

# Circular numbers of certain abelian fields

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Throughout this thesis, we will use the convention that whenever any of the indices  $i, j, l, h$  appear on the same line, they are pairwise distinct and moreover  $1 \leq i, j, l, h \leq 4$ .

## 1 Basic definitions and assumptions

Let  $k$  be a real abelian field with exactly four ramified primes  $p_1, p_2, p_3, p_4$ . Let  $K$  be the genus field (in the narrow sense) of  $k$  and assume  $K \neq k$ . Let  $G := \text{Gal}(K/\mathbb{Q})$ , then (by the properties of the genus field) we can make the identification  $G = T_1 \times T_2 \times T_3 \times T_4$ , where  $T_i$  is the inertia group corresponding the ramified prime  $p_i$ . Next, we will define:

- $H := \text{Gal}(K/k)$ ,
- $m := |H|$ ,
- the canonical projections  $\pi_i : G \rightarrow T_i$ ,
- $a_i := [T_i : \pi_i(H)]$ ,
- $r_i := |H \cap \ker \pi_i|$ ,
- $s_{ij} := |H \cap \ker(\pi_i \pi_j)|$ ,
- $K_i$  as the maximal subfield of  $K$  ramified only at  $p_i$  (so that

$$T_i = \text{Gal}(K/K_j K_l K_h) \cong \text{Gal}(K_i/\mathbb{Q}).)$$

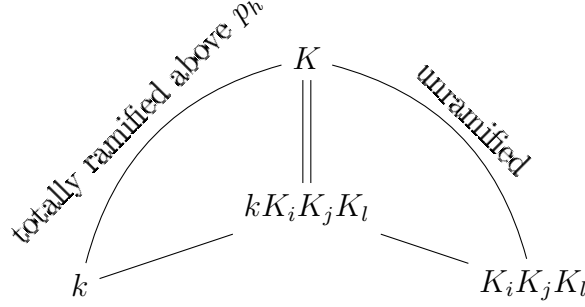
We will assume the following:

- $K \neq k$ ,
- $H$  is cyclic, generated by  $\tau$ ,
- each  $T_i$  is cyclic, generated by  $\sigma_i$ .

## 2 Auxiliary results

**Lemma 1.** *We have  $kK_iK_jK_l = K$  and  $K_1K_2K_3K_4 = K$ .*

*Proof.* The extension  $K/K_iK_jK_l$  is totally ramified at the prime ideals above  $p_h$ , so the same must be true for the extension  $K/kK_iK_jK_l$ . But since the extension  $K/k$  is unramified (by the definition of  $K$ ), so is  $K/kK_iK_jK_l$ . Therefore  $[K : kK_iK_jK_l] = 1$ . The second claim follows from the fact  $\text{Gal}(K_i/\mathbb{Q}) = T_i$ .  $\square$



**Proposition 2.** *We have  $a_i = [k \cap K_i : \mathbb{Q}]$ ,  $r_i = [K : kK_i]$ ,  $|T_i| = a_i \frac{m}{r_i}$ ,  $s_{ij} = [K : kK_iK_j]$ . Also  $[K_i : k \cap K_i] = \frac{m}{r_i}$ ,  $[K_iK_j : k \cap K_iK_j] = \frac{m}{s_{ij}}$  and  $[K_iK_jK_l : k \cap K_iK_jK_l] = m$ .*

*Proof.* Since

$$\text{Gal}(K/K_i) \cong \text{Gal}(K/\mathbb{Q})/\text{Gal}(K_i/\mathbb{Q}) \cong T_1T_2T_3T_4/T_i \cong T_jT_lT_h$$

and  $\text{Gal}(K/k) = H$ , it follows that  $\text{Gal}(K/k \cap K_i) \cong T_jT_lT_h \cdot H$ . Now consider the short exact sequence

$$0 \rightarrow H \cap \ker \pi_i \rightarrow H \xrightarrow{\pi_i|_H} \pi_i(H) \rightarrow 0.$$

It follows that  $|\pi_i(H)| = \frac{m}{r_i}$  and

$$\pi_i(H) \cong \frac{H}{H \cap \ker \pi_i} = \frac{H}{H \cap T_jT_lT_h} \cong \frac{T_jT_lT_h \cdot H}{T_jT_lT_h} \cong \frac{\text{Gal}(K/k \cap K_i)}{\text{Gal}(K/K_i)} \cong \text{Gal}(K_i/k \cap K_i).$$

