



Abelian quandles and quandles with abelian structure group

Victoria Lebed, Arnaud Mortier

► To cite this version:

Victoria Lebed, Arnaud Mortier. Abelian quandles and quandles with abelian structure group. 2019.
hal-02266880v2

HAL Id: hal-02266880

<https://normandie-univ.hal.science/hal-02266880v2>

Preprint submitted on 20 Aug 2019 (v2), last revised 2 Sep 2019 (v3)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

ABELIAN QUANDLES AND QUANDLES WITH ABELIAN STRUCTURE GROUP

VICTORIA LEBED AND ARNAUD MORTIER

ABSTRACT. Sets with a self-distributive operation (in the sense of $(a \triangleleft b) \triangleleft c = (a \triangleleft c) \triangleleft (b \triangleleft c)$), in particular quandles, appear in knot and braid theories, Hopf algebra classification, the study of the Yang–Baxter equation, and other areas. An important invariant of quandles is their structure group. The structure group of a finite quandle is known to be either “boring” (free abelian), or “interesting” (non-abelian with torsion). In this paper we explicitly describe all finite quandles with abelian structure group. To achieve this, we show that such quandles are abelian (i.e., satisfy $(a \triangleleft b) \triangleleft c = (a \triangleleft c) \triangleleft b$); present the structure group of any abelian quandle as a central extension of a free abelian group by an explicit finite abelian group; and determine when the latter is trivial. In the second part of the paper, we relate the structure group of any quandle to its 2nd homology group H_2 . We use this to prove that the H_2 of a finite quandle with abelian structure group is torsion-free, but general abelian quandles may exhibit torsion. Torsion in H_2 is important for constructing knot invariants and pointed Hopf algebras.

1. INTRODUCTION

A *quandle* is a set X with an idempotent binary operation \triangleleft such that the right translation by any element is a quandle automorphism. In other words, it should satisfy the following axioms for all $a, b, c \in X$:

- (1) self-distributivity: $(a \triangleleft b) \triangleleft c = (a \triangleleft c) \triangleleft (b \triangleleft c)$;
- (2) the right translation $- \triangleleft b$ is a bijection $X \rightarrow X$;
- (3) idempotence: $a \triangleleft a = a$.

Removing the last axiom, one gets the notion of *rack*. Groups with the conjugation operation $a \triangleleft b = b^{-1}ab$ are fundamental examples of quandles. This yields a functor $\text{Conj}: \mathbf{Grp} \rightarrow \mathbf{Quandle}$. Numerous other quandle families of various nature are known. The systematic study of self-distributivity was motivated by applications to low-dimensional topology, and goes back to [Joy82, Mat82].

The *structure group* (also called the *enveloping group*) of a quandle (X, \triangleleft) is defined by the following presentation:

$$G(X, \triangleleft) = \langle g_a, a \in X \mid g_a g_b = g_b g_{a \triangleleft b}, a, b \in X \rangle.$$

It brings group-theoretic tools into the study of quandles. More conceptually, it yields a functor $\text{SGr}: \mathbf{Quandle} \rightarrow \mathbf{Grp}$ which is left adjoint to Conj . The structure group of a rack can be defined along the same lines; however, since the structure groups of a rack and of its associated quandle are isomorphic (see for instance [LV19]), we treat only the quandle case here.

Structure groups of finite quandles exhibit the following dichotomy:

2010 *Mathematics Subject Classification.* 20N02, 20F05 20E22, 20K01, 55N35, 16T25.

Key words and phrases. Quandle, structure group, Yang–Baxter equation, rack homology.

- (1) either they are free abelian of rank $r = \# \text{Orb}(X, \triangleleft)$ (the number of orbits of X with respect to all right translations $- \triangleleft b$),
- (2) or they are non-abelian and have torsion.

In the second case, $G(X, \triangleleft)$ has a finite index free abelian subgroup of rank r ; see [LV19] for more details.

It is natural to ask which quandles fall into the first, “boring”, category above. The condition $G(X, \triangleleft) \cong \mathbb{Z}$ is easily seen to be equivalent to X being one-element. Quandles with $G(X, \triangleleft) \cong \mathbb{Z}^2$ were completely characterised in [BN19]. They are parametrised by coprime couples (m, n) , with $m \leq n$, and are presented as

$$(1.1) \quad U_{m,n} = \{x_0, x_1, \dots, x_{m-1}, y_0, y_1, \dots, y_{n-1}\},$$

$$x_i \triangleleft x_j = x_i, \quad y_k \triangleleft y_l = y_k, \quad x_i \triangleleft y_k = x_{i+1}, \quad y_k \triangleleft x_i = y_{k+1},$$

where $0 \leq i, j \leq m-1$, $0 \leq k, l \leq n-1$, and we identify $x_m = x_0$ and $y_n = y_0$.

In this paper we describe all finite quandles with $G(X, \triangleleft) \cong \mathbb{Z}^r$ for arbitrary r (Theorem 4.2). Up to an action of the symmetric group S_r , they are parametrised by $\frac{r^2(r-1)}{2}$ natural numbers subject to some inequalities and a coprimality condition. We simplify this condition in the case $r = 3$ (Theorem 5.1).

To achieve our characterisation, we first show that quandles with abelian structure group are necessarily *abelian*¹, i.e., satisfy the condition

$$(1.2) \quad (a \triangleleft b) \triangleleft c = (a \triangleleft c) \triangleleft b.$$

This class of quandles is of independent interest—cf. [Plo85, RR89, JPSZD15, JPZD18, BCW18]. We parametrise r -orbit abelian quandles by $\frac{r^2(r-1)}{2}$ natural numbers subject to some inequalities (Theorem 2.3). This classification is implicit in [JPSZD15], where it is derived from structural results on more general medial quandles². Our parametrisation is explicit, which is essential for further results in this paper, and constructive, hence easily programmable. Further, we present the structure group of an abelian r -orbit quandle (X, \triangleleft) as a central extension of \mathbb{Z}^r by an explicit finite abelian group $G'(X, \triangleleft)$ (Theorem 3.2). Finally, we show that $G'(X, \triangleleft)$ is trivial (equivalently, $G(X, \triangleleft)$ is free abelian) if and only if certain greatest common divisor constructed out of the parameters of (X, \triangleleft) is trivial.

