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Lower Bounds for the Height and Size of the Ideal Class Group in CM-Fields

By

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Abstract. We prove that, under the assumption of the Generalized Riemann Hypothesis, the exponent of the ideal class group of a CM-field goes to infinity with its absolute discriminant. This gives a positive answer to a question raised by Louboutin and Okazaki [4].

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1. Introduction

In a recent talk given at the University of Caen, S. Louboutin conjectured that the exponent of the ideal class group of a CM field goes to infinity with its absolute discriminant. Subsequently, he has also succeeded to prove a weak version of his conjecture. Let K be a CM field, and denote by d_K, Δ_K and E_K the degree, the discriminant and the exponent of the ideal class group of K, respectively. Then Louboutin and Okazaki [4] proved that, restricting to the CM fields with given degree $d_K = d$, one has

$$E_K \gg_d \frac{\log|\Delta_K|}{\log\log|\Delta_K|}, \tag{1}$$

where the constant involved depends on d only.

In this paper we develop the methods introduced in [2] and we investigate further the links between lower bounds for the height and the class group of CM-fields; this will give, in particular, a complete positive answer to Louboutin's conjecture.

Consider first the simpler case of cyclotomic extensions. Let ζ_m be a primitive m-root of unity and denote by E_m the exponent of the ideal class group of the cyclotomic field $\mathbb{Q}(\zeta_m)$. Corollary 2 of [2] gives the lower bound

$$E_m \geqslant \frac{\log 5}{12} \times \frac{\phi(m)}{\log p},$$

where p is a rational prime which splits completely in $\mathbb{Q}(\zeta_m)$. It is well-known that p splits completely in $\mathbb{Q}(\zeta_m)$ if and only if $p \equiv 1 \pmod{m}$, and therefore, by a celebrated result of Linnik, there exists an effective and absolute constant $L > 0$ and a rational prime $p < m^L$ which splits completely in $\mathbb{Q}(\zeta_m)$. Using Mertens' inequality $\phi(m) \gg \frac{m}{\log\log m}$, one gets the lower bound

$$E_m \geqslant \frac{\log 5}{12L} \times \frac{\phi(m)}{\log m} \gg \frac{m}{(\log m)(\log\log m)}$$

that depends only on m.

Let now K be a complex abelian extension, and let d_K, Δ_K and E_K be as above. Then, again by Corollary 2 of [2],

$$E_K \geqslant \frac{\log 5}{12} \times \frac{d_K}{\log p}, \tag{2}$$

where p is a rational prime which splits completely in K. Using the Generalized Riemann Hypothesis, we can find (see [3]) a rational prime $p \ll (\log|\Delta_K|)^2$ which splits completely in K; hence

$$E_K \gg \frac{d_K}{\log\log|\Delta_K|},$$

where the implicit constant in $\gg$ is absolute and effectively computable. To obtain an estimate depending only on the degree d_K, or only on the discriminant Δ_K, it is enough to show that, if the exponent E_K is small, then Δ_K is bounded in terms of d_K. We shall use a result of Silverman (see Lemma 4.3) to prove that

$$E_K \gg \frac{\max\left\{d_K^{-1}\log|\Delta_K| - \log d_K, d_K\right\}}{\log\log|\Delta_K|}.$$

Therefore, E_K goes to infinity with $|\Delta_K|$. More precisely,

$$E_K \gg \max\left\{\frac{\sqrt{\log|\Delta_K|}}{\log\log|\Delta_K|}, \frac{d_K}{\log d_K}\right\}.$$