Therefore

$$[k \cap K_i : \mathbb{Q}] = \frac{|\text{Gal}(K_i/\mathbb{Q})|}{|\text{Gal}(K_i/k \cap K_i)|} = \frac{|T_i|}{|\pi_i(H)|} = a_i$$

and

$$[K : kK_i] = \frac{|\text{Gal}(K/k)|}{|\text{Gal}(kK_i/k)|} = \frac{|H|}{|\text{Gal}(K_i/k \cap K_i)|} = \frac{m}{\pi_i(H)} = r_i.$$

Putting everything together, we obtain

$$|T_i| = [K_i : k \cap K_i] \cdot [k \cap K_i : \mathbb{Q}] = a_i |\pi_i(H)| = a_i \frac{m}{r_i}.$$

Next, we also have

$$\text{Gal}(K/K_iK_j) \cong \text{Gal}(K/\mathbb{Q})/\text{Gal}(K_iK_j/\mathbb{Q}) \cong T_1T_2T_3T_4/T_iT_j \cong T_lT_h,$$

so that  $\text{Gal}(K/k \cap K_iK_j) = T_lT_h \cdot H$ . Thus we can consider the short exact sequence

$$0 \rightarrow H \cap \ker \pi_i\pi_j \rightarrow H \xrightarrow{\pi_i\pi_j|_H} \pi_i\pi_j(H) \rightarrow 0$$

to conclude that  $|\pi_i\pi_j(H)| = \frac{m}{s_{ij}}$  and

$$\begin{aligned} \pi_i\pi_j(H) &\cong \frac{H}{H \cap \ker \pi_i\pi_j} = \frac{H}{H \cap T_lT_h} \cong \frac{T_lT_h \cdot H}{T_lT_h} \\ &\cong \frac{\text{Gal}(K/k \cap K_iK_j)}{\text{Gal}(K/K_iK_j)} \cong \text{Gal}(K_iK_j/k \cap K_iK_j). \end{aligned}$$

Then it follows that

$$[K : kK_iK_j] = \frac{|\text{Gal}(K/k)|}{|\text{Gal}(kK_iK_j/k)|} = \frac{|H|}{|\text{Gal}(K_iK_j/k \cap K_iK_j)|} = \frac{m}{\pi_i\pi_j(H)} = s_{ij}.$$

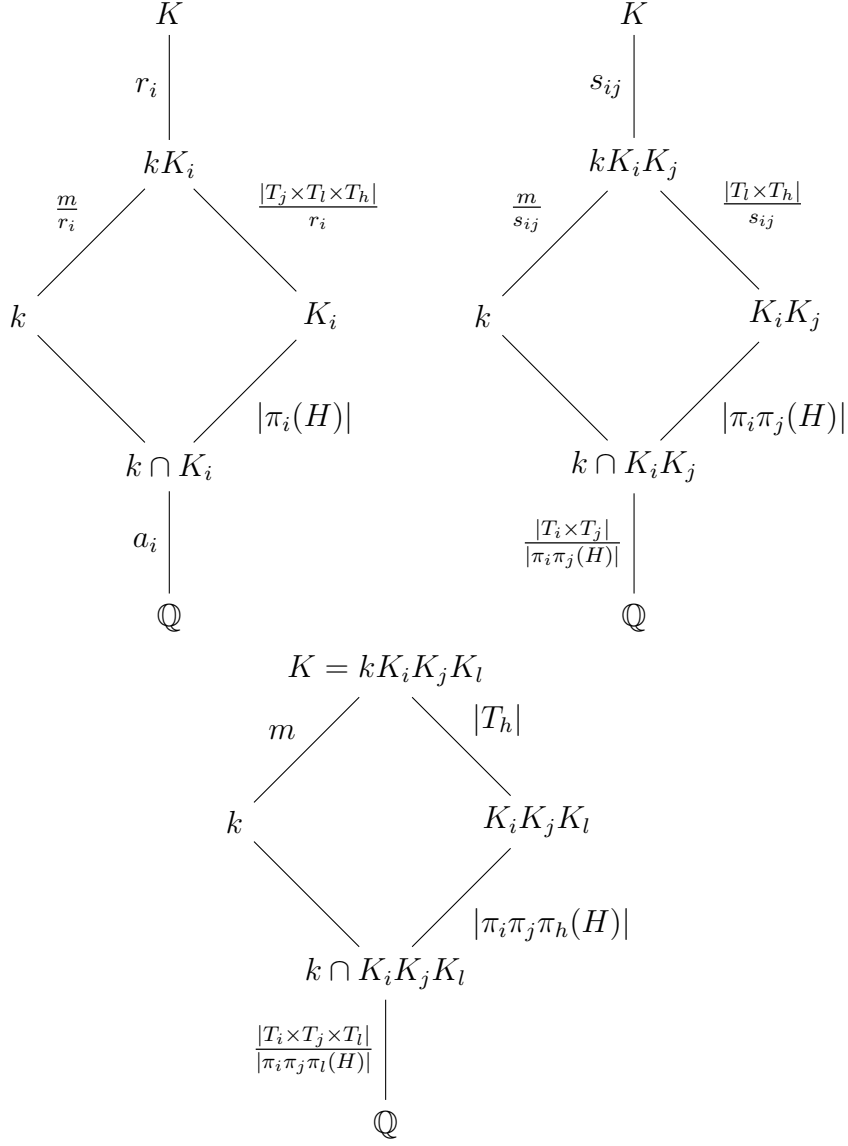
The last part of the statement is a consequence of Lemma 1, since we have

