is well-defined and we have $\mathrm{ord}_\mathfrak{p}(\zeta) = \mathrm{ord}(\zeta)$. The order of G' modulo $\mathfrak{p}$ is then the least common multiple between the order of G modulo $\mathfrak{p}$ and a fixed integer

$$\mathrm{ord}_\mathfrak{p}(G') = [\mathrm{ord}_\mathfrak{p}(G), \mathrm{ord}(\zeta)]\,.$$

We may then reformulate the given problem.

Remark 21. Let G be a finitely generated and torsion-free subgroup of $K^\times$, and fix some integer $n \geqslant 2$. Given two integers a and $d \geqslant 2$, we investigate the density of primes $\mathfrak{p}$ of K for which

$$[\mathrm{ord}_\mathfrak{p}(G), n] \equiv a \bmod d\,. \tag{9}$$

Assuming (GRH), the case $n = 1$ is known, and our aim is reducing to this case. Notice that our method also shows that the considered density exists. We denote this density by $\mathrm{dens}'_K(G, n; a \bmod d)$.

Let ℓ be a prime divisor of n. The aim is finding a way to replace n with $\frac{n}{\ell}$ (or to conclude directly). We distinguish various cases.

Case (i). If $\ell \mid d$ and $\ell \nmid a$, then we have $\mathrm{dens}'_K(G, n; a \bmod d) = 0$ because ℓ divides $[\mathrm{ord}_\mathfrak{p}(G), n]$ and (9) cannot hold.

Case (ii). If $\ell \mid d$ and $\ell \mid a$, then the congruence $[\mathrm{ord}_\mathfrak{p}(G), n] \equiv a \bmod d$ is equivalent to

$$\left[\mathrm{ord}_\mathfrak{p}(G^\ell), \frac{n}{\ell}\right] \equiv \frac{a}{\ell} \bmod \frac{d}{\ell}\,,$$

so we have

$$\mathrm{dens}'_K(G, n; a \bmod d) = \mathrm{dens}'_K\left(G^\ell, \frac{n}{\ell}; \frac{a}{\ell} \bmod \frac{d}{\ell}\right).$$

Case (iii). Suppose that $\ell \nmid d$. Let $\tilde{\ell}$ be a multiplicative inverse for ℓ modulo d, and set $v := v_\ell(n)$. If $\ell^v \mid \mathrm{ord}_{\mathfrak{p}}(G)$, then we have

$$[\mathrm{ord}_{\mathfrak{p}}(G), n] \equiv a \bmod d \quad \Longleftrightarrow \quad \left[\mathrm{ord}_{\mathfrak{p}}(G), \frac{n}{\ell}\right] \equiv a \bmod d\,. \tag{10}$$

If $\ell^v \nmid \mathrm{ord}_{\mathfrak{p}}(G)$, then we have

$$[\mathrm{ord}_{\mathfrak{p}}(G), n] \equiv a \bmod d \quad \Longleftrightarrow \quad \left[\mathrm{ord}_{\mathfrak{p}}(G), \frac{n}{\ell}\right] \equiv a\tilde{\ell} \bmod d\,.$$

The condition $\ell^v \mid \mathrm{ord}_{\mathfrak{p}}(G)$ amounts to

$$\left[\mathrm{ord}_{\mathfrak{p}}(G), \frac{n}{\ell}\right] \;\equiv\; 0 \bmod \ell^v$$

and hence (recalling that ℓ and d are coprime) we can easily combine this congruence and the congruence in (10) with the Chinese Remainder Theorem. The first subcase thus amounts to

$$\left[\mathrm{ord}_{\mathfrak{p}}(G), \frac{n}{\ell}\right] \;\equiv\; a\tilde{\ell}^v\ell^v \bmod d\ell^v.$$