Our result has the following application. The structure group construction extends to set-theoretic solutions $\sigma: X \times X \rightarrow X \times X$ to the Yang–Baxter equation; the quandle case corresponds to the solutions $(a, b) \mapsto (b, a \triangleleft b)$. Structure groups of involutive solutions ($\sigma^2 = \text{Id}$) are particularly well understood. One of the tools making involutive solutions accessible is the bijective group 1-cocycle $G(X, \sigma) \rightarrow \mathbb{Z}^{\#X}$. For a general invertible non-degenerate solution, one has a bijective group 1-cocycle $G(X, \sigma) \rightarrow G(X, \triangleleft_\sigma)$, where $(X, \triangleleft_\sigma)$ is the structure rack of (X, σ) . Thus some results for involutive solutions extend to solutions with $G(X, \triangleleft_\sigma)$ free abelian. See [GIVdB98, ESS99, Sol00, LYZ00, LV17, LV19] for more detail.

This discussion raises the following questions:

Question 1.1. *What structural property of a YBE solution corresponds to its structure rack $(X, \triangleleft_\sigma)$ being abelian? having abelian structure group $G(X, \triangleleft_\sigma)$?*

¹Terminology varies a lot in the area: some authors assign the term *abelian* to the property $a \triangleleft b = b \triangleleft a$, others to $(a \triangleleft b) \triangleleft (c \triangleleft d) = (a \triangleleft c) \triangleleft (b \triangleleft d)$.

²I.e., satisfying the condition $(a \triangleleft b) \triangleleft (c \triangleleft d) = (a \triangleleft c) \triangleleft (b \triangleleft d)$. They are also known as *entropic*, and sometimes called *abelian*.

The (rack) homology³ $H_\bullet(X, \triangleleft)$ of a quandle (X, \triangleleft) is the homology of the following chain complex:

$$(1.3) \quad \begin{aligned} C_k(X, \triangleleft) &= \mathbb{Z}X^k, \\ d_k(a_1, \dots, a_k) &= \sum_{i=2}^k (-1)^{i-1} [(a_1, \dots, \widehat{a_i}, \dots, a_k) \\ &\quad - (a_1 \triangleleft a_i, \dots, a_{i-1} \triangleleft a_i, a_{i+1}, \dots, a_k)]. \end{aligned}$$

Here $\widehat{a_i}$ means that the entry a_i is omitted, and the formula for d_k is extended to the whole $\mathbb{Z}X^k$ by linearity. The rank of $H_k(X, \triangleleft)$ is known to be r^k (as before, $r = \# \text{Orb}(X, \triangleleft)$) [EG03]. The torsion part of $H_\bullet(X, \triangleleft)$, which is the part needed for powerful knot invariants and Hopf algebra classification [FRS95, CJK⁺03, AG03], is much less uniform. Even the case of $H_2(X, \triangleleft)$, the most useful in practice, is understood only for particular families of quandles: Alexander, one-orbit etc. [FRS07, Cla10, NP11, GIV17, PIM⁺18].

In this paper we show that $H_2(X, \triangleleft)$ is torsion-free for a finite quandle with abelian structure group (Corollary 7.3). For a general finite abelian quandle, the torsion part of $H_2(X, \triangleleft)$ is a sum of r (possibly different) quotients of $G'(X, \triangleleft)$ (Theorem 7.1). These quotients can be anything between trivial, like in Corollary 7.6, and the whole $G'(X, \triangleleft)$, like in

$$H_2(U_{m,n}) \cong \mathbb{Z}^4 \oplus G'(U_{m,n})^2 \cong \mathbb{Z}^4 \oplus \mathbb{Z}_{\gcd(m,n)}^2$$

(Proposition 7.4). The situation here resembles what happens for one-orbit quandles: there $H_2(X, \triangleleft)$ is also controlled by a finite group [GIV17]. Our main tool is an explicit group morphism (working for any rack)

$$\prod_{i=1}^r \text{Stab}(a_i, G(X, \triangleleft)) \twoheadrightarrow H_2(X, \triangleleft),$$

where the a_i are representatives of the orbits of (X, \triangleleft) , and the stabiliser subgroups refer to the classical $G(X, \triangleleft)$ -action on X (Proposition 6.1).

We finish with an open question:

Question 1.2. *How does the (general degree) homology of a finite abelian quandle depend on its parameters?*

In this paper we give several examples suggesting that the answer might be rather subtle. In particular we show that the group $G'(X, \triangleleft)$ does not determine the torsion of $H_2(X, \triangleleft)$ completely.

2. A PARAMETRISATION OF ABELIAN QUANDLES

In this section we classify finite abelian quandles with r orbits. Our description generalises the presentation (1.1) of the quandles $U_{m,n}$.

Fix a positive integer $r \geq 2$. Take a collection of $\frac{r(r-1)}{2}$ integers

$$(2.1) \quad M = (m_{i,j})_{1 \leq j \leq i < r}, \quad \text{with } 1 \leq m_{i,i}, \text{ and } 0 \leq m_{j,i} < m_{i,i} \text{ for } i < j.$$

³One could also discuss the *quandle homology* of (X, \triangleleft) , or consider more complicated coefficients than \mathbb{Z} . Classical results [LN03] allow one to reduce these broader contexts to our case.

It can be considered as a lower triangular matrix of size $r - 1$. To these parameters we associate an abelian group

$$G(M) = \langle x_1, x_2, \dots, x_{r-1} \mid x_i x_j = x_j x_i, x_1^{m_{i,1}} x_2^{m_{i,2}} \cdots x_i^{m_{i,i}} = 1 \rangle,$$

where i and j vary between 1 and $r - 1$. In what follows, it will be convenient to use the notations $x_0 := 1$ and $m_i := m_{i,i}$. The group $G(M)$ is finite abelian, of order $m_1 m_2 \cdots m_{r-1}$.

For example, for $r = 2$ we get a cyclic group of order m_1 , and for $r = 4$ and $M = \begin{pmatrix} m_1 & & & \\ m_{2,1} & m_2 & & \\ m_{3,1} & m_{3,2} & m_3 & \end{pmatrix}$ we get 3 commuting generators subject to 3 relations

$$\begin{aligned} x_1^{m_1} &= 1, \\ x_1^{m_{2,1}} x_2^{m_2} &= 1, \\ x_1^{m_{3,1}} x_2^{m_{3,2}} x_3^{m_3} &= 1. \end{aligned}$$

Now, take r collections $M^{(1)}, \dots, M^{(r)}$ as above, and consider the disjoint union

$$Q(M^{(1)}, \dots, M^{(r)}) = G(M^{(1)}) \sqcup \dots \sqcup G(M^{(r)}).$$

The generator x_i of $G(M^{(j)})$ will be denoted by $x_i^{(j)}$. We endow $Q(M^{(1)}, \dots, M^{(r)})$ with a binary operation \triangleleft as follows. For any $a^{(i)} \in G(M^{(i)})$ and $b^{(i+k)} \in G(M^{(i+k)})$ (here $0 \leq k < r$, and the sum $i + k$ is considered modulo r), put

$$a^{(i)} \triangleleft b^{(i+k)} = a^{(i)} x_k^{(i)} \in G(M^{(i)}).$$

In particular, $a^{(i)} \triangleleft b^{(i)} = a^{(i)}$. In the simplest case $r = 2$, we recover the quandle $U_{m_1^{(1)}, m_1^{(2)}}$ from (1.1). For general r , we still get a quandle operation:

Proposition 2.1. *The data $(Q(M^{(1)}, \dots, M^{(r)}), \triangleleft)$ above define an abelian quandle. The r components $G(M^{(i)})$ are its orbits.*

Definition 2.2. The quandles above will be called *filtered-permutation*, or *FP*.