$$\text{Gal}(K_iK_jK_l/k \cap K_iK_jK_l) \cong \text{Gal}(kK_iK_jK_l/k) = \text{Gal}(K/k) = H.$$

Finally note that in the same way as above, we could show that

$$\pi_i\pi_j\pi_l(H) \cong \text{Gal}(K_iK_jK_l/k \cap K_iK_jK_l).$$

□



**Corollary 3.** We have  $[k \cap K_iK_j : \mathbb{Q}] = a_i a_j \frac{m}{r_i r_j} s_{ij}$ ,  $[k \cap K_iK_jK_l : \mathbb{Q}] = a_i a_j a_l \frac{m^2}{r_i r_j r_l}$  and  $[k : \mathbb{Q}] = a_1 a_2 a_3 a_4 \frac{m^3}{r_1 r_2 r_3 r_4}$ .

*Proof.* This follows from the computations

$$\begin{aligned}
[k \cap K_iK_j : \mathbb{Q}] &= \frac{[K_iK_j : \mathbb{Q}]}{[K_iK_j : k \cap K_iK_j]} = \frac{|T_i| \cdot |T_j|}{m/s_{ij}} = a_i a_j \frac{m}{r_i r_j} s_{ij}, \\
[k \cap K_iK_jK_l : \mathbb{Q}] &= \frac{[K_iK_jK_l : \mathbb{Q}]}{[K_iK_jK_l : k \cap K_iK_jK_l]} = \frac{|T_i| \cdot |T_j| \cdot |T_l|}{m} = a_i a_j a_l \frac{m^2}{r_i r_j r_l}
\end{aligned}$$

and

$$\begin{aligned} [k : \mathbb{Q}] &= [k \cap K_i : \mathbb{Q}] \cdot [k : k \cap K_i] = a_i \cdot [kK_i : K_i] = a_i \frac{[K : K_i]}{[K : kK_i]} \\ &= a_i \frac{|T_j| \cdot |T_l| \cdot |T_h|}{r_i} = a_1 a_2 a_3 a_4 \frac{m^3}{r_1 r_2 r_3 r_4}. \end{aligned}$$

□

**Lemma 4.** *We have  $s_{ij} = \gcd(r_i, r_j)$ ,  $\gcd(r_i, r_j, r_l) = 1$  (this is also equivalent to  $\text{lcm}(\frac{m}{r_i}, \frac{m}{r_j}, \frac{m}{r_l}) = m$  and to  $\gcd(s_{ij}, r_l) = 1$ ) and  $s_{ij} \frac{m}{r_i r_j} = \gcd(\frac{m}{r_i}, \frac{m}{r_j})$ .*

*Proof.* It follows from Proposition 2 that  $s_{ij} \mid r_i, s_{ij} \mid r_j$  and from its proof that  $|\pi_i(H)| = \frac{m}{r_i}$ ,  $|\pi_i \pi_j(H)| = \frac{m}{s_{ij}}$  and  $|\pi_i \pi_j \pi_l(H)| = m$ . The cyclicity of  $H$  then implies

$$\frac{m}{s_{ij}} = |\pi_i \pi_j(H)| = |\langle \pi_i \pi_j(\tau) \rangle| = |\langle \pi_i(\tau) \pi_j(\tau) \rangle| = \text{lcm}\left(\frac{m}{r_i}, \frac{m}{r_j}\right),$$

because  $\langle \pi_i(\tau) \rangle = \pi_i(H)$  and the elements  $\pi_i(H), \pi_j(H)$  have different non-zero coordinates in  $G$ . Now for any common divisor  $t$  of  $r_i, r_j$ , we have  $\frac{m}{s_{ij}} = \text{lcm}\left(\frac{m}{r_i}, \frac{m}{r_j}\right) \mid \frac{m}{t}$ , which implies  $t \mid s_{ij}$  and we are done.