Similarly, the second subcase amounts to letting $\left[\mathrm{ord}_{\mathfrak{p}}(G), \frac{n}{\ell}\right]$ be in the difference of congruence classes

$$(a\tilde{\ell} \bmod d) \;\setminus\; (a\tilde{\ell}^{v+1}\ell^v \bmod d\ell^v)\,.$$

Notice that the congruence classes for the first and second subcase are distinct. Thus if $\ell \nmid d$ we can explicitly write

$$\begin{aligned}\mathrm{dens}'_K(G, n;\, a \bmod d) \;=\; &\mathrm{dens}'_K\left(G, \frac{n}{\ell};\, a_0 \bmod d\ell^v\right)\\ &+ \mathrm{dens}'_K\left(G, \frac{n}{\ell};\, a\tilde{\ell} \bmod d\right)\\ &- \mathrm{dens}'_K\left(G, \frac{n}{\ell};\, a_0\tilde{\ell} \bmod d\ell^v\right),\end{aligned}$$

where we have set $a_0 := a\tilde{\ell}^v\ell^v \bmod d\ell^v$.

We have thus proven the following result.

Theorem 22. *Assume (GRH). Let K be a number field, and let G' be a finitely generated subgroup of $K^\times$ of positive rank. Let $n \geqslant 1$ be the order of the torsion of G', and let G be a torsion-free subgroup of G' such that $G' = G \times \langle\zeta_n\rangle$. Let a and $d \geqslant 2$ be fixed integers. The density of the set of primes $\mathfrak{p}$ of K*

$$\{\mathfrak{p} : \mathrm{ord}_{\mathfrak{p}}(G') \equiv a \bmod d\}$$

exists and can be expressed as a finite sum of terms of the type

$$(-1)^k \cdot \mathrm{dens}_K(G^m, a' \bmod d'),$$

where k, m, a', d' are integers and $m \mid n$.

5. Examples

In this last section we work out some examples and collect some numerical data to illustrate our results.

Example 23. Let $K = \mathbb{Q}(\zeta_3)$ and consider the group $G = \langle 5, 7\rangle \leqslant \mathbb{Q}(\zeta_3)^\times$. We compute the density

$$\mathrm{dens}_K(G, a \bmod 9) \quad \text{for } 0 \leqslant a < 9.$$

Since $\zeta_3 \in K$, we can use [2, Theorem 2] to compute the density of primes $\mathfrak{p}$ of K for which the order of $G \bmod \mathfrak{p}$ is coprime to 3, and we have

$$\mathrm{Dens}_K(G, 3) = \frac{1}{13}\,.$$

Then by Theorem 2 we have

$$\mathrm{dens}_K(G, a \bmod 9) = \frac{1}{78} \quad \text{for } a \in \{1, 2, 4, 5, 7, 8\}\,.$$

For $a = 3$ or $a = 6$, by [2, Theorem 3] we have

$$\mathrm{Dens}_K\big(G^3, 3\big) = \frac{9}{13}$$

and applying Lemma 9 we obtain by the equidistribution property

$$\begin{aligned}\mathrm{dens}_K(G, a \bmod 9) &= \mathrm{dens}_K(G^3, 1 \bmod 3) - 3\,\mathrm{dens}_K(G, 1 \bmod 9)\\ &= \frac{9}{2 \cdot 13} - 3 \cdot \frac{1}{78} = \frac{4}{13}\,.\end{aligned}$$

For $a = 0$ we get the complementary density of $\mathrm{Dens}_K(G^3, 3)$ and hence

$$\mathrm{dens}_K(G, 0 \bmod 9) = \frac{4}{13}\,.$$

Example 24. Let $K = \mathbb{Q}(\zeta_4)$ and consider the group $G = \langle 3, 5\rangle \leqslant \mathbb{Q}(\zeta_4)^\times$. We compute the density of primes $\mathrm{dens}_K(G, a \bmod 8)$ for $0 \leqslant a < 8$. Since $\zeta_4 \in K$, by [2, Theorem 2] the density of primes $\mathfrak{p}$ of K for which the order of $G \bmod \mathfrak{p}$ is odd is given by

$$\mathrm{Dens}_K(G, 2) = \frac{1}{28}\,.$$

Then by Theorem 2 we have

$$\mathrm{dens}_K(G, a \bmod 8) = \frac{1}{112} \quad \text{for } a \in \{1, 3, 5, 7\}\,.$$