Proof. Quandle axioms (3) and (2), and the assertion about the orbits, are clear from the construction. Moreover, the groups $G(M^{(i)})$ are commutative, so all right \triangleleft -actions commute, hence the abelianity axiom (1.2). Let us check the self-distributivity axiom (1). By construction, all elements from the same orbit $G(M^{(i)})$ of $Q := Q(M^{(1)}, \dots, M^{(r)})$ right \triangleleft -act in the same way. Hence for all $a, b, c \in Q$ one has

$$(a \triangleleft b) \triangleleft c = (a \triangleleft c) \triangleleft b = (a \triangleleft c) \triangleleft (b \triangleleft c),$$

as required. \square

Recall that a quandle (X, \triangleleft) is called *2-reductive* if the relation

$$(2.2) \quad a \triangleleft (b \triangleleft c) = a \triangleleft b$$

holds for all $a, b, c \in X$.

Theorem 2.3. *For a finite quandle (X, \triangleleft) , the following conditions are equivalent:*

- (1) (X, \triangleleft) is abelian;
- (2) (X, \triangleleft) is 2-reductive;
- (3) (X, \triangleleft) is (isomorphic to) a filtered-permutation quandle.

Moreover, two FP quandles with r **ordered orbits** are isomorphic if and only if they have the same parameters $M^{(1)}, \dots, M^{(r)}$.

Definition 2.4. If $(X, \triangleleft) \cong Q(M^{(1)}, \dots, M^{(r)})$, as in (3), we call $M^{(1)}, \dots, M^{(r)}$ the *parameters* of (X, \triangleleft) . To make this definition unambiguous, from now on we will work with finite quandles with **ordered orbits**.

The equivalence (1) \Leftrightarrow (2) is folklore; the equivalence (1) \Leftrightarrow (3) and the uniqueness assertion are implicit in [JPSZD15].

Proof. (1) \Rightarrow (2). If (X, \triangleleft) is abelian, then

$$(a \triangleleft b) \triangleleft c = (a \triangleleft c) \triangleleft b = (a \triangleleft b) \triangleleft (c \triangleleft b) \text{ for all } a, b, c \in X.$$

Since the right translation $- \triangleleft b$ is bijective, we deduce

$$a \triangleleft c = a \triangleleft (c \triangleleft b) \text{ for all } a, b, c \in X.$$

(2) \Rightarrow (1). If (X, \triangleleft) is 2-reductive, then

$$(a \triangleleft b) \triangleleft c = (a \triangleleft c) \triangleleft (b \triangleleft c) = (a \triangleleft c) \triangleleft b \text{ for all } a, b, c \in X.$$

(3) \Rightarrow (1) was proved in Proposition 2.1.

The implication (1) \Rightarrow (3) requires more work. Let (X, \triangleleft) be a finite abelian, hence 2-reductive, quandle. In particular, $a \triangleleft a' = a \triangleleft a = a$ for a and a' from the same orbit. Let O_1, \dots, O_r be the orbits of (X, \triangleleft) . The 2-reductivity yields permutations $f_{i,j} \in \text{Perm}(O_i)$, $1 \leq i, j \leq r$ such that

$$a \triangleleft b = f_{i,j}(a) \text{ for all } a \in O_i, b \in O_j.$$

These permutations satisfy the following conditions:

- (a) commutativity: $f_{i,j}f_{i,k} = f_{i,k}f_{i,j}$;
- (b) transitivity: the $f_{i,j}$, $1 \leq j \leq r$, generate a transitive subgroup G_i of $\text{Perm}(O_i)$;
- (c) freeness: $a \cdot g = a$ for some $a \in O_i$ and $g \in G_i$ implies $a' \cdot g = a'$ for all $a' \in O_i$.

Indeed, (a) follows from abelianity, and (b) from the definition of orbits and the finiteness of X . For (c), using transitivity, write $a' = a \cdot h$ for some $h \in G_i$ to get

$$a' \cdot g = (a \cdot h) \cdot g = a \cdot (hg) = a \cdot (gh) = (a \cdot g) \cdot h = a \cdot h = a'.$$

Now, fix an index i . All the indices below are considered modulo r . By the freeness, the permutation $f_{i,i+1}$ consists of cycles of the same length; denote this length by $m_1^{(i)}$. Further, take an $a \in O_i$; the permutation $f_{i,i+2}$ will send a to a possibly different $f_{i,i+1}$ -cycle, but after $m_2^{(i)}$ iterations will bring it back to the original $f_{i,i+1}$ -cycle for the first time. This yields a condition $f_{i,i+2}^{m_2^{(i)}}(a) = f_{i,i+1}^{-m_2^{(i)}}(a)$ for some $0 \leq m_{2,1}^{(i)} < m_1^{(i)}$. Once again, freeness yields the relation $f_{i,i+1}^{m_{2,1}^{(i)}} f_{i,i+2}^{m_2^{(i)}} = 1$ in $\text{Perm}(O_i)$. Similarly, by looking when $f_{i,i+3}$ brings a back to its original $\langle f_{i,i+1}, f_{i,i+2} \rangle$ -orbit (where we are considering the subgroup of $\text{Perm}(O_i)$ generated by $f_{i,i+1}$ and $f_{i,i+2}$), one finds a relation $f_{i,i+1}^{m_{3,1}^{(i)}} f_{i,i+2}^{m_{3,2}^{(i)}} f_{i,i+3}^{m_3^{(i)}} = 1$ in $\text{Perm}(O_i)$, with $0 \leq m_{3,1}^{(i)} < m_1^{(i)}$ and $0 \leq m_{3,2}^{(i)} < m_2^{(i)}$. See Fig. 2.1 for an example: here $r = 4$, $i = 1$, and $M^{(1)} = \begin{pmatrix} 3 & 2 \\ 0 & 0 & 2 \end{pmatrix}$.

