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Relative block semigroups and their arithmetical applications

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Abstract. We introduce relative block semigroups as an appropriate tool for the study of certain phenomena of non-unique factorizations in residue classes. Thereby the main interest lies in rings of integers of algebraic number fields, where certain asymptotic results are obtained.

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In a series of papers A. Geroldinger, W. Narkiewicz and myself investigated phenomena of non-unique factorizations in an abstract context but mainly with emphasis to rings of integers of algebraic number fields. If we are merely interested in the different lengths of factorizations of a given integer, the concept of block semigroups turned out to be the appropriate combinatorial tool for this question. It was introduced in [8] and investigated in a systematical way in [1], [2] and [3]. In this paper we shall refine this tool: we introduce relative blocks; with the aid of them we shall study lengths of factorizations of elements in given residue classes.

In § 1 we introduce relative block semigroups and determine their algebraic structure; in § 2 we apply them to the arithmetic of arbitrary Krull semigroups. In § 3 we recall some abstract analytic number theory in the context of arithmetical formations, and we determine an asymptotic formula for the number of elements with a given block. Finally, in § 4 we give some arithmetical applications for algebraic number fields.

§ 1. Relative block semigroups

Throughout this paper, a semigroup is a multiplicatively written commutative and cancellative monoid. We shall use the concept of divisor theories and Krull semigroups, cf. [4] and [3]. For a set P, we denote by $\mathcal{F}(P)$ the free abelian monoid with basis P, and we write the elements of $\mathcal{F}(P)$ in the form

$$a = \prod_{p\in P} p^{v_p(a)}$$

with (uniquely determined) exponents $v_p(a) \in \mathbb{N}_0$, $v_p(a) = 0$ for all but finitely many $p \in P$.

Definition 1. Let G be an (additively written) abelian group. For an element

$$S = \prod_{g \in G} g^{v_g(S)} \in \mathcal{F}(G)$$

we call

$$\sigma(S) = \sum_{g \in G} v_g(S) \in \mathbb{N}_0 \quad \text{the } \textit{size of} \quad S,$$
$$\iota(S) = \sum_{g \in G} v_g(S) g \in G \quad \text{the } \textit{content of} \quad S \quad \text{and}$$
$$\chi(S) = \prod_{g \in G} \frac{1}{v_g(S)!} \quad \text{the } \textit{characteristic} \text{ of} \quad S.$$

For a subgroup $G^* < G$, we set

$$\mathcal{B}(G, G^*) = \{S \in \mathcal{F}(G) \mid \iota(S) \in G^*\};$$

the elements of $\mathcal{B}(G, G^*)$ are called *relative blocks over G with respect to G^**. In particular, $\mathcal{B}(G, G) = \mathcal{F}(G)$, and

$$\mathcal{B}(G) = \mathcal{B}(G, \{0\})$$

is the ordinary block semigroup investigated in [2] and [3].

Proposition 1. *Let G be an abelian group and $G^* < G$ a subgroup.*

i) *$\mathcal{B}(G, G^*)$ is a Krull semigroup.*

ii) *Suppose that either $G^* \neq \{0\}$ or $\# G > 2$. Then the injection $\mathcal{B}(G, G^*) \hookrightarrow \mathcal{F}(G)$ is a divisor theory; the divisor class group $C = \mathcal{F}(G)/\mathcal{B}(G, G^*)$ is isomorphic to G/G^*. If $[S] \in C$ denotes the divisor class of an element $S \in \mathcal{F}(G)$, then an isomorphism $\iota^* \colon C \to G/G^*$ is given by $\iota^*([S]) = \iota(S) + G^*$. For every $g \in G$, the set $g + G^* \subset [g] = \iota^{*-1}(g + G^*)$ is the set of prime elements contained in $[g] \in C$.*

Proof: If $G^* = \{0\}$, all this is well known, cf. [4, Beispiel 5]. If $G^* \neq \{0\}$, we consider the unique semigroup homomorphism $\varphi \colon \mathcal{F}(G) \to G/G^*$ satisfying $\varphi(g) = g + G^*$ for all $g \in G$, and apply [4, Satz 4]. $\square$