Now, let us consider the case when K is a CM-field, *i.e.* an imaginary quadratic extension of a totally real field. As K need not to be abelian, we cannot apply inequality (2). However, the argument of Corollary 2 in [2] works also in this case, provided that one has some lower bound for the height of elements of K. Using the general estimate for the height given in [1], we can prove that for any $\varepsilon > 0$,

$$E_K \gg_\varepsilon \frac{\max\left\{d_K^{-1}\log|\Delta_K| - \log d_K, d_K^{1-\varepsilon}\right\}}{\log\log|\Delta_K|} \tag{3}$$

where the implicit constant in $\gg_\varepsilon$ depends only on ε and is effectively computable. Therefore, E_K goes again to infinity with $|\Delta_K|$. More precisely, if $\varepsilon < 1/2$ we have

$$\max\left\{d_K^{-1}\log|\Delta_K| - \log d_K, d_K^{1-\varepsilon}\right\} \gg_\varepsilon \max\{(\log|\Delta_K|)^{1/2-\varepsilon}, d_K^{1-\varepsilon}\};$$

thus, for any $\varepsilon' > 0$ the exponent E_K is bounded from below by a positive quantity depending on ε' times

$$\max\{(\log|\Delta_K|)^{1/2-\varepsilon'}, d_K^{1-\varepsilon'}\}.$$

It is to be remarked that our result (3) includes inequality (1) as a special case.

We shall deduce these bounds from a more general result concerning the size of the multiplicative relations in the class group of a CM-field. Let G be a group and let l be a positive integer. We define $\mathscr{M}_G(l)$ as the least integer A such that for all $g_1, \ldots, g_l \in G$ there exists $\underline{a} \in \mathbb{Z}^l \backslash \{0\}$ such that $g_1^{a_1} \cdots g_l^{a_l} = e$ and $\sum_j |a_j| \leqslant A$. Then we have:

Theorem 1.1. *Let $K/\mathbb{Q}$ be a CM-field and let G be the ideal class group of K. Let also l be a positive integer. Then, for any $\varepsilon > 0$ and under the assumption of the Generalized Riemann Hypothesis for the Dedekind zeta function of K, we have*

$$\mathscr{M}_G(l) \gg_\varepsilon \frac{\max\left\{d_K^{-1}\log|\Delta_K| - \log d_K, d_K^{1-\varepsilon}\right\}}{\log l + \log\log|\Delta_K|}.$$

Moreover, if $K/\mathbb{Q}$ is abelian, then the conclusion holds also for $\varepsilon = 0$.

This theorem gives some information on the invariants of the ideal class group of a CM field (we recall that the positive integers $\lambda_1, \lambda_2, \ldots, \lambda_n$ are the invariants of a finite abelian group G if G is isomorphic to the direct product of cyclic groups of order $\lambda_1, \lambda_2, \ldots, \lambda_n$ with $\lambda_n | \lambda_{n-1} | \cdots | \lambda_1$).

Corollary 1.2. *Let $\lambda_1, \lambda_2, \ldots, \lambda_n$ be the invariants of G and put $\lambda_{n+1} = 1$. Let also $\varepsilon > 0$ and $j \in \{1, \ldots, n+1\}$. Then, again under the assumption of the Generalized Riemann Hypothesis for the Dedekind zeta function of K*

$$\lambda_j \log\left(\frac{\lambda_1 \cdots \lambda_{j-1}}{\lambda_j^{j-1}} \log|\Delta_K|\right) \gg_\varepsilon \max\left\{d_K^{-1}\log|\Delta_K| - \log d_K, d_K^{1-\varepsilon}\right\}.$$

Moreover, if $K/\mathbb{Q}$ is abelian, then the above conclusions hold also for $\varepsilon = 0$.

By choosing $j = 1$ we find the announced lower bounds for the exponent. On the other hand, the choice $j = n+1$ gives a 'good' lower bound for the class number of a CM-field:

Corollary 1.3. *Let $\varepsilon \in (0, 1/2)$; then, still under the assumption of the Generalized Riemann Hypothesis for the Dedekind zeta function of K,*

$$\log h_K \gg_\varepsilon \max\left\{d_K^{-1}\log|\Delta_K| - \log d_K, d_K^{1-\varepsilon}\right\}.$$

Hence

$$\log h_K \gg_\varepsilon \max\{(\log|\Delta_K|)^{1/2-\varepsilon}, d_K^{1-\varepsilon}\}.$$

Moreover, if $K/\mathbb{Q}$ is abelian, then the above conclusions hold also for $\varepsilon = 0$.