Similarly, we have

$$m = |\pi_i \pi_j \pi_l(H)| = |\langle \pi_i \pi_j \pi_l(\tau) \rangle| = |\langle \pi_i(\tau) \pi_j(\tau) \pi_l(\tau) \rangle| = \text{lcm}\left(\frac{m}{r_i}, \frac{m}{r_j}, \frac{m}{r_l}\right),$$

so if  $t$  is any common divisor of  $r_i, r_j, r_l$ , we have  $m = \text{lcm}\left(\frac{m}{r_i}, \frac{m}{r_j}, \frac{m}{r_l}\right) \mid \frac{m}{t}$ , which implies  $t = 1$ .

Finally, using the first result, we have  $s_{ij} \frac{m}{r_i r_j} = \frac{m}{\text{lcm}(r_i, r_j)}$ , which clearly divides both  $\frac{m}{r_i}$  and  $\frac{m}{r_j}$ . Moreover, if  $t$  is any common divisor of  $\frac{m}{r_i}$  and  $\frac{m}{r_j}$ , then both  $r_i t$  and  $r_j t$  divide  $m$ , hence  $t \cdot \text{lcm}(r_i, r_j) = \text{lcm}(r_i t, r_j t) \mid m$ . Thus  $t \mid \frac{m}{\text{lcm}(r_i, r_j)}$  and we are done. □

**Proposition 5.** *We have*

$$\begin{aligned} \text{Gal}(k/\mathbb{Q}) &\cong \{(\sigma_1^{x_1} \sigma_2^{x_2} \sigma_3^{x_3} \sigma_4^{x_4})|_k; 0 \leq x_1 < a_1 \frac{m}{r_1}, 0 \leq x_2 < a_2 \frac{m}{r_2 s_{34}}, \\ &\quad 0 \leq x_3 < a_3 \frac{m}{r_3 r_4} s_{34}, 0 \leq x_4 < a_4\}, \end{aligned}$$

where each automorphism of  $k$  determines the quadruple  $(x_1, x_2, x_3, x_4)$  uniquely.

*Proof.* First off, the cardinalities of the sets on both sides agree. Now let  $\rho$  be any automorphism of  $k$ . Since  $\text{Gal}(k \cap K_4/\mathbb{Q})$  is a cyclic group of order  $a_4$  (by lemma 2) generated by  $\sigma_4|_{k \cap K_4}$  (as a quotient of  $\text{Gal}(K_4/\mathbb{Q}) = \langle \sigma_4|_{K_4} \rangle$ ), there must exist unique

$x_4 \in \mathbb{Z}$ ,  $0 \leq x_4 < a_4$  such that  $\rho$  and  $\sigma_4^{x_4}$  have the same restrictions to  $k \cap K_4$ . Therefore  $\rho\sigma_4^{-x_4}|_k \in \text{Gal}(k/k \cap K_4)$ .

Next,  $\text{Gal}(k \cap K_3K_4/k \cap K_4)$  is a cyclic group of order  $\frac{[k \cap K_3K_4 : \mathbb{Q}]}{[k \cap K_4 : \mathbb{Q}]} = a_3 \frac{m}{r_3 r_4} s_{34}$  (by Corollary 3) generated by  $\sigma_3|_{k \cap K_3K_4}$  (as a quotient of  $\text{Gal}(K_3K_4/K_4) = \langle \sigma_3|_{K_3K_4} \rangle$ ), so there must exist unique  $x_3 \in \mathbb{Z}$ ,  $0 \leq x_3 < a_3 \frac{m}{r_3 r_4} s_{34}$  such that  $\rho\sigma_4^{-x_4}$  and  $\sigma_3^{x_3}$  have the same restriction to  $k \cap K_3K_4$ . Therefore  $\rho\sigma_3^{-x_3}\sigma_4^{-x_4}|_k \in \text{Gal}(k/k \cap K_3K_4)$ .