Definition 2. Let G be an abelian group and $G^* < G$ a subgroup. Then

$$\theta \colon \mathcal{F}(G) \to \mathcal{F}(G/G^*)$$

denotes the unique semigroup epimorphism satisfying $\theta(g) = g + G^*$ for all $g \in G$, i.e.

$$\theta\Big(\prod_{g \in G} g^{n(g)}\Big) = \prod_{g \in G} (g + G^*)^{n(g)}.$$

Proposition 2. *Let G be an abelian group and $G^* < G$ a subgroup.*

i) *If $S \in \mathcal{F}(G)$, then*

$$\iota(\theta(S)) = \iota(S) + G^* \in G/G^*;$$

in particular: $S \in \mathcal{B}(G, G^*)$ if and only if $\theta(S) \in \mathcal{B}(G/G^*)$.

ii) *Given $S^* \in \mathcal{F}(G/G^*)$ and $g \in G$ such that $\sigma(S^*) > 0$ and $\iota(S^*) = g + G$, there exists some $S \in \mathcal{F}(G)$ satisfying $\theta(S) = S^*$ and $\iota(S) = g$.*

iii) *Let G be finite, $S^* \in \mathcal{F}(G/G^*)$ and $g \in G$ such that $\sigma(S^*) > 0$ and $\iota(S^*) = g + G^*$; then*

$$\sum_{\substack{S \in \mathcal{F}(G) \\ \theta(S) = S^*,\ \iota(S) = g}} \chi(S) = d^{\sigma(S^*)-1} \chi(S^*),$$

where $d = \#G^*$.

Proof: **i)** Let $\pi\colon G \to G/G^*$ be the canonical epimorphism. Then $\pi \circ \iota\colon \mathcal{F}(G) \to G/G^*$ and $\iota \circ \theta\colon \mathcal{F}(G) \to G/G^*$ are semigroup homomorphisms which coincide on G; this implies $\pi \circ \iota = \iota \circ \theta$, i.e. $\iota(S) + G^* = \iota \circ \theta(S)$ for all $S \in \mathcal{F}(G)$.

ii) Since $\sigma(S^*) > 0$, we have $S^* = (g_1 + G)\bar{S}$, where $\bar{S} \in \mathcal{F}(G/G^*)$ and $g_1 \in G$, which implies $\iota(\bar{S}) = g - g_1 + G^* \in G/G^*$. Let $S' \in \mathcal{F}(G)$ be arbitrary such that $\theta(S') = \bar{S}$. By **i)**, $\iota(S') = g - g_1 + g^*$ for some $g^* \in G^*$, and the element $S = (g_1 - g^*)S' \in \mathcal{F}(G)$ fulfills our requirements.

iii) Suppose that $G^* = \{g_1, \ldots, g_d\}$. We use induction on $\sigma(S^*)$ and consider first the case where

$$S^* = (g^* + G^*)^n \in \mathcal{F}(G/G^*)$$

for some $g^* \in G$ and $n \in \mathbb{N}$. In this case we have $g + G^* = \iota(S^*) = ng^* + G^*$, and

$$\begin{aligned} &\{S \in \mathcal{F}(G) \bigm| \theta(S) = S^*,\ \iota(S) = g\} \\ &= \Big\{\prod_{i=1}^{d} (g^* + g_i)^{n_i} \Bigm| (n_1, \ldots, n_d) \in \mathbb{N}_0^d,\ \sum_{i=1}^{d} n_i = n,\ \sum_{i=1}^{d} n_i(g^* + g_i) = g\Big\}. \end{aligned}$$

If $\bar{g} = g - ng^* \in G^*$, this implies

$$\sum_{\substack{S \in \mathcal{F}(G) \\ \theta(S) = S^*,\ \iota(S) = g}} \chi(S) = \sum_{\substack{(n_1, \ldots, n_d) \in \mathbb{N}_0^d \\ n_1 + \cdots + n_d = n \\ n_1 g_1 + \cdots + n_d g_d = \bar{g}}} \frac{1}{n_1! \cdot \ldots \cdot n_d!} = N^* \quad \text{(say)}.$$