These bounds for h_K must be compared with [5], Theorem 2, p. 279 and with [8], Theorem 2, p. 136.

2. Analytic Results

Throughout the paper $c_1, c_2, \ldots$ will be positive absolute constants which are effectively computable.

Let K be any number field and let $x > 1$. We denote by $\pi_K'(x)$ the number of primes $P \subseteq \mathcal{O}_K$ of degree 1, non-ramified over $\mathbb{Q}$, and such that $|N_{\mathbb{Q}}^K P| \leqslant x$. The following lemma is an easy corollary of a very special case of the effective version of the Čebotarev Density Theorem proved by Lagarias and Odlyzko (see [3]).

Lemma 2.1. *If the Generalized Riemann Hypothesis holds for the Dedekind zeta function of K, then for every* $x \geqslant c_1(\log|\Delta_K|)^2(\log\log|\Delta_K|)^4$,

$$\pi'_K(x) \geqslant c_2\frac{x}{\log x}.$$

Proof. Applying Theorem 1.1 of [3] (with $L = K$), we get the following estimate for the cardinality $\pi_K(x)$ of the primes $P \subseteq \mathcal{O}_K$ of norm $\leqslant x$,

$$\pi_K(x) \geqslant \mathrm{Li}(x) - c_3\big((\sqrt{x}+1)\log|\Delta_K| + d_K\log x\big).$$

Using the well-known lower bound $\log|\Delta_K| \geqslant c_4 d_K$, the asymptotic equality $\mathrm{Li}(x) \sim \frac{x}{\log x}$ and our assumption on x, we get

$$\pi_K(x) \geqslant c_5\frac{x}{\log x}.$$

If p is a rational prime ramified in K, then p divides $|\Delta_K|$. Since in K there are at most d_K primes over p, we obtain

$$\#\{P \subseteq \mathcal{O}_K,\ P \text{ ramified over } \mathbb{Z}\} \leqslant d_K\frac{\log|\Delta_K|}{\log 2} \leqslant c_6(\log|\Delta_K|)^2 \leqslant c_7\frac{x}{(\log x)^4}.$$

Moreover, if P has degree >1 and norm $\leqslant x$, then the rational prime p under P satisfies $p \leqslant \sqrt{x}$. Hence

$$\#\{P \subseteq \mathcal{O}_K,\ P \text{ of degree} > 1,\ N^K_{\mathbb{Q}}P \leqslant x\} \leqslant d_K\pi(\sqrt{x}) \leqslant c_8\frac{x}{(\log x)^2}.$$

Now Lemma 2.1 easily follows. □

3. Algebraic Results

Lemma 3.1. *Let K be a number field, let p be a rational prime and P be an ideal prime above p such that* $e(P|p) = e_P$, $f(P|p) = f_P$. *Let L be the normal closure of K in* $\overline{\mathbb{Q}}$. *Then*

$$|\{\sigma(P\mathcal{O}_L)|\sigma \in \mathrm{Gal}(L/\mathbb{Q})\}| \geqslant \frac{d_K}{e_P f_P}.$$

Proof. Let $d = d_K$ and $[L:K] = s$, so that $[L:\mathbb{Q}] = ds$. Since $L/\mathbb{Q}$ is normal, the factorization into prime ideals of $p\mathcal{O}_L$ can be written as

$$p\mathcal{O}_L = (Q_1,\ldots,Q_r)^e$$

where all Q_i have the same inertial degree f and $ref = ds$. By the multiplicativity of the ramification index and of the inertial degree in towers, we have, possibly after a renumbering of $Q_1,\ldots,Q_r$,

$$(P\mathcal{O}_L)^{e_P} = (Q_1,\ldots,Q_h)^e$$

where $\frac{hef}{e_P f_P} = s$. The Galois group $\mathrm{Gal}(L/\mathbb{Q})$ acts transitively on the set $\{Q_1,\ldots,Q_r\}$, hence the number of conjugates of P is not less that $\frac{r}{h} = \frac{d}{e_P f_P}$. □

We recall that a CM-field is an imaginary quadratic extension of a totally real field. If K is a CM-field, we denote by K^+ the totally real field $K \cap \mathbb{R}$.