Following the pattern,  $\text{Gal}(k \cap K_2K_3K_4/k \cap K_3K_4)$  is a cyclic group of order

$$\frac{[k \cap K_2K_3K_4 : \mathbb{Q}]}{[k \cap K_3K_4 : \mathbb{Q}]} = a_2 \frac{m}{r_2 s_{34}}$$

(by Corollary 3) generated by  $\sigma_2|_{k \cap K_2K_3K_4}$  (as a quotient of

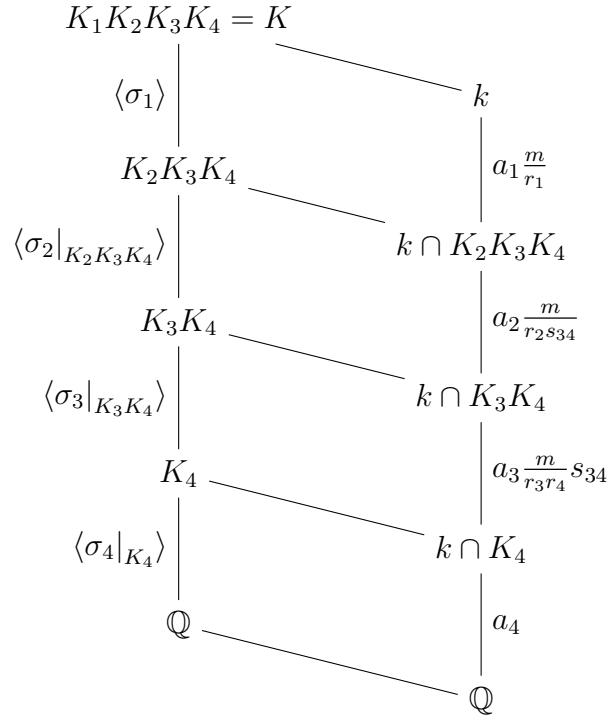
$$\text{Gal}(K_2K_3K_4/K_3K_4) = \langle \sigma_2|_{K_2K_3K_4} \rangle,$$

so there must exist unique  $x_2 \in \mathbb{Z}$ ,  $0 \leq x_2 < a_2 \frac{m}{r_2 s_{34}}$  such that  $\rho\sigma_3^{-x_3}\sigma_4^{-x_4}$  and  $\sigma_2^{x_2}$  have the same restriction to  $k \cap K_2K_3K_4$ . Therefore  $\rho\sigma_2^{-x_2}\sigma_3^{-x_3}\sigma_4^{-x_4}|_k \in \text{Gal}(k/k \cap K_2K_3K_4)$ .

Finally, we have

$$\text{Gal}(k/k \cap K_2K_3K_4) \cong \text{Gal}(kK_2K_3K_4/K_2K_3K_4) = \text{Gal}(K_1K_2K_3K_4/K_2K_3K_4) = \langle \sigma_1 \rangle$$

(using Lemma 1), where the isomorphism is given by restriction. Since the order of  $\sigma_1$  is  $a_1 \frac{m}{r_1}$ , it follows that there must exist unique  $x_1 \in \mathbb{Z}$ ,  $0 \leq x_1 < a_1 \frac{m}{r_1}$  such that  $\rho\sigma_2^{-x_2}\sigma_3^{-x_3}\sigma_4^{-x_4}$  and  $\sigma_1^{x_1}$  have the same restriction to  $k$ . Thus  $\rho = \sigma_1^{x_1}\sigma_2^{x_2}\sigma_3^{x_3}\sigma_4^{x_4}$  and the proof is finished.



□

**Lemma 6.** *Without loss of generality, we can assume  $\tau = \sigma_1^{a_1} \sigma_2^{a_2} \sigma_3^{a_3} \sigma_4^{a_4}$ .*

*Proof.* We know that  $a_i = [T_i : \pi_i(H)]$ , hence  $\pi_i(\tau)$  generates a subgroup of  $T_i$  of index  $a_i$ . The cyclicity of  $T_i$  then implies that  $\pi_i(\tau)$  must be the  $a_i$ -th power of some generator of  $T_i$ , WLOG  $\sigma_i$ . The statement now follows, because  $\tau$  is determined by its four projections. □

### 3 The group of circular numbers

Recall that  $D^+$ , the non-torsion part of the group  $D$  of circular numbers of an abelian field  $k'$  (using Lettl's modification of Sinnott's definition), has one generator  $\eta_I$  for each nonempty subset  $I \subseteq P$ , where  $P$  is the set of ramified primes of  $k'$ .