Let $\widehat{G^*}$ be a multiplicative abelian group isomorphic to G^*, fix an isomorphism

$$\begin{cases} G^* & \xrightarrow{\sim} \widehat{G^*} \\ g_j & \mapsto \widehat{g_j} \end{cases}$$

and consider the group ring $\mathbb{Z}[\widehat{G^*}]$; here the multinomial formula yields

$$(\hat{g}_1 + \cdots + \hat{g}_d)^n = \sum_{\substack{(n_1,\ldots,n_d)\in\mathbb{N}_0^d \\ n_1+\cdots+n_d=n}} \frac{n!}{n_1!\cdot\ldots\cdot n_d!}\, \hat{g}_1^{n_1}\cdot\ldots\cdot\hat{g}_d^{n_d}.$$

Writing the right-hand side in the canonical form

$$\sum_{\hat{g}\in\widehat{G^*}} N(\hat{g})\hat{g}, \quad \text{where} \quad N(\hat{g}) \in \mathbb{Z},$$

and comparing the coefficient of $\hat{\hat{g}}$, yields

$$N(\hat{\hat{g}}) = n!N^*.$$

On the other hand, induction on n gives

$$(\hat{g}_1 + \cdots + \hat{g}_d)^n = d^{n-1}(\hat{g}_1 + \cdots + \hat{g}_d),$$

and consequently

$$N^* = \frac{d^{n-1}}{n!} = d^{\sigma(S^*)-1}\chi(S^*).$$

For the general case, let $h_1,\ldots,h_m \in G$ be a system of representatives for G/G^*; then

$$S^* = \prod_{j=1}^{m} (h_j + G^*)^{n_j},$$

where $n_j \in \mathbb{N}_0$, and since $\sigma(S^*) = n_1+\cdots+n_m > 0$, we may assume that $n_m > 0$. We set

$$S_0^* = \prod_{j=1}^{m-1} (h_j + G^*)^{n_j}$$

and obtain

$$\begin{aligned}&\{S \in \mathcal{F}(G) \mid \theta(S) = S^*,\ \iota(S) = g\}\\ &= \{S_0S' \mid S_0,\ S' \in \mathcal{F}(G),\ \theta(S_0) = S_0^*,\ \theta(S') = (h_m + G^*)^{n_m},\ \iota(S') = g - \iota(S_0)\}.\end{aligned}$$

If $S_0,\ S' \in \mathcal{F}(G)$, $\theta(S_0) = S_0^*$ and $\theta(S') = (h_m + G^*)^{n_m}$, then S_0 and S' are relatively prime, and therefore $\chi(S) = \chi(S_0)\chi(S')$. This implies

$$\sum_{\substack{S\in\mathcal{F}(G) \\ \theta(S)=S^*,\ \iota(S)=g}} \chi(S) = \sum_{\substack{S_0\in\mathcal{F}(G) \\ \theta(S_0)=S_0^*}} \chi(S_0) \sum_{\substack{S'\in\mathcal{F}(G) \\ \theta(S')=(h_m+G^*)^{n_m} \\ \iota(S')=g-\iota(S_0)}} \chi(S');$$

by the special case considered above we obtain

$$\sum_{\substack{S' \in \mathcal{F}(G) \\ \theta(S')=(h_m+G^*)^{n_m} \\ \iota(S')=g-\iota(S_0)}} \chi(S') = \frac{d^{n_m-1}}{n_m!}.$$

By induction hypothesis,

$$\sum_{\substack{S_0 \in \mathcal{F}(G) \\ \theta(S_0)=S_0^*}} \chi(S_0) = d \cdot d^{\sigma(S_0^*)-1}\chi(S_0^*) = d^{\sigma(S_0^*)}\chi(S_0^*);$$

since $\chi(S^*) = \chi(S_0^*)/n_m!$ and $\sigma(S^*) = \sigma(S_0^*) + n_m$, the assertion follows. □

§ 2. Relative blocks and Krull semigroups

If H is a Krull semigroup and $\partial\colon H \to \mathcal{F}(P)$ is a divisor theory, then ∂ induces an injective divisor theory $\bar{\partial}\colon H/H^\times \to \mathcal{F}(P)$ (where $H^\times$ denotes the group of invertible elements of H). If H is reduced (i.e., $H^\times = \{1\}$), then we may assume that $H \subset \mathcal{F}(P)$ and $H \hookrightarrow \mathcal{F}(P)$ is a divisor theory. We shall adopt this viewpoint in the sequel.