Iterating this argument, one obtains a parameter collection $M^{(i)}$ of the form (2.1), and a transitive action of the group $G(M^{(i)})$ on O_i : the generator $x_k^{(i)}$ of $G(M^{(i)})$ act by $f_{i,i+k}$. Let us prove that this action is free. If it were not, one would have

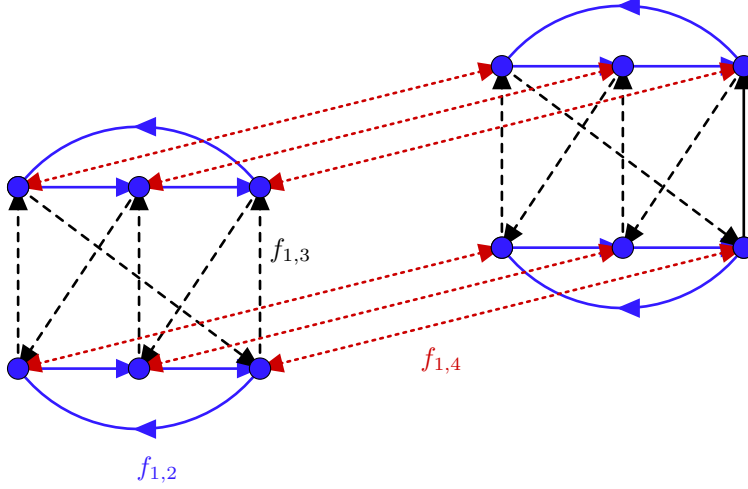


FIGURE 2.1. An orbit of a 4-orbit abelian quandle.

a relation $f_{i,i+1}^{m'_{k,1}} f_{i,i+2}^{m'_{k,2}} \cdots f_{i,i+k-1}^{m'_{k,k-1}} f_{i,i+k}^{m'_k} = 1$ in $\text{Perm}(O_i)$, with $1 \leq k \leq r-1$, and $0 < m'_k < m_k^{(i)}$. But this contradicts the minimality in the choice of $m_k^{(i)}$.

Now, choosing an $a_i \in \text{Perm}(O_i)$ for all i , one gets the following identifications:

$$G(M^{(i)}) \leftrightarrow O_i,$$

$$(x_1^{(i)})^{n_1} (x_2^{(i)})^{n_2} \cdots (x_{r-1}^{(i)})^{n_{r-1}} \leftrightarrow f_{i,i+1}^{n_1} f_{i,i+2}^{n_2} \cdots f_{i,i+r-1}^{n_{r-1}}(a_i).$$

Moreover, the action of $f_{i,i+k}$ on O_i corresponds to multiplying by $x_k^{(i)}$ in $G(M^{(i)})$. One obtains a quandle isomorphism $Q(M^{(1)}, \dots, M^{(r)}) \cong (X, \triangleleft)$, thus (3).

Finally, by the freeness of the G_i -action on O_i , the parameter collection $M^{(i)}$ is independent of the choice of the orbit representative a_i , and is thus uniquely determined by the isomorphism class of (X, \triangleleft) , where we require isomorphisms to preserve a chosen order of orbits. \square

Remark 2.5. The parameters $M^{(1)}, \dots, M^{(r)}$ describe abelian quandles uniquely up to component reordering, that is, up to the permutation action of the symmetric group S_r . For $r = 2$, one gets rid of this redundancy by imposing $m_1^{(1)} \leq m_1^{(2)}$.

3. STRUCTURE GROUPS OF ABELIAN QUANDLES

In this section we describe the structure group of a finite abelian quandle in terms of its parameters.

Definition 3.1. Let (X, \triangleleft) be a finite abelian quandle with parameters $M^{(i)}$. Its *parameter group* is the following quotient of the direct product of the groups $G(M^{(i)})$:

$$G'(X, \triangleleft) := \prod_{i=1}^r G(M^{(i)}) \Big/ \left\langle x_{j-i}^{(i)} x_{i-j}^{(j)}, 1 \leq i < j \leq r \right\rangle.$$

In the simplest case $r = 2$ we have

$$\begin{aligned} G' &= G(M^{(1)}) \times G(M^{(2)}) \Big/ \langle x_1^{(1)} x_1^{(2)} \rangle \\ &\cong \langle x_1^{(1)}, x_1^{(2)} \mid (x_1^{(1)})^{m_1^{(1)}}, (x_1^{(2)})^{m_1^{(2)}}, x_1^{(1)} x_1^{(2)} \rangle \cong \mathbb{Z}_{\gcd(m_1^{(1)}, m_1^{(2)})}. \end{aligned}$$

Theorem 3.2. *Let (X, \triangleleft) be a finite r -orbit abelian quandle. Its structure group $G(X, \triangleleft)$ is a central extension of \mathbb{Z}^r by its parameter group $G'(X, \triangleleft)$. Moreover, $G'(X, \triangleleft)$ is a finite abelian group, and is (isomorphic to) the commutator subgroup of $G(X, \triangleleft)$.*

In the proof we describe this extension explicitly. For $r = 2$ it looks as follows:

$$G \cong \langle h_1, h_2, q \mid h_2 h_1 = q h_1 h_2, h_1 q = q h_1, h_2 q = q h_2, q^d = 1 \rangle,$$

where $d = \gcd(m_1^{(1)}, m_1^{(2)})$.

In what follows we will often identify G' with the commutator subgroup of G .

Proof. By Theorem 2.3, it suffices to work with the filtered-permutation quandle $Q := Q(M^{(1)}, \dots, M^{(r)})$. The defining relations of its structure group G are

$$(3.1) \quad g_a g_b = g_b g_{a x_{j-i}} \quad \text{for } a \in G(M^{(i)}), b \in G(M^{(j)}).$$

As usual, the index $j - i$ is taken modulo r . The decorations $^{(i)}$ are omitted when clear from the context.

Denote by G_i the subgroup of G generated by the g_a with $a \in G(M^{(i)})$. Since $x_0^{(i)} = 1$, it is commutative. Further, one can rewrite (3.1) as

$$(3.2) \quad g_a^{-1} g_b^{-1} g_a g_b = g_a^{-1} g_{a x_{j-i}} \in G_i.$$

In particular, this expression is independent of b . Exchanging the roles of a and b , one gets

$$g_b^{-1} g_a^{-1} g_b g_a = g_b^{-1} g_{b x_{i-j}} \in G_j,$$

which is independent of a , and is the inverse of the preceding expression. Denoting both sides of (3.2) by $g_{i,j}$, one thus obtains elements $g_{i,j} \in G_i \cap G_j$ (and hence commuting with G_i and G_j), which allow one to break (3.2) into two parts:

$$(3.3) \quad g_a g_b = g_{i,j} g_b g_a \quad \text{for } a \in G(M^{(i)}), b \in G(M^{(j)}),$$

$$(3.4) \quad g_{a x_{j-i}} = g_{i,j} g_a \quad \text{for } a \in G(M^{(i)}).$$

Moreover, the $g_{i,j}$ satisfy

$$(3.5) \quad g_{i,j} g_{j,i} = 1 \quad \text{for } 1 \leq i < j \leq r,$$

$$(3.6) \quad g_{i,i} = 1 \quad \text{for } 1 \leq i \leq r.$$

We will now prove that

$$(3.7) \quad g_{i,j} \text{ is central in } G \quad \text{for } 1 \leq i, j \leq r.$$

Indeed, it can be written as $g_a^{-1} g_{a'}$, with a and a' from the same orbit $G(M^{(i)})$. Taking $b \in G(M^{(j)})$, one computes

$$(3.8) \quad g_a^{-1} g_{a'} g_b = g_a^{-1} g_{i,j} g_b g_{a'} = g_{i,j} g_a^{-1} g_b g_{a'} = g_{i,j} g_{j,i} g_b g_a^{-1} g_{a'} = g_b g_a^{-1} g_{a'},$$

where we used that $g_{i,j}$ commutes with G_i .