More explicitly, if we let  $K'_i$  be the largest subfield of  $K'$  (the genus field of  $k'$ ) in which  $p_i$  is the only ramified prime for any  $i \in I$ , we have

$$\eta_I = N_{\mathbb{Q}(\zeta_{\text{cond}(\prod_{i \in I} K'_i)) / (\prod_{i \in I} K'_i) \cap k'} \left( 1 - \zeta_{\text{cond}(\prod_{i \in I} K'_i)} \right).$$

It is well known that  $D^+$  is a  $\mathbb{Z}[G]$ -module of  $\mathbb{Z}$ -rank  $[k : \mathbb{Q}] + |P| - 1$ .

(In our case, we have  $k' = k, K' = K, K'_i = K_i, |P| = 4, \eta := \eta_{\{1,2,3,4\}}$ .)

Our goal will be to find a basis of  $D^+$  (it can then be easily modified in order to obtain a basis of the group of circular units). The generators of  $D^+$  are subject to norm relations that correspond to the sum of all elements of the respective inertia groups.

Let

$$R_i = \sum_{u=0}^{a_i-1} \sigma_i^u, \quad N_i = \sum_{u=0}^{\frac{m}{r_i}-1} \sigma_i^{au_i}.$$

Then the norm operators from  $k$  to the maximal subfield ramified at less primes can be given as  $R_i N_i$  (i.e. the sum of all elements of  $T_i$ ). If we denote the congruence corresponding to the canonical projection  $\mathbb{Z}[G] \rightarrow \mathbb{Z}[G/H]$  by  $\equiv$ , then we have  $N_4 \equiv \sum_{u=0}^{m-1} \sigma_1^{ua_1} \sigma_2^{ua_2} \sigma_3^{ua_3}$ .

Moreover, we will denote the congruence corresponding to the composition of canonical projections  $\mathbb{Z}[G] \rightarrow \mathbb{Z}[G/H] \rightarrow \mathbb{Z}[G/H]/(R_1 N_1, R_2 N_2, R_3 N_3, R_4 N_4)$  by  $\sim$ , where  $(R_1 N_1, R_2 N_2, R_3 N_3, R_4 N_4)$  is the ideal generated in  $\mathbb{Z}[G/H]$  by the images of the elements  $R_i N_i$ . When we apply any element of this ideal to the highest generator  $\eta$ , we will obtain a circular unit belonging to a field with less ramified primes. We will make use of this extensively.

To construct the basis of  $D^+$ , we can take the union of all bases for the fields

$$k \cap K_1 K_2 K_3, k \cap K_1 K_2 K_4, k \cap K_1 K_3 K_4, k \cap K_2 K_3 K_4$$

(which have three ramified primes, so we can use the results in [1]) and add in

$$\begin{aligned} c &:= [k : \mathbb{Q}] + 3 - \sum_{i,j,l} ([k \cap K_i K_j K_l : \mathbb{Q}] + 2) - \sum_{i,j} ([k \cap K_i K_j : \mathbb{Q}] + 1) - \sum_i [k \cap K_i : \mathbb{Q}] \\ &= a_1 a_2 a_3 a_4 \frac{m^3}{r_1 r_2 r_3 r_4} - \sum_{i,j,l} a_i a_j a_l \frac{m^2}{r_i r_j r_l} + \sum_{i,j} a_i a_j s_{ij} \frac{m}{r_i r_j} - \sum_i a_i + 1 \end{aligned}$$

(by the principle of inclusion and exclusion) conjugates of  $\eta$ . Then we will need to show how to obtain the missing conjugates of  $\eta$  using the relations

$$R_1 N_1 \sim 0, R_2 N_2 \sim 0, R_3 N_3 \sim 0, R_4 \sum_{u=0}^{m-1} \sigma_1^{ua_1} \sigma_2^{ua_2} \sigma_3^{ua_3} \sim 0.$$

We will always refer to the conjugates of  $\eta$  by their coordinates  $x_1, x_2, x_3, x_4$  according to Proposition 5. This allows for geometric interpretation.

## 4 The case $r_1 = r_2 = r_4 = a_3 = 1$

(Note that in this case we have  $s_{34} = 1$ .)