Lemma 3.2. *Let K be a CM-field, let p be a rational prime, and assume that P is a prime of K above p such that $e(P|p) = f(P|p) = 1$. Then $\bar{P} \neq P$.*

Proof. Let $Q = P \cap K^+$. Then the factorization of $Q\mathcal{O}_K$ is of type $Q = PP'$, where $P' \neq P$. On the other hand, P and P' are conjugate under the Galois group $\mathrm{Gal}(K/K^+)$. Since this Galois group consists of the identity and of the complex conjugation, we have $P' = \bar{P}$. □

CM-fields are characterized by the following property: let $\alpha \in K$ and assume that $|\alpha| = 1$; then for any $\sigma \in \mathrm{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$ we have $|\sigma\alpha| = 1$. This property will play a central role in the sequel. The link between primes of small norm and algebraic numbers of small height in CM-fields is given by the following proposition, which generalizes Corollary 2 of [2].

Proposition 3.3. *Let K be a CM-field and let $P_1, \dots, P_k \subseteq \mathcal{O}_K$ be primes of degree 1 and not ramified over $\mathbb{Q}$. Assume that $P_i \neq P_j$ and $P_i \neq \bar{P}_j$ for $i \neq j$. Let also $a_1, \dots, a_k$ be integers such that $P_1^{a_1} \cdots P_l^{a_k} = (\gamma)$ is a principal ideal and let $\alpha = \gamma/\bar{\gamma}$. Then:*

$$d_K h(\alpha) = \sum_{j=1}^{k} |a_j| \log N_{\mathbb{Q}}^K P_j.$$

Moreover, if $(a_1, \dots, a_l) \neq (0, \dots, 0)$ and if the rational primes $P_1 \cap \mathbb{Z}, \dots, P_k \cap \mathbb{Z}$ are all distinct, then α is a generator of K over $\mathbb{Q}$.

Proof. Since $P_j \neq \bar{P}_j$ by Lemma 3.2, the prime ideals $P_1, \dots, P_k, \bar{P}_1, \dots, \bar{P}_k$ are distinct. For $j = 1, \dots, k$ let v_j be the place relative to P_j and $\bar{v}_j$ be the place relative to $\bar{P}_j$. Then

$$|\alpha|_{v_j}^{n_{v_j}} = (N_{\mathbb{Q}}^K P_j)^{-a_j} \quad \text{and} \quad |\alpha|_{\bar{v}_j}^{n_{\bar{v}_j}} = (N_{\mathbb{Q}}^K P_j)^{a_j}.$$

Hence, $\log \max\{|\alpha|_{v_j}^{n_{v_j}}, 1\} + \log \max\{|\alpha|_{\bar{v}_j}^{n_{\bar{v}_j}}, 1\} = |a_j| \log N_{\mathbb{Q}}^K P_j$. Moreover $|\alpha| = 1$, hence $|\alpha|_v = 1$ for any archimedean place v, since K is a CM-field. Therefore,

$$dh(\alpha) = \sum_{\substack{v \in M_K \\ v|\infty}} \log \max\{|\alpha|_v^{n_v}, 1\}|\} + \sum_{\substack{v \in M_K \\ v \nmid \infty}} \log \max\{|\alpha|_v^{n_v}, 1\}|\} = \sum_{j=1}^{k} |a_j| \log N_{\mathbb{Q}}^K P_j.$$