Further, from (3.4) one sees that the $g_{i,j}$ together with the elements

$$h_i := g_{1(i)} \in G_i$$

generate the whole group G . Indeed, one can put

$$g_{(x_1^{(i)})^{n_1}(x_2^{(i)})^{n_2}\dots(x_{r-1}^{(i)})^{n_{r-1}}} = g_{i,i+1}^{n_1} g_{i,i+2}^{n_2} \dots g_{i,i+r-1}^{n_{r-1}} h_i.$$

This is well defined if and only if one has

$$(3.9) \quad g_{i,i+1}^{m_{j,1}^{(i)}} g_{i,i+2}^{m_{j,2}^{(i)}} \dots g_{i,i+j}^{m_{j,j}^{(i)}} = 1 \quad \text{for } 1 \leq i \leq r, 1 \leq j < r.$$

If one assumes these conditions, relations (3.4) become redundant. Finally, since the $g_{i,j}$ are central, it is sufficient to check relations (3.3) for the generators h_i only:

$$(3.10) \quad h_i h_j = g_{i,j} h_j h_i.$$

This yields a new presentation for the group G :

$$(3.11) \quad G \cong \langle g_{i,j}, 1 \leq i, j \leq r; h_i, 1 \leq i \leq r \mid (3.5), (3.6), (3.7), (3.9), (3.10) \rangle.$$

Next, denote by G'' the subgroup of G generated by the $g_{i,j}$. From the presentation (3.11), one sees that G'' is the commutator subgroup of G . It is well known⁴ that the abelianisation of G is $\mathbb{Z}^r = \oplus_{i=1}^r \mathbb{Z}e_i$. Indeed from the relations $g_b g_a = g_a g_b = g_b g_{a \triangleleft b}$ in G_{ab} one deduces that $g_a = g_{a'}$ whenever a and a' lie in the same orbit, thus the map $g_a \mapsto e_i$ for a from the orbit $O_i = G(M^{(i)})$ yields a group isomorphism $G_{\text{ab}} \cong \mathbb{Z}^r$. Hence the short exact sequence

$$0 \rightarrow G'' \rightarrow G \rightarrow \mathbb{Z}^r \rightarrow 0.$$

Since the $g_{i,j}$ are central in G , this presents G as a central extension of \mathbb{Z}^r by G'' .

It remains to prove that the groups $G' := G'(X, \triangleleft)$ and G'' are isomorphic. Relations (3.5), (3.6), and (3.9) allow one to construct a surjective group morphism

$$\begin{aligned} \psi: G' &\twoheadrightarrow G'', \\ x_j^{(i)} &\mapsto g_{i,i+j}. \end{aligned}$$

To show its injectivity, we will construct a set-theoretic map

$$\pi: G \rightarrow G'$$

as follows. Take an element $g \in G$ written using the generators $g_{i,j}$ and h_i . Move all the occurrences of $h_1^{\pm 1}$ to the left using the centrality of the $g_{i,j}$ and the twisted commutativity (3.10) of the h_i . Similarly, move all the occurrences of $h_2^{\pm 1}$ right after the $h_1^{\pm 1}$, and so on. Use the relations $h_i h_i^{-1} = h_i^{-1} h_i = 1$ to get a word of the form $h_1^{k_1} \dots h_r^{k_r} g''$, where $k_1, \dots, k_r \in \mathbb{Z}$, and g'' is a product of the $g_{i,j} \pm 1$. Next, in g'' replace each generator $g_{i,j}$ by $x_{j-i}^{(i)}$. Denote by g' the word obtained. Considering it as an element of G' , put $\pi(g) = g'$. This is well defined. Indeed, relations (3.5), (3.6), (3.9), and $g_{i,j}^{\pm 1} g_{i,j}^{\mp 1} = 1$ have counterparts in G' ; relation (3.7) does not change the result by construction; and neither do (3.10) and $h_i^{\pm 1} h_i^{\mp 1} = 1$, as shows a computation similar to (3.8), combined with (3.5). Consider the restriction

$$\varphi := \pi|_{G''}: G'' \rightarrow G'.$$

It simply replaces each $g_{i,j}$ by $x_{j-i}^{(i)}$ in any representative of an element of G'' , and is thus the desired inverse of ψ .

Finally, G' is a finite abelian group, since so are the groups $G(M^{(i)})$. □

⁴and true for any rack

4. QUANDLES WITH ABELIAN STRUCTURE GROUP

Finally, we are ready to classify all finite quandles with abelian structure group.

Definition 4.1. Let (X, \triangleleft) be a finite abelian quandle with r orbits. Its *parameter matrix* $\mathcal{M}(X, \triangleleft)$ is constructed from its parameters $M^{(i)}$ as follows. Its columns are indexed by couples (i, j) with $1 \leq i < j \leq r$. Its rows are indexed by couples (i, j) with $1 \leq i \leq r, 1 \leq j < r$. All couples are ordered lexicographically here. The row (i, j) corresponds to the j th row of $M^{(i)}$; for all $1 \leq k \leq \min\{j, r - i\}$, it contains $m_{j,k}^{(i)}$ in the column $(i, i + k)$, and for all $r - i < k \leq j$, it contains $-m_{j,k}^{(i)}$ in the column $(i + k - r, i)$.

For $r = 2$ and the parameters $M^{(1)} = (m_1^{(1)})$ and $M^{(2)} = (m_1^{(2)})$, one gets

$$\mathcal{M}(X, \triangleleft) = \begin{pmatrix} m_1^{(1)} \\ -m_1^{(2)} \end{pmatrix}.$$

For $r = 3$, there are 3 columns: $(1, 2)$, $(1, 3)$, $(2, 3)$, and

$$\mathcal{M}(X, \triangleleft) = \begin{pmatrix} m_1^{(1)} & \cdot & \cdot \\ m_{2,1}^{(1)} & m_2^{(1)} & \cdot \\ \cdot & \cdot & m_1^{(2)} \\ -m_2^{(2)} & \cdot & m_{2,1}^{(2)} \\ \cdot & -m_1^{(3)} & \cdot \\ \cdot & -m_{2,1}^{(3)} & -m_2^{(3)} \end{pmatrix}$$

(the dots are zeroes).