We will add all the conjugates of  $\eta$  to our basis except the following cases:

- $x_1 = a_1 m - 1$  or  $x_2 = a_2 m - 1$  or  $x_1 = \frac{m}{r_3} - 1$ ,
- $a_1 \leq x_1 < a_1 m - 1, a_2(m - 1) - 1 \leq x_2 < a_2 m - 1, 0 \leq x_3 < \frac{m}{r_3} - 1, x_4 = 0$ ,
- $0 \leq x_1 < a_1, a_2(m - 1) \leq x_2 < a_2 m - 1, 0 \leq x_3 < \frac{m}{r_3} - 1, x_4 = 0$ .

These cases are all disjoint, so it's easy to see that the number of conjugates of  $\eta$  that we chose is exactly

$$((a_1 m - 1)a_2(m - 2) + (a_1 m - 1)(a_2 - 1) + a_1 + (a_4 - 1)(a_1 m - 1)(a_2 m - 1)) \left( \frac{m}{r_3} - 1 \right) = c.$$

First we will recover the cases  $0 < x_4 < a_4, x_1 = a_1 m - 1$  or  $x_2 = a_2 m - 1$  or  $x_1 = \frac{m}{r_3} - 1$  using the relations  $R_1 N_1 \sim 0, R_2 N_2 \sim 0, R_3 N_3 \sim 0$ . From now on, we only need to deal with the cases where  $x_4 = 0$ .

Next, we will recover the cases

$$x_1 = a_1 m - 1, 0 \leq x_2 < a_2(m - 1) - 1, 0 \leq x_3 < \frac{m}{r_3} - 1$$

using the relation  $R_1 N_1 \sim 0$  and subsequently the cases

$$0 \leq x_1 < a_1 m - 1, 0 \leq x_2 < a_2(m - 1) - 1, 0 \leq x_3 < \frac{m}{r_3} - 1$$



and

$$0 \leq x_1 < a_1 - 1, x_2 = a_2(m-1) - 1, 0 \leq x_3 < \frac{m}{r_3} - 1$$

using the relation  $R_3 N_3 \sim 0$ .

Next, we will sequentially recover all the cases

$$0 \leq x_1 < a_1 m - 1, a_2(m-1) \leq x_2 < a_2 m - 1, 0 \leq x_3 < \frac{m}{r_3} - 1$$

using the relation  $R_4 \sum_{u=0}^{m-1} \sigma_1^{a_1 u} \sigma_2^{a_2 u} \sigma_3^u$ . We can do this since any two conjugates of  $\eta$  used in this relation differ by at least  $a_2$  in their second coordinate. After this, we can recover the cases

$$0 \leq x_1 < a_1, x_2 = a_2 m - 1, 0 \leq x_3 < \frac{m}{r_3} - 1$$

using the relation  $R_2 N_2 \sim 0$ .

Finally, we can use the relation  $R_4 \sum_{u=0}^{m-1} \sigma_1^{a_1 u} \sigma_2^{a_2 u} \sigma_3^u$  to recover the cases

$$a_1 \leq x_1 < 2a_1, x_2 = a_2 m - 1, 0 \leq x_3 < \frac{m}{r_3} - 1$$

and subsequently  $R_4 N_4$  to recover the cases

$$a_1 \leq x_1 < 2a_1, x_2 = a_2(m-1) - 1, 0 \leq x_3 < \frac{m}{r_3} - 1.$$

By repeating these two steps  $(m-2)$  more times, increasing the first coordinate by  $a_1$  each time, we will recover all the conjugates.

## 5 The case $a_1 = a_2 = a_3 = a_4 = r_3 = r_3 = 1, \gcd(\frac{m}{r_1}, \frac{m}{r_2}) = 1, (\frac{m}{r_2} = 2)$

In this case, using Lemma 4, we have

$$c = \left(\frac{m}{r_1} - 1\right) \left(\frac{m}{r_2} - 1\right) (m-2) + \gcd\left(\frac{m}{r_1}, \frac{m}{r_2}\right) - 1.$$

$$0 \sim \left( \left( \sum_{u=0}^{m-1} \sigma_1^{ua_1} \sigma_2^{ua_2} \sigma_3^{ua_3} \right) + \sigma_1^{\frac{m}{r_1}-2} \sigma_2^{\frac{m}{r_2}-2} N_3 \right) \left( \sum_{u=0}^{\frac{\frac{m}{r_1}-3}{2}} \sigma_1^{2u} \right)$$

## 6 The module of relations

## 7 Construction of suitable abelian fields

Let  $m, a_1, a_2, a_3, a_4, r_1, r_2, r_3, r_4$  be positive integers such that

$$m > 1, r_i \mid m, \gcd(r_i, r_j, r_l) = 1.$$

We will construct an infinite family of fields  $k$  that satisfy all of our assumptions such that these integers correspond to the parameters in our problem of the same name.