We now assume that the rational primes $P_1 \cap \mathbb{Z}, \dots, P_k \cap \mathbb{Z}$ are all distinct and we show that α is a generator of K over $\mathbb{Q}$. Since $\alpha \in K$, it is enough to show that $[\mathbb{Q}(\alpha) : \mathbb{Q}] \geqslant d_K$. Let L be the normal closure of K in $\overline{\mathbb{Q}}$ and assume $a_1 \neq 0$; by Lemma 3.1, $P_1\mathcal{O}_L$ has at least d_K distinct conjugate ideals $\sigma_1(P_1\mathcal{O}_L), \dots, \sigma_{d_K}(P_1\mathcal{O}_L)$. Assume that, for some $i, j \in \{1, \dots, d_K\}$, we have $\sigma_i(\alpha) = \sigma_j(\alpha)$. Then

$$\begin{aligned} &\sigma_i(P_1\mathcal{O}_L)^{a_1} \sigma_i(\bar{P}_1\mathcal{O}_L)^{-a_1} \cdots \sigma_i(P_k\mathcal{O}_L)^{a_k} \sigma_i(\bar{P}_k\mathcal{O}_L)^{-a_k} \\ &\quad = \sigma_j(P_1\mathcal{O}_L)^{a_1} \sigma_j(\bar{P}_1\mathcal{O}_L)^{-a_1} \cdots \sigma_j(\bar{P}_k\mathcal{O}_L)^{a_k} \sigma_j(\bar{P}_k\mathcal{O}_L)^{-a_k}. \end{aligned}$$

Since $P_1 \cap \mathbb{Z}, \dots, P_k \cap \mathbb{Z}$ are all distinct, we must have

$$\sigma_i(P_1\mathcal{O}_L)^{a_1} \sigma_i(\bar{P}_1\mathcal{O}_L)^{-a_1} = \sigma_j(P_1\mathcal{O}_L)^{a_1} \sigma_j(\bar{P}_1\mathcal{O}_L)^{-a_1}.$$

Since $P_1 \neq \bar{P}_1$ by Lemma 3.2, the ideals $\sigma_i(P_1\mathcal{O}_L)^{a_1}$ and $\sigma_i(\bar{P}_1\mathcal{O}_L)^{a_1}$ are coprime; by unique factorization of the ideals in $\mathcal{O}_L$, we get $\sigma_i(P_1\mathcal{O}_L)^{a_1} = \sigma_j(P_1\mathcal{O}_L)^{a_1}$, whence $\sigma_i(P_1\mathcal{O}_L) = \sigma_j(P_1\mathcal{O}_L)$ and $i = j$. It follows that α has at least d_K distinct conjugates in $\overline{\mathbb{Q}}$, whence $[\mathbb{Q}(\alpha) : \mathbb{Q}] \geqslant d_K$, as claimed. This completes the proof of the proposition. □

4. Diophantine Results

We now state three "diophantine results" concerning lower bounds for the Weil absolute logarithmic height $h(\cdot)$, that we shall need later for the proof of our main result.

Lemma 4.3. *Let K be a number field. Then, for any generator α of K we have:*

$$h(\alpha) \geqslant \frac{d_K^{-1}\log|\Delta_K| - \log d_K}{2(d_K - 1)}.$$

Proof. The lemma is a special case of Theorem 2 of [6]. It is also an easy consequence of the inequality $|\Delta_K| \leqslant |\mathrm{disc}(\alpha)|$ (see [7]) and of Hadamard's inequality. □

The next two lower bounds for the height are respectively the main result of [2] (Theorem at p. 261) and of [1] (Theorem 1.6, p. 148).

Theorem 4.4. *Let $K/\mathbb{Q}$ be an abelian extension and let $\alpha \in K^*$, α not a root of unity. Then*

$$h(\alpha) \geqslant \frac{\log 5}{12}.$$

Theorem 4.5. *Let $K/\mathbb{Q}$ be any number field and let $\alpha_1, \ldots, \alpha_m \in K^*$ multiplicatively independent. Then*

$$\big(h(\alpha_1)\cdots h(\alpha_m)\big)^{1/m} \geqslant c_9(m) d_K^{-1/m} \log(3d_K)^{-k(m)}$$

where $c_9(m)$ and $k(m)$ are positive constant depending only on m.

5. Size of the Ideal Class Group in CM-Fields

We now prove Theorem 1.1.