Definition 3. Let H be a reduced Krull semigroup, $H \hookrightarrow \mathcal{F}(P)$ a divisor theory and G its divisor class group. We write G additively, and for $a \in \mathcal{F}(P)$ we denote by $[a] \in G$ the class containing a. The unique semigroup homomorphism $\boldsymbol{\beta}^H\colon \mathcal{F}(P) \to \mathcal{F}(G)$ satisfying $\boldsymbol{\beta}^H(p) = [p]$ for all $p \in P$ is called the *H-block homomorphism*. For $a \in \mathcal{F}(P)$, the element $\boldsymbol{\beta}^H(a) \in \mathcal{F}(G)$ is called the *H-block of a*.

Clearly, $\iota(\boldsymbol{\beta}^H(a)) = [a] \in G$; in particular, $a \in H$ if and only if $\boldsymbol{\beta}^H(a) \in \mathcal{B}(G)$. The significance of the block homomorphism $\boldsymbol{\beta}^H$ for the arithmetic of H is given as follows (cf. [1, Prop. 1]):

An element $a \in H$ is irreducible in H if and only if $\boldsymbol{\beta}^H(a)$ is irreducible in $\mathcal{B}(G)$. If $a \in H$ and $a = u_1 \cdot \ldots \cdot u_r$ is a factorization of a into irreducible elements $u_i \in H$, then $\boldsymbol{\beta}^H(a) = \boldsymbol{\beta}^H(u_1) \cdot \ldots \cdot \boldsymbol{\beta}^H(u_r)$ is a factorization of $\boldsymbol{\beta}^H(a)$ into irreducible elements of $\mathcal{B}(G)$, and every factorization of $\boldsymbol{\beta}^H(a)$ into irreducible elements of $\mathcal{B}(G)$ arises in this way. In particular, if $\mathcal{L}(a)$ denotes the set of all lengths of factorizations of a in H, i.e.,

$$\mathcal{L}(a) = \{r \in \mathbb{N} \mid a = u_1 \cdot \ldots \cdot u_r \quad \text{with irreducible} \quad u_i \in H\},$$

then $\mathcal{L}(a) = \mathcal{L}(\boldsymbol{\beta}^H(a))$. If every class $g \in G$ contains at least one prime $p \in P$, then $\boldsymbol{\beta}^H(H) = \mathcal{B}(G)$ and $\boldsymbol{\beta}^H(\mathcal{F}(P)) = \mathcal{F}(G)$.

We need the following relative construction.

Proposition 3. *Let H be a reduced Krull semigroup, $H \hookrightarrow \mathcal{F}(P)$ a divisor theory, G its divisor class group and $G^* < G$ a subgroup. We assume that $g \cap P \neq \emptyset$ for every $g \in G$, and we set*

$$H^* = \{a \in \mathcal{F}(P) \mid [a] \in G^*\}$$

where $[a] \in G$ denotes the divisor class of an element $a \in \mathcal{F}(P)$ under $H \hookrightarrow \mathcal{F}(P)$.

- **i)** *$H^* \hookrightarrow \mathcal{F}(P)$ is a divisor theory with divisor class group G/G^*. If $a \in \mathcal{F}(P)$, then $[a] + G^* \in G/G^*$ is the divisor class of a under $H^* \hookrightarrow \mathcal{F}(P)$, $\theta(\boldsymbol{\beta}^H(a)) = \boldsymbol{\beta}^{H^*}(a)$, and $a \in H^*$ if and only if $\boldsymbol{\beta}^H(a) \in \mathcal{B}(G, G^*)$.*
- **ii)** *Given $S^* \in \mathcal{B}(G/G^*)$ such that $\sigma(S^*) > 0$ and $g^* \in G^*$, there exists an element $a \in H^*$ such that $\boldsymbol{\beta}^{H^*}(a) = S^*$ and $[a] = g^*$.*