First, we will fix distinct primes  $p_1, p_2, p_3, p_4$  such that  $p_i \equiv 1 \pmod{2a_i \frac{m}{r_i}}$  (by Dirichlet's theorem on primes in arithmetic progressions, there are infinitely many ways of doing this). Then there exist even Dirichlet characters  $\chi_i$  of conductors  $p_i$  and orders  $a_i \frac{m}{r_i}$  (namely, these can be given as  $\chi_i := \chi^{\frac{p_i-1}{a_i m_i / r_i}}$ , where  $\chi$  is any generator of the cyclic group  $(\widehat{\mathbb{Z}/p_i\mathbb{Z}})^\times$  (note that  $p_i > 2$ )).

Now let  $K_i$  be the field associated to  $\langle \chi_i \rangle$ . Then  $K_i$  is real (because  $\chi_i$  is even) and  $\text{Gal}(K_i/\mathbb{Q})$  is cyclic of order  $a_i \frac{m}{r_i}$ , say  $\text{Gal}(K_i/\mathbb{Q}) = \langle \sigma_i \rangle$ . Moreover, since the conductors  $p_i$  are coprime, the group  $\langle \chi_1, \chi_2, \chi_3, \chi_4 \rangle$  corresponds to the compositum field  $K = K_1 K_2 K_3 K_4$ . By the theory of Dirichlet characters,  $K$  is ramified exactly at primes  $p_i$  (with inertia subgroups isomorphic to  $\text{Gal}(K_i/\mathbb{Q})$ ) and

$$\text{Gal}(K/\mathbb{Q}) = \text{Gal}(K_1/\mathbb{Q})\text{Gal}(K_2/\mathbb{Q})\text{Gal}(K_3/\mathbb{Q})\text{Gal}(K_4/\mathbb{Q}) = \langle \sigma_1, \sigma_2, \sigma_3, \sigma_4 \rangle,$$

so that  $[K : \mathbb{Q}] = a_1 a_2 a_3 a_4 \frac{m^4}{r_1 r_2 r_3 r_4}$ . Now let  $\tau := \sigma_1^{a_1} \sigma_2^{a_2} \sigma_3^{a_3} \sigma_4^{a_4}$  and let  $k$  be the subfield of  $K$  fixed by  $\tau$ . Since  $k$  is a subfield of a compositum of real fields, it must also be real. In order to reach our goal, we now only need to prove the following theorem (it is not hard to see that we could have used the results from Lemma 1 and Proposition 2 as definitions instead).

**Theorem 7.** *In the above notation, we have  $[K : k] = m$ ,  $[K : kK_i] = r_i$ ,  $[k \cap K_i : \mathbb{Q}] = a_i$  and  $kK_i K_j K_l = K$  (i.e.  $K$  is the genus field of  $k$ ).*

*Proof.* Using Lemma 4 several times, we can compute

$$[K : k] = |\langle \tau \rangle| = \text{lcm} \left( \frac{m}{r_i}, \frac{m}{r_j}, \frac{m}{r_l} \right) = m,$$

$$[K : kK_i] = |\langle \tau \rangle \cap \langle \sigma_j \sigma_l \sigma_h \rangle| = |\langle \tau^{a_i m / r_i} \rangle| = r_i,$$

$$[k \cap K_i : \mathbb{Q}] = [\langle \sigma_1, \sigma_2, \sigma_3, \sigma_4 \rangle : \langle \tau, \sigma_j, \sigma_l, \sigma_h \rangle] = [\langle \sigma_1, \sigma_2, \sigma_3, \sigma_4 \rangle : \langle \sigma_i^{a_i}, \sigma_j, \sigma_l, \sigma_h \rangle] = a_i$$

and

$$[K : kK_i K_j K_l] = |\langle \tau \rangle \cap \langle \sigma_h \rangle| = |\langle \tau^{\text{lcm}(\frac{m}{r_i}, \frac{m}{r_j}, \frac{m}{r_l})} \rangle| = |\langle \tau^m \rangle| = 1.$$

□