Theorem 4.2. *For a finite quandle (X, \triangleleft) , the following conditions are equivalent:*

- (1) *the structure group of (X, \triangleleft) is abelian;*
- (2) *the quandle (X, \triangleleft) is abelian, and its parameter group $G'(X, \triangleleft)$ is trivial;*
- (3) *the quandle (X, \triangleleft) is abelian, and the maximal minors of its parameter matrix $\mathcal{M}(X, \triangleleft)$ are globally coprime.*

For $r = 2$, the coprimality condition from the theorem becomes $\gcd(m_1^{(1)}, m_1^{(2)}) = 1$, and we recover the classification of finite quandles with structure group \mathbb{Z}^2 from [BN19]. For $r = 3$, we will simplify the condition from the theorem in Section 5.

Proof. Let us first show that a finite quandle (X, \triangleleft) with abelian structure group $G := G(X, \triangleleft)$ is abelian. Indeed, by the construction of the structure group, and due to quandle axioms (1) and (2), the assignment $a \cdot g_b := a \triangleleft b$ extends to a right action of G on X . Since G is abelian, we get

$$(a \triangleleft b) \triangleleft c = (a \cdot g_b) \cdot g_c = a \cdot (g_b g_c) = a \cdot (g_c g_b) = (a \cdot g_c) \cdot g_b = (a \triangleleft c) \triangleleft b.$$

Thus we only need to understand which finite abelian quandles have abelian structure group. By Theorem 3.2, this happens if and only the parameter group $G' := G'(X, \triangleleft)$ is trivial. Indeed, if G' is trivial, then $G \cong \mathbb{Z}^r$; and if G is abelian, then by [LV19] it is free abelian, hence the only possibility for its finite subgroup G' is to be trivial. We thus proved (1) \iff (2).

Let us show the equivalence (2) \iff (3). Assume the quandle (X, \triangleleft) abelian, with parameters $M^{(i)}$. The group G' admits as generators the elements $x_j^{(i)}$ for $i + j \leq r$, since for $i + j > r$ one has $x_j^{(i)} = (x_{r-j}^{(j+i-r)})^{-1}$. With these $n := \frac{r(r-1)}{2}$ generators, G' is isomorphic to the quotient of \mathbb{Z}^n by the row space of the matrix $\mathcal{M} := \mathcal{M}(X, \triangleleft)$. Indeed, the rows of \mathcal{M} encode the defining relations of the components $G(M^{(i)})$

of G , taking into account the identification $x_j^{(i)} = (x_{r-j}^{(j+i-r)})^{-1}$. By a classical argument, the triviality of G' is then equivalent to the maximal minors of \mathcal{M} being globally coprime. This can be seen as follows: given a finitely generated abelian group, both its isomorphism class and the greatest common divisor of the maximal minors of its presentation matrix as above are invariant under elementary row and column operations, and for a matrix in Smith normal form, the triviality of the group and the minors condition are both equivalent to the matrix being of maximal rank with all diagonal entries equal to 1. \square

One can ask whether there are many quandles satisfying the conditions from the theorem. The answer is yes, as is shown by the following example:

Proposition 4.3. *Let (X, \triangleleft) be a finite abelian quandle with r orbits, and assume that its parameters $m_{j,k}^{(i)}$ vanish whenever $k < j$. Then the following conditions are equivalent:*

- (a) *the structure group of (X, \triangleleft) is \mathbb{Z}^r ;*
- (b) *$\gcd(m_j^{(i)}, m_{r-j}^{(j+i-r)}) = 1$ whenever $i + j > r$.*

The quandles from the proposition have $r(r-1)$ non-zero parameters $m_j^{(i)}$, and condition (b) divides them into $\frac{r(r-1)}{2}$ coprime pairs. One thus obtains, for each r , an infinite family of quandles with structure group \mathbb{Z}^r .

Proof. One could compute the maximal minors from the point (3) of Theorem 4.2. Instead, we choose here to check the triviality of the abelian group $G' := G'(X, \triangleleft)$, and use the equivalence (1) \iff (2) from the theorem. In our situation, G' has the following presentation:

$$G' \cong \langle x_j^{(i)} \mid (x_j^{(i)})^{m_j^{(i)}} = 1, x_{k-l}^{(l)} x_{l-k}^{(k)} = 1 \rangle,$$

where $1 \leq i \leq r$, $1 \leq j < r$, and $1 \leq l < k \leq r$. The last condition means that the generators $x_{k-l}^{(l)}$ and $x_{l-k}^{(k)}$ are mutually inverse. The above presentation then rewrites as

$$G' \cong \langle x_j^{(i)}, i + j > r \mid (x_j^{(i)})^{\gcd(m_j^{(i)}, m_{r-j}^{(j+i-r)})} = 1, i + j > r \rangle,$$

where $1 \leq i \leq r$, $1 \leq j < r$. But this is the direct product of the cyclic groups of orders $\gcd(m_j^{(i)}, m_{r-j}^{(j+i-r)})$, where $1 \leq i \leq r$, $1 \leq j < r$, and $i + j > r$. \square

5. QUANDLES WITH STRUCTURE GROUP \mathbb{Z}^3

In the case $r = 3$, instead of computing the $\binom{6}{3} = 20$ maximal minors of the 6×3 parameter matrix, it is in fact sufficient to compute only 7 simple greatest common divisors:

Theorem 5.1. *The structure group of a finite quandle is \mathbb{Z}^3 if and only if it is abelian with 3 orbits, and its parameters satisfy the following conditions:*

- (1) $\gcd(m_1^{(1)}, m_{2,1}^{(1)}, m_2^{(2)}) = \gcd(m_2^{(1)}, m_1^{(3)}, m_{2,1}^{(3)}) = \gcd(m_1^{(2)}, m_{2,1}^{(2)}, m_2^{(3)}) = 1$;
- (2) $\gcd(m_1^{(1)}, m_{2,1}^{(1)}, m_1^{(2)}, m_2^{(3)}) = \gcd(m_1^{(1)}, m_2^{(2)}, m_1^{(3)}, m_{2,1}^{(3)})$
 $= \gcd(m_2^{(1)}, m_1^{(2)}, m_{2,1}^{(2)}, m_1^{(3)}) = 1$;
- (3) $\gcd(m_1^{(1)}, m_1^{(2)}, m_1^{(3)}, m_{2,1}^{(1)} m_{2,1}^{(2)} m_{2,1}^{(3)} - m_2^{(1)} m_2^{(2)} m_2^{(3)}) = 1$.