PROOF: **i)** It suffices to consider the case $G^* \neq \{0\}$. If $\varphi\colon \mathcal{F}(P) \to G/G^*$ is defined by $\varphi(a) = [a] + G^*$, then $H^* = \varphi^{-1}(G^*)$ and $\#P \cap \varphi^{-1}(g + G^*) \geq \#G^* \geq 2$ for every $g \in G$. Therefore $H^* \hookrightarrow \mathcal{F}(P)$ is a divisor theory by [4, Satz 4]. Clearly, G/G^* is the associated divisor class group, and $[a] + G^* \in G/G^*$ is the divisor class of an element $a \in \mathcal{F}(P)$. The mappings $\theta \circ \boldsymbol{\beta}^H$ and $\boldsymbol{\beta}^{H^*}$ are semigroup homomorphisms $\mathcal{F}(P) \to \mathcal{F}(G/G^*)$; for $p \in P$, we have $\theta \circ \boldsymbol{\beta}^H(p) = \theta([p]) = [p] + G^* = \boldsymbol{\beta}^{H^*}(p)$, which implies $\theta \circ \boldsymbol{\beta}^H = \boldsymbol{\beta}^{H^*}$. Since $\iota(\boldsymbol{\beta}^H(a)) = [a] \in G$, we have $a \in H^*$ if and only if $\boldsymbol{\beta}^H(a) \in \mathcal{B}(G, G^*)$.

ii) By Proposition 2, there exists an element $S \in \mathcal{F}(G)$ satisfying $\theta(S) = S^*$ and $\iota(S) = g^*$, whence $S \in \mathcal{B}(G, G^*)$. Since $g \cap P \neq \emptyset$ for every $g \in G$, there exists an element $a \in H^*$ such that $\boldsymbol{\beta}^H(a) = S$; this implies $\boldsymbol{\beta}^{H^*}(a) = \theta(S) = S^*$ and $[a] = \iota(S) = g^*$. □

Main Example. Let R be a Dedekind domain and $\mathfrak{f}$ a non-zero ideal of R (more generally, $\mathfrak{f}$ may be a cycle; see [5]). Let H be the semigroup of all principal ideals aR of R generated by elements $a \equiv 1 \mod \mathfrak{f}$, and let H^* be the semigroup of all principal ideals of R which are relatively prime to $\mathfrak{f}$. If P denotes the set of all maximal ideals $\mathfrak{p}$ of R not containing $\mathfrak{f}$, then $D = \mathcal{F}(P)$ is the semigroup of all ideals of R which are relatively prime to $\mathfrak{f}$, and

$$H \hookrightarrow H^* \hookrightarrow D = \mathcal{F}(P)$$

satisfies the assumption of Proposition 3; here G is the ray class group modulo $\mathfrak{f}$ in R, and G^* is the subgroup of all ray classes represented by principal ideals. Consequently, $C = G/G^*$ is isomorphic to the ideal class group of R (we identify!), and there is a canonical isomorphism

$$G^* \xrightarrow{\sim} (R/\mathfrak{f})^\times / U(\mathfrak{f}),$$

where $U(\mathfrak{f})$ denotes the subgroup of all prime residue classes modulo $\mathfrak{f}$ which are represented by elements of $R^\times$.

With an element $a \in R \setminus (R^\times \cup \{0\})$ we associate its block

$$\boldsymbol{\beta}(a) = \boldsymbol{\beta}^{H^*}(aR) \in \mathcal{B}(C);$$

then we have $\mathcal{L}(a) = \mathcal{L}(\boldsymbol{\beta}(a)) \subset \mathbb{N}$. Therefore Proposition 3, **ii)** describes the distribution of the elements $a \in R$ having the same block in $\mathcal{B}(C)$ in the various prime residue classes modulo $\mathfrak{f}$, provided that each ray class modulo $\mathfrak{f}$ contains at least one prime ideal of R. In fact, it is sufficient to assume that every ideal class of R which contains a prime ideal splits into ray classes each of which contains a prime ideal; details are left to the reader.