I) We start by proving that

$$\mathcal{M}_G(l) \geqslant c_{10} \frac{d_K^{-1}\log|\Delta_K| - \log d_K}{\log l + \log\log|\Delta_K|} \tag{4}$$

for some positive absolute constant c_{10}. We choose

$$x = c_{11} l d_K \log(l d_K) + c_1 (\log|\Delta_K|)^2 (\log\log|\Delta_K|)^4,$$

where c_{11} is such that $c_2 x (\log x)^{-1} \geqslant l d_K$. Since there at most d_K distinct primes in K over a rational prime, by Lemma 2.1 we can find l distinct rational primes $p_1, \ldots, p_l \leqslant x$ and l primes ideals $P_1, \ldots, P_l \subseteq \mathcal{O}_K$ such that $P_i \cap \mathbb{Z} = (p_i)$ and $e(P_i|p_i) = f(P_i|p_i) = 1$ for $i = 1, \ldots, l$. Let g_i be the class of P_i in G and assume that there exists a non-trivial multiplicative relation

$$g_1^{a_1}\cdots g_l^{a_l}=1$$

with a_i integers. Let $A=\sum_i |a_i|$; by assumption, $P_1^{a_1}\cdots P_l^{a_l}=(\gamma)$ is a principal ideal. Let $\alpha=\gamma/\bar{\gamma}$; by Proposition 3.3, α is a generator of K over $\mathbb{Q}$ and

$$d_K h(\alpha)=\sum_{i=1}^{l}|a_i|\log N_{\mathbb{Q}}^{K}P_i\leqslant A\log x.$$

Remark that

$$\log x\leqslant c_{12}(\log l+\log d_K+\log\log|\Delta_K|)\leqslant c_{13}(\log l+\log\log|\Delta_K|),$$

since $\log|\Delta_K|\geqslant c_4 d_K$. Hence, by Lemma 4.3,

$$\frac{d_K^{-1}\log|\Delta_K|-\log d_K}{2(d_K-1)}\leqslant c_{13}A\frac{\log l+\log\log|\Delta_K|}{d_K}.$$

We get

$$A\geqslant c_{10}\frac{d_K^{-1}\log|\Delta_K|-\log d_K}{\log l+\log\log|\Delta_K|}.$$

II) We now prove that if $K/\mathbb{Q}$ is abelian, then

$$\mathscr{M}_G(l)\geqslant c_{14}\frac{d_K}{\log l+\log\log|\Delta_K|} \tag{5}$$

for some positive absolute constant c_{14}. We choose

$$x=c_{15}l\log l+c_1(\log|\Delta_K|)^2(\log\log|\Delta_K|)^4$$

where c_{15} is such that $c_2x(\log x)^{-1}\geqslant 2l$. By Lemma 2.1 we can find l primes ideals $P_1,\ldots,P_l\subseteq\mathscr{O}_K$ of degree 1 and not ramified over $\mathbb{Q}$, such that

$$P_i\neq P_j\quad\text{and}\quad P_i\neq\bar{P}_j$$

for $i\neq j$. Let g_i be the class of P_i in G and assume that there exists a non-trivial multiplicative relation

$$g_1^{a_1}\cdots g_l^{a_l}=e$$

with a_i integers. Let $A=\sum_i |a_i|$; by assumption, $P_1^{a_1}\cdots P_l^{a_l}=(\gamma)$ is a principal ideal. Let $\alpha=\gamma/\bar{\gamma}$; by Proposition 3.3,

$$d_K h(\alpha)=\sum_{i=1}^{l}|a_i|\log N_{\mathbb{Q}}^{K}P_i\leqslant A\log x\leqslant c_{16}A(\log l+\log\log|\Delta_K|).$$