For $a = 2$ or $a = 6$, by [2, Theorem 3] we have

$$\mathrm{Dens}_K\big(G^2, 2\big) = \frac{1}{7}\,,$$

and applying Lemma 9 we obtain by the equidistribution property

$$\begin{aligned}\mathrm{dens}_K(G, a \bmod 8) &= \mathrm{dens}_K\big(G^2, 1 \bmod 4\big) - 2\,\mathrm{dens}_K\big(G, 1 \bmod 8\big)\\ &= \frac{1}{14} - 2 \cdot \frac{1}{112} = \frac{3}{56}\,.\end{aligned}$$

For $a = 4$ we proceed similarly. By [2, Theorem 3] we have

$$\mathrm{Dens}_K\big(G^4, 2\big) = \frac{4}{7}\,,$$

and then, by Lemma 9, we obtain by the equidistribution property

$$\begin{aligned}\mathrm{dens}_K(G, 4 \bmod 8) &= \mathrm{dens}_K\big(G^4, 1 \bmod 2\big) - 2\,\mathrm{dens}_K\big(G^2, 1 \bmod 4\big)\\ &= \frac{4}{7} - \frac{1}{7} = \frac{3}{7}\,.\end{aligned}$$

Finally, for $a = 0$ we obtain the complementary density

$$\mathrm{dens}_K(G, 0 \bmod 8) = \frac{3}{7}\,.$$

Example 25. Let $K = \mathbb{Q}(\zeta_{12})$ and consider the group $G = \langle 7, 11\rangle \leqslant \mathbb{Q}(\zeta_{12})^\times$. We compute the density of primes $\mathrm{dens}_K(G, a \bmod 12)$ for $a \in \{1, 5, 7, 11\}$, which are all equal by Theorem 4 as $\zeta_{12} \in K$. By [7, Corollary 12] the density of primes $\mathfrak{p}$ of K for which the order of $G \bmod \mathfrak{p}$ is coprime to 12 can be computed as in the previous examples

$$\mathrm{Dens}_K(G, 12) = \mathrm{Dens}_K(G, 4) \cdot \mathrm{Dens}_K(G, 3) = \frac{1}{364}\,.$$

Hence we obtain by the equidistribution

$$\mathrm{dens}_K(G, a \bmod 12) = \frac{1}{1456}\,.$$

In the following two examples we also compute with SageMath [9] approximated densities to support the validity of the equidistribution property of Corollary 3.

Example 26. Consider the group $\langle 2\rangle \leqslant \mathbb{Q}^\times$. Focusing on the set of primes up to 10^6, we find with SageMath the following approximated values for the density $\mathrm{dens}_{\mathbb{Q}}(2, a \bmod d)$

$a \bmod d$	$\mathrm{dens}_{\mathbb{Q}}(2, a \bmod d)$	primes up to 10^6
4 mod 16	$1/6 \approx 0.1667$	0.1676
12 mod 16	$1/6 \approx 0.1667$	0.1652
3 mod 9	$1/8 = 0.125$	0.1236
6 mod 9	$1/8 = 0.125$	0.1266
9 mod 27	$1/24 \approx 0.0417$	0.0422
18 mod 27	$1/24 \approx 0.0417$	0.0411
3 mod 27	$1/24 \approx 0.0417$	0.0416
6 mod 27	$1/24 \approx 0.0417$	0.0421
15 mod 27	$1/24 \approx 0.0417$	0.0420
21 mod 27	$1/24 \approx 0.0417$	0.0405

For instance, by Corollary 3, for $3 \mid a$ and $d = 9$ or $d = 27$ we have

$$\mathrm{dens}_{\mathbb{Q}}(2, a \bmod d) = \frac{1}{[\mathbb{Q}(\zeta_3) : \mathbb{Q}]} \cdot \mathrm{dens}_{\mathbb{Q}(\zeta_3)}(2, a \bmod d)\,,$$

and similarly for $4 \mid a$ and $d = 16$. Thus we can compute these densities by following the same procedure as in the previous examples.