Proof. By Theorem 4.2, we may assume our quandle abelian with 3 orbits. For the sake of readability, let us rename the entries of its parameter matrix and permute its rows, to get the matrix

$$(5.1) \quad M = \begin{pmatrix} a & \cdot & \cdot \\ \cdot & b & \cdot \\ \cdot & \cdot & c \\ u & v & \cdot \\ w & \cdot & x \\ \cdot & y & z \end{pmatrix}.$$

The conditions from the theorem then become:

- (1) $\gcd(a, u, w) = \gcd(b, v, y) = \gcd(c, x, z) = 1$;
- (2) $\gcd(a, b, w, y) = \gcd(a, c, u, z) = \gcd(b, c, v, x) = 1$;
- (3) $\gcd(a, b, c, \Delta) = 1$,

where $\Delta = uxy + vwz = -\det \begin{pmatrix} u & v & \cdot \\ w & \cdot & x \\ \cdot & y & z \end{pmatrix}$. By Theorem 4.2, we need to prove

that these three conditions are equivalent to the coprimality of the maximal minors of M , which here means

- (4) $D := \gcd(abc, abx, abz, avc, avx, avz, ayc, ayx, bcu, bcw, bux, buz, bwz, cvw, cuy, cwy, \Delta) = 1$.

All monomials in these minors contain one element from each column of M , so (4) \implies (1). Similarly, all monomials contain, say, one element from the first column and one from the second, and never u and v simultaneously, so $\gcd(a, b, w, y)$ divides D . A similar argument for the remaining pairs of columns yields (4) \implies (2). Finally, all the minors except for Δ are divisible by a , b , or c , hence (4) \implies (3).

In the opposite direction, $\gcd(a, u, w) = 1$ implies $\gcd(abc, bcu, bcw) = bc$. Similarly, $\gcd(b, v, y) = 1$ implies $\gcd(abc, avc, ayc) = ac$, and $\gcd(c, x, z) = 1$ implies $\gcd(abc, abx, abz) = ab$. Hence (1) allows one to simplify D as

$$D = \gcd(bc, ac, ab, avx, avz, ayx, bux, buz, bwz, cvw, cuy, cwy, \Delta).$$

Also, $\gcd(c, x, z) = 1$ implies $\gcd(avc, avx, avz) = av$. Analogous arguments lead to further simplifications:

$$D = \gcd(bc, ac, ab, av, ax, bu, bz, cw, cy, \Delta).$$

Now, $\gcd(a, b, w, y) = 1$ yields $\gcd(ac, bc, wc, yc) = c$. Repeating the same argument for other conditions from (2), one gets

$$D = \gcd(a, b, c, \Delta),$$

which is 1 by (3). □

One could deduce conditions (1)-(3) above from the triviality of the parameter group G' in a more conceptual way. Indeed, if G' is trivial, it remains so when one forgets any two of its three generators—that is, when one removes any two of the three columns of the matrix M from (5.1). The maximal minors of the remaining 6×1 matrices yield conditions (1). Similarly, when one forgets, say, the third

generator, one is left with the matrix

$$\begin{pmatrix} a & \cdot \\ \cdot & b \\ \cdot & \cdot \\ u & v \\ w & \cdot \\ \cdot & y \end{pmatrix}.$$

Since the relations $x^m = x^n = 1$ are equivalent to $x^{\gcd(m,n)} = 1$, this matrix defines the same group as the matrix

$$\begin{pmatrix} \gcd(a, w) & \cdot \\ \cdot & \gcd(b, y) \\ u & v \end{pmatrix}.$$

Applying to this matrix the proposition below, one gets conditions (2).

Proposition 5.2. *Define the abelian group G as the quotient of \mathbb{Z}^2 by the row space of the matrix*

$$M = \begin{pmatrix} a & \cdot \\ \cdot & b \\ c & d \end{pmatrix}.$$

Then the following are equivalent:

- (a) G is trivial;
- (b) $\gcd(ab, ad, bc) = 1$;
- (c) $\gcd(a, b) = \gcd(a, c) = \gcd(b, d) = 1$.

Proof.

- (a) \Leftrightarrow (b): This follows by computing the maximal minors of M . (Cf. the argument at the end of the proof of Theorem 4.2.)
- (b) \Rightarrow (c): This follows from the obvious inclusion of $\langle ab, ad, bc \rangle$ in the three subgroups of \mathbb{Z} that are $\langle a, b \rangle$, $\langle a, c \rangle$, $\langle b, d \rangle$.
- (c) \Rightarrow (b): Let $u, v \in \mathbb{Z}$ be such that $au + bv = 1$. Let $p, q, r, s \in \mathbb{Z}$ be such that $pb + qd = u$ and $ra + sc = v$. Then

$$(ab)(p + r) + (ad)q + (bc)s = 1$$

implies (b) as desired. \square

Finally, assume $p := \gcd(a, b, c, \Delta)$ greater than 1. Our group G' remains trivial when one requires the p th powers of its generators to vanish. This corresponds to considering the coefficients of the matrix M from (5.1) modulo p . Since p divides a , b , and c , the first three rows of the matrix obtained vanish. Since p also divides

$\Delta = -\det \begin{pmatrix} u & v & \cdot \\ w & \cdot & x \\ \cdot & y & z \end{pmatrix}$, all maximal minors of our matrix vanish. But for the group to be trivial, these maximal minors have to be coprime.

6. STRUCTURE GROUP VS HOMOLOGY

Before investigating the homology of abelian quandles, let us describe a relation between the structure group G and the second homology group H_2 of any quandle (or even rack) (X, \triangleleft) . To do this, we will reverse the usual order in the definition

of H_2 (restrict to the kernel Z_2 of d_2 , then mod out the image B_2 of d_3): we will instead consider the quotient $Q_2 := C_2/B_2$ before restricting it to $H_2 = Z_2/B_2$.

We will use the classical rack homology decomposition. Let O_i be the orbits of (X, \triangleleft) . By the formula (1.3), the differentials d_k preserve the decomposition

$$(6.1) \quad C_k(X, \triangleleft) = \bigoplus_i \mathbb{Z}O_i \times X^{k-1}.$$

For $L \in \{C, Z, B, Q, H\}$, denote by $L_{k;i}$ the part of L_k corresponding to $\mathbb{Z}O_i \times X^{k-1}$.