§ 3. Formations

We develop the quantitative theory in an abstract setting following [6]. Let Λ be the set of all complex functions which are regular in the closed half-plane $\Re s > 1$. We denote by log that branch of the complex logarithm which is real for positive arguments, and we set $z^s = \exp(z \log s)$.

Definition 4. An *arithmetical formation* $\mathfrak{D}$ consists of

1) a reduced Krull monoid H, together with a divisor theory $H \hookrightarrow D = \mathcal{F}(P)$ such that the divisor class group $G = D/H$ is of finite order $N \in \mathbb{N}$;

2) a completely multiplicative function $|\cdot|\colon D \to \mathbb{N}_0$ satisfying $|a| > 1$ for all $a \neq 1$ such that, for every $g \in G$,

$$\sum_{p \in P \cap g} |p|^{-s} = \frac{1}{N} \log \frac{1}{s-1} + h(s)$$

holds in the half-plane $\Re s > 1$ for some function $h \in \Lambda$.

Whenever we deal with an arithmetical formation $\mathfrak{D}$, we use all notations as introduced above. We write G additively, and for $a \in D$ we denote by $[a] \in G$ the divisor class containing a. By **2)**, $g \cap P$ is infinite for every $g \in G$.

Main Example (continued). We pick up again the main example discussed in § 2 and let now R be the ring of integers of an algebraic number field. For $\mathfrak{a} \in D$ (an ideal of R which is relatively prime to $\mathfrak{f}$), we set $|\mathfrak{a}| = (R\colon \mathfrak{a})$; then $|\cdot|\colon D \to \mathbb{N}$ is completely multiplicative and defines on D the structure of an arithmetical formation (with respect to H^* as well as with respect to H), see [10, Ch. VII, § 2]. For $0 \neq a \in R$, we have $|aR| = |\mathcal{N}(a)|$, where $\mathcal{N}$ denotes the ordinary norm to $\mathbb{Q}$.

Proposition 4. *Let $\mathfrak{D}$ be an arithmetical formation as in Definition 4 and $S \in \mathcal{F}(G)$ such that $\sigma(S) > 0$. Then we have, as $x \to \infty$,*

$$\#\{a \in D \mid \boldsymbol{\beta}^H(a) = S\} \sim \frac{\sigma(S)\chi(S)}{N^{\sigma(S)}} \, \frac{x}{\log x} (\log\log x)^{\sigma(S)-1}.$$

Proof: It is sufficient to prove that

$$(*) \qquad \sum_{\substack{a \in D \\ \boldsymbol{\beta}^H(a) = S}} |a|^{-s} = \frac{\chi(S)}{N^{\sigma(S)}} \Big(\log \frac{1}{s-1}\Big)^{\sigma(S)} + P\Big(\log \frac{1}{s-1}\Big)$$

for $\Re s > 1$, where $P \in \Lambda[X]$ is a polynomial of degree less than $\sigma(S)$. Then we apply the Tauberian Theorem of Ikehara and Delange, see [9, Ch. III, § 3]. The proof of (*) can be given in two different ways: one may either follow the arguments in the proof of [10, Theorem 9.4] or those in the proof of [6, Proposition 4]; details are left to the reader. □

Theorem. *Let $\mathfrak{D}$ be an arithmetical formation as in Definition 4, $G^* < G$ a subgroup and $H^* = \{a \in D \mid [a] \in G^*\}$. Let $S^* \in \mathcal{B}(G/G^*)$ be a block satisfying $\sigma(S^*) > 0$, and $g^* \in G^*$. Then we have, as $x \to \infty$,*

$$\#\{a \in g^* \mid |a| \le x,\ \boldsymbol{\beta}^{H^*}(a) = S^*\} \sim \frac{1}{\#G^*}\,\frac{\sigma(S^*)\chi(S^*)}{(G\colon G^*)^{\sigma(S^*)}}\,\frac{x}{\log x}(\log\log x)^{\sigma(S^*)-1}.$$