Hence, by Theorem 4.4,

$$c_{16}A(\log l+\log\log|\Delta_K|)\geqslant\frac{d_K\log 5}{12}.$$

We get

$$A\geqslant c_{14}\frac{d_K}{\log l+\log\log|\Delta_K|}.$$

III) We finally prove that for any $\varepsilon > 0$ we have

$$\mathscr{M}_G(l) \geqslant c_{17}(\varepsilon) \frac{d_K^{1-\varepsilon}}{\log l + \log\log|\Delta_K|} \tag{6}$$

for some positive constant $c_{17}(\varepsilon)$. Let $m = [1/\varepsilon] + 1$ and choose

$$x = c_{18} lm \log(lm) + c_1 (\log|\Delta_K|)^2 (\log\log|\Delta_K|)^4,$$

where c_{18} is such that $c_2 x(\log x)^{-1} \geqslant 2lm$. By Lemma 2.1 we can find $l \times m$ prime ideals $P_{ij} \subseteq \mathscr{O}_K (i = 1, \dots, l;\ j = 1, \dots, m)$ of degree 1 and not ramified over $\mathbb{Q}$, such that

$$P_{i_1 j_1} \neq P_{i_2 j_2} \quad \text{and} \quad P_{i_1 j_1} \neq \bar{P}_{i_2 j_2}$$

for $(i_1, j_1) \neq (i_2, j_2)$. Let g_{ij} be the class of P_{ij} in G and assume that for $j = 1, \dots, m$ there exists a non-trivial multiplicative relation

$$g_{1j}^{a_{1j}} \cdots g_{lj}^{a_{lj}} = e$$

with a_{ij} integers. Let $A = \max_j \sum_i |a_{ij}|$; by assumption, $P_{1j}^{a_{1j}} \cdots P_{lj}^{a_{lj}} = (\gamma_j)$ is a principal ideal. Let $\alpha_j = \gamma_j / \bar{\gamma}_j$; by Proposition 3.3,

$$d_K h(\alpha_j) = \sum_{i=1}^{l} |a_{ij}| \log N_{\mathbb{Q}}^K P_{ij} \leqslant A \log x \leqslant c_{19} A (\log l + \log m + \log\log|\Delta_K|).$$

Therefore

$$\big(h(\alpha_1) \cdots h(\alpha_m)\big)^{1/m} \leqslant c_{19} A \frac{\log l + \log m + \log\log|\Delta_K|}{d_K}.$$

Moreover, $\alpha_1, \dots, \alpha_m$ are multiplicatively independent (in fact, if $\alpha_1^{e_1} \cdots \alpha_m^{e_1} = 1$, then, again by Proposition 3.3, $0 = \sum_j |e_j| \sum_i |a_{ij}| \log N_{\mathbb{Q}}^K P_{ij}$ and hence $e_1 = \cdots = e_m = 0$). We can apply Theorem 4.5, obtaining

$$c_{19} A \frac{\log l + \log m + \log\log|\Delta_K|}{d_K} \geqslant c_9(m) d_K^{-1/m} \log(3d_K)^{-k(m)}.$$

By the choice of m, this yields

$$A \geqslant \frac{c_9(m) d_K^{1-1/m} \log(3d_K)^{-k(m)}}{c_{19}(\log l + \log m + \log\log|\Delta_K|)} \geqslant c_{17}(\varepsilon) \frac{d_K^{1-\varepsilon}}{\log l + \log\log|\Delta_K|}.$$

The conclusion of Theorem 1.1 follows from (4), (5) and (6). □

For the proof of Corollary 1.2 we need the following lemma.

Lemma 5.1. *Let G be a finite group of exponent E and order m. Then*

(i) $\mathscr{M}_G(1) = E$;
(ii) $\mathscr{M}_G(m) \leqslant 2$;
(iii) *Assume that G is abelian. If λ divides $o(G)$ then $\mathscr{M}_G(o(G/G_\lambda)) \leqslant 2\lambda$, where $G_\lambda = \{g \in G | g^\lambda = 1\}$.*