Example 27. We consider the group $G = \langle 2, 3 \rangle \leqslant \mathbb{Q}^\times$ and compute the densities $\mathrm{dens}_{\mathbb{Q}}(G, a \bmod d)$ using the methods of the previous examples. Again we study the set of primes up to 10^6 and find with SageMath the following approximated values for the considered densities:

$a \bmod d$	$\mathrm{dens}_{\mathbb{Q}}(G, a \bmod d)$	primes up to 10^6
4 mod 16	$17/112 \approx 0.1518$	0.1522
12 mod 16	$17/112 \approx 0.1518$	0.1508
3 mod 9	$2/13 \approx 0.1538$	0.1538
6 mod 9	$2/13 \approx 0.1538$	0.1540
9 mod 27	$2/39 \approx 0.0513$	0.0513
18 mod 27	$2/39 \approx 0.0513$	0.0513
3 mod 27	$2/39 \approx 0.0513$	0.0518
6 mod 27	$2/39 \approx 0.0513$	0.0512
15 mod 27	$2/39 \approx 0.0513$	0.0513
21 mod 27	$2/39 \approx 0.0513$	0.0507

Example 28. Let $K = \mathbb{Q}(\zeta_3)^\times$, and let G be a finitely generated and torsion-free subgroup of $\mathbb{Q}(\zeta_3)^\times$. Consider the group $G' = G \times \langle \zeta_6 \rangle$. We study the density of primes $\mathfrak{p}$ of K such that $\mathrm{ord}_{\mathfrak{p}}(G') \equiv a \bmod 10$, as considered in Section 4.

For $a = 1, 3, 5, 7, 9$, we have $\mathrm{dens}'_K(G, 6; a \bmod 10) = 0$. For $a = 4$ we have

$$\begin{aligned}\mathrm{dens}'_K(G, 6; 4 \bmod 10) &= \mathrm{dens}'_K(G, 2; 24 \bmod 30) + \mathrm{dens}'_K(G, 2; 8 \bmod 10) \\ &\quad - \mathrm{dens}'_K(G, 2; 18 \bmod 30) \\ &= \mathrm{dens}_K(G^2, 12 \bmod 15) + \mathrm{dens}_K(G^2, 4 \bmod 5) \\ &\quad - \mathrm{dens}_K(G^2, 9 \bmod 15)\,,\end{aligned}$$

and also

$$\begin{aligned}\mathrm{dens}'_K(G, 6; 4 \bmod 10) &= \mathrm{dens}'_K(G^2, 3; 2 \bmod 5) \\ &= \mathrm{dens}_K(G^2, 12 \bmod 15) + \mathrm{dens}_K(G^2, 4 \bmod 5) \\ &\quad - \mathrm{dens}_K(G^2, 9 \bmod 15)\,,\end{aligned}$$

where the difference in the two calculations consists only in whether we consider the prime 2 or the prime 3 first for the method described in Section 4. For $a = 2, 6, 8$ we can make a similar computation. Finally, for $a = 0$ we have

$$\mathrm{dens}'_K(G, 6; 0 \bmod 10) = \mathrm{dens}_K(G, 0 \bmod 5)\,,$$

as 2 always divides $\mathrm{ord}_{\mathfrak{p}}(G')$, and

$$\mathrm{ord}_{\mathfrak{p}}(G') \equiv 0 \bmod 5 \quad \text{if and only if} \quad \mathrm{ord}_{\mathfrak{p}}(G) \equiv 0 \bmod 5.$$

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