Proof: Since

$$\{a \in g^* \mid \boldsymbol{\beta}^{H^*}(a) = S^*\} \;=\; \biguplus_{\substack{S\in\mathcal{F}(G)\\ \theta(S)=S^*,\ \iota(S)=g^*}} \{a \in D \mid \boldsymbol{\beta}^{H}(a) = S\}$$

(disjoint union), Proposition 4 implies, observing $\sigma(\theta(S)) = \sigma(S)$,

$$\#\{a \in g^* \mid |a| \le x,\ \boldsymbol{\beta}^{H^*}(a) = S^*\} \sim c\frac{x}{\log x}(\log\log x)^{\sigma(S^*)-1},$$

where

$$c = \frac{\sigma(S^*)}{N^{\sigma(S^*)}} \sum_{\substack{S\in\mathcal{F}(G)\\ \theta(S)=S^*,\ \iota(S)=g^*}} \chi(S^*);$$

now the assertion follows from Proposition 2, **iii)**. □

§ 4. Arithmetical applications

Proposition 5. *Let R be the ring of integers of an algebraic number field with class group C and $B \in \mathcal{B}(C)$ such that $\sigma(B) > 0$. Let $\mathfrak{f}$ be a cycle of R, and $a_0 \in R$ an element relatively prime to $\mathfrak{f}$. Then we have, as $x \to \infty$,*

$$\#\{aR \mid a \in R,\ a \equiv a_0 \bmod \mathfrak{f},\ |\mathcal{N}(a)| \le x,\ \boldsymbol{\beta}(a) = B\} \sim \frac{\sigma(B)\chi(B)}{\phi^*(\mathfrak{f})h^{\sigma(B)}}\,\frac{x}{\log x}(\log\log x)^{\sigma(B)-1},$$

where $h = \#C$ and $\phi^*(\mathfrak{f}) = \#(R/\mathfrak{f})^\times/\mathcal{U}(\mathfrak{f})$.

Proof: Obvious by Proposition 4, applied to the Main Example. □

Remark. The case $B = 0$ in Proposition 5 yields the prime ideal theorem for principal primes in residue classes modulo $\mathfrak{f}$.

Corollary. *Let R be the ring of integers of an algebraic number field with class group C and $L \subset \mathbb{N}$ such that there exists a block $B \in \mathcal{B}(C)$ satisfying $\mathcal{L}(B) = L$. Let $\mathfrak{f}$ be a cycle of R and $a_0 \in R$ an element relatively prime to $\mathfrak{f}$. Then we have, as $x \to \infty$,*

$$\#\{aR \mid a \in R,\ a \equiv a_0 \bmod \mathfrak{f},\ |\mathcal{N}(a)| \le x,\ \mathcal{L}(a) = L\} \sim c\frac{\sigma}{\phi^*(\mathfrak{f})h^\sigma}\ \frac{x}{\log x}(\log\log x)^{\sigma-1},$$

where $\phi^*(\mathfrak{f}) = \#(R/\mathfrak{f})^\times/\mathcal{U}(\mathfrak{f})$, $h = \#C$, and $c \in \mathbb{Q}_{>0}$, $\sigma \in \mathbb{N}$ are given as follows:

$$\sigma = \max\{\sigma(B) \mid B \in \mathcal{B}(C),\ \mathcal{L}(B) = L\}, \quad c = \sum_{\substack{B\in\mathcal{B}(C) \\ \mathcal{L}(B)=L,\ \sigma(B)=\sigma}} \chi(B);$$

in particular, c and σ depend only on C and L.

Proof: The set $\mathfrak{L} = \{B \in \mathcal{B}(C) \mid \mathcal{L}(B) = L\}$ is finite, and for $a \in R \setminus (R^\times \cup \{0\})$ we have $\mathcal{L}(a) = L$ if and only if $\boldsymbol{\beta}(a) \in \mathfrak{L}$. Now the assertion follows from Proposition 5. □

Remarks. 1) Using the methods of J. Kaczorowski [7], it is possible to obtain more precise asymptotic formulas, from which we presented only the main term.

2) Using the methods developed in [6], it is possible to derive analogous results for algebraic function fields.

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