Proof. (i) is clear. As to (ii), let $g_1, \ldots, g_m \in G$. If $g_i = 1$ for some i, we have an obvious non-trivial multiplicative relation. Otherwise there exists i, j such that $i \neq j$ and $g_i g_j^{-1} = 1$. In any case there exists a non-trivial multiplicative relation $g_1^{a_1} \cdots g_m^{a_m} = 1$ with $\sum_j |a_j| \leqslant 2$. Finally, we have trivially

$$\mathscr{M}_G(o(G/G_\lambda)) \leqslant \lambda\, \mathscr{M}_{G/G_\lambda}(o(G/G_\lambda))$$

and hence (iii) follows from (ii). □

Proof of Corollary 1.2. We apply Lemma 5.1 (iii) by choosing $\lambda = \lambda_j$. Since $o(G_{\lambda_j}) = \lambda_j^j \lambda_{j+1} \cdots \lambda_n$, we obtain:

$$\mathscr{M}_G(\lambda_1 \cdots \lambda_{j-1}/\lambda_j^{j-1}) \leqslant 2\lambda_j.$$

By theorem 1.1 we have

$$2\lambda_j \geqslant c_{20}(\varepsilon) \frac{\max\left\{d_K^{-1}\log|\Delta_K| - \log d_K, d_K^{1-\varepsilon}\right\}}{\log(\lambda_1 \cdots \lambda_{j-1}/\lambda_j^{j-1}) + \log\log|\Delta_K|}$$

for some $c_{20}(\varepsilon) > 0$ depending only on ε. Therefore

$$\lambda_j \log\left(\frac{\lambda_1 \cdots \lambda_{j-1}}{\lambda_j^{j-1}} \log|\Delta_K|\right) \geqslant \frac{c_{20}(\varepsilon)}{2} \max\left\{d_K^{-1}\log|\Delta_K| - \log d_K, d_K^{1-\varepsilon}\right\}.$$

To prove the last assertion, remark that

$$\log\left(\frac{\lambda_1 \cdots \lambda_{j-1}}{\lambda_j^{j-1}} \log|\Delta_K|\right) \leqslant \log(\lambda_1 \cdots \lambda_{j-1}) + \log\log|\Delta_K|$$

and apply the inequality between the arithmetic and geometric mean. □

Remark. One could also prove Corollary 1.2 directly by using the effective version of the Cebotarev Density Theorem [3] in its full strength. We give a sketch of the argument in the simplest case when K is abelian. Let $H(K)$ be the Hilbert class field of K and let G be its Galois group over K, which we identify with the ideal class group of K. Let $L = L_j$ be the fixed field of G_{λ_j}; then L is an abelian unramified extension of K with Galois group G/G_{λ_j} and $|\Delta_L| = |\Delta_K|^{[L:K]}$. As in Lemma 2.1 we can find a prime ideal P of K such that

i) the class of P, viewed as an element of G, is in G_{λ_j}
ii) P is of degree 1 and non-ramified over $\mathbb{Q}$;
iii) the norm of P satisfies

$$|N_{\mathbb{Q}}^K P| \leqslant c_{21}(\log|\Delta_L|)^2(\log\log|\Delta_L|)^4.$$

Since the class of P is in G_{λ_j}, we have that $P^{\lambda_j} = (\gamma)$ is a principal ideal. By Proposition 3.3, $\alpha = \gamma/\bar{\gamma}$ is a generator of K with height

$$d_K h(\alpha) = \lambda_j \log N_{\mathbb{Q}}^K P.$$

A fortiori α is not a root of unity. Also remark that

$$\log|\Delta_L| = [L:K]\log|\Delta_K| = o(G/G_{\lambda_j})\log|\Delta_K| = \frac{\lambda_1 \cdots \lambda_{j-1}}{\lambda_j^{j-1}}\log|\Delta_K|.$$

Hence

$$d_K h(\alpha) \leqslant c_{22}\lambda_j \log\left(\frac{\lambda_1 \cdots \lambda_{j-1}}{\lambda_j^{j-1}} \log|\Delta_K|\right).$$

On the other hand, using Lemma 4.3 and Theorem 4.4,

$$d_K h(\alpha) \geqslant c_{23} \max\left\{d_K^{-1} \log|\Delta_K| - \log d_K, d_K\right\}.$$

Combining the upper and the lower bounds, we obtain the desired conclusion.

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