Recall also the classical (truncated) topological realisation BX for Q_2 [FRS07]: it consists of X -labelled vertices, X -labelled directed edges $a \xrightarrow{b} a \triangleleft b$ (corresponding to the generator (a, b) of C_2), and squares of the form

$$\begin{array}{ccc} a \triangleleft c & \xrightarrow{b \triangleleft c} & (a \triangleleft b) \triangleleft c \\ c \uparrow & & c \uparrow \\ a & \xrightarrow{b} & a \triangleleft b \end{array}$$

The homology group H_2 of a quandle is the 1st homology group $H_1(BX, \mathbb{Z})$ of this space, since the boundary of the edge $a \xrightarrow{b} a \triangleleft b$ coincides with

$$d_2(a, b) = a \triangleleft b - a,$$

and the boundary of a square as above coincides with

$$d_3(a, b, c) = (a \triangleleft b, c) - (a, c) - (a \triangleleft c, b \triangleleft c) + (a, b).$$

The orbit decomposition (6.1) becomes the connected component decomposition for the CW space BX .

Now, fix an $a \in X$, and take a $g \in G$ written as a word w in the generators g_b . Consider the path in BX starting from the vertex a and consisting of edges labelled by the letters from w ; an edge points to the right or to the left depending on whether the corresponding generator or its inverse is in w . The labels of the remaining vertices are reconstructed from the edge labels in a unique way. The rightmost vertex label will be denoted by $a \cdot g$; it will be shown to be independent of the choice of the representative w of g , and to yield the classical G -action on X .

Here is an example with $w = g_b g_c^{-1} g_a$:

$$a \xrightarrow{b} a \triangleleft b \xleftarrow{c} (a \triangleleft b) \widetilde{\triangleleft} c \xrightarrow{d} ((a \triangleleft b) \widetilde{\triangleleft} c) \triangleleft d.$$

As usual, $-\widetilde{\triangleleft} c$ is the inverse of the right translation $-\triangleleft c$. This path corresponds to (the class of) the element

$$(a, b) - ((a \triangleleft b) \widetilde{\triangleleft} c, c) + ((a \triangleleft b) \widetilde{\triangleleft} c, d) \in Q_2,$$

and we have $a \cdot g_b g_c^{-1} g_a = ((a \triangleleft b) \widetilde{\triangleleft} c) \triangleleft d$.

Proposition 6.1. *Let (X, \triangleleft) be a rack. Fix an $a \in X$ lying in the orbit O_i . The construction above defines a (set-theoretic) map*

$$p_a: G(X, \triangleleft) \rightarrow Q_{2;i}(X, \triangleleft).$$

It restricts to a surjective group morphism

$$p'_a: G_a \rightarrow H_{2;i}(X, \triangleleft),$$

where G_a is the stabiliser subgroup of a in $G(X, \triangleleft)$ for the action \cdot above.

The maps p'_a will help us deduce things about the cohomology of abelian quandles from what we know about their structure groups. We hope that in other situations they might also transport insights about homology to structure groups.

Proof. We need to check that p_a is compatible with the relations $g_b g_b^{-1} = g_b^{-1} g_b = 1$ and $g_b g_c g_{c \triangleleft b}^{-1} g_c^{-1} = 1$ in $G := G(X, \triangleleft)$. By construction, consecutive g_b and g_b^{-1} are sent to the same edge travelled in opposite directions, which can be omitted. The expression $g_b g_c g_{c \triangleleft b}^{-1} g_c^{-1}$ is sent to the boundary of a square, hence can be omitted in Q_2 as well. Thus the map p_a is well defined. In particular, the rightmost vertex label of $p_a(g)$, denoted by $a \cdot g$, is well defined, and yields a transitive right action of G on O_i . This action is determined by the property $a \cdot g_b = a \triangleleft b$ for all $a, b \in X$.

By construction, we have

$$(6.2) \quad \begin{aligned} p_a(gg') &= p_a(g)p_{a \cdot g}(g'), \\ d_2(p_a(g)) &= a \cdot g - a \end{aligned}$$

for all $g, g' \in G$. If g fixes a , these become $p_a(gg') = p_a(g)p_a(g')$ and $d_2(p_a(g)) = 0$, so p_a restricts to a group morphism $G_a \rightarrow H_{2;i}$.

It remains to check that this restriction p'_a is surjective. Elements of $H_{2;i}$ are linear combinations of classes of loops in BX . If a loop representative starts at some $a' \in O_i$, we may conjugate it by a path connecting a to a' , as a and a' lie in the same orbit O_i . This does not change the homology class of the loop. Hence each loop is in the image of p'_a . \square

Definition 6.2. The maps p_a above will be referred to as *path maps*.

By (6.2), path maps are group 1-cocycles.

Remark 6.3. For a and a' from the same orbit, the stabiliser subgroups G_a and $G_{a'}$ are related by a conjugation in G , which intertwines the restricted path maps p'_a and $p'_{a'}$.

7. HOMOLOGY OF ABELIAN QUANDLES

For abelian quandles, path maps relate the torsion of H_2 , which is the interesting part for applications, to the parameter group G' , which we studied above:

Theorem 7.1. *Let (X, \triangleleft) be a finite abelian quandle with r orbits. Then*

$$(7.1) \quad H_2(X, \triangleleft) \cong \mathbb{Z}^{r^2} \bigoplus \bigoplus_{i=1}^r T_i,$$

where the finite groups T_i are all quotients of the parameter group $G'(X, \triangleleft)$.

More precisely, T_i is the image of G' (seen as the commutator subgroup of G) by the path map p_a for any a from the orbit O_i .

Definition 7.2. The groups T_i will be called the *torsion groups* of (X, \triangleleft) .

By Theorem 4.2, the parameter group of a finite quandle with abelian structure group is trivial. Hence all its quotients T_i are trivial as well, and we obtain

Corollary 7.3. *Let (X, \triangleleft) be a finite r -orbit quandle with abelian structure group. Then its 2nd homology group is torsion-free: $H_2(X, \triangleleft) \cong \mathbb{Z}^{r^2}$.*

Proof of Theorem 7.1. We will show the decomposition $H_{2;i} \cong \mathbb{Z}^r \oplus T_i$ for all $1 \leq i \leq r$, which implies (7.1).

Let O_1, \dots, O_r be the orbits of (X, \triangleleft) . Fix an $a \in O_i$, and recall the restricted path map $p'_a: G_a \rightarrow H_{2;i}$.

Since our quandle is abelian, commutators in G act trivially on any element of X , so the commutator subgroup G' is a subgroup of the stabiliser subgroup G_a . The subgroup G' is normal (even central) in G , hence in G_a . So, p'_a induces a surjective group morphism $\bar{p}'_a: G_a/G' \rightarrow H_{2;i}/p'_a(G')$. The group $T_i := p'_a(G')$ is an isomorphic image, hence a quotient, of G' . It is finite since G' is so. By Remark 6.3, it is independent of the choice of the representative a of the orbit O_i .

Further, the inclusion $G_a \hookrightarrow G$ induces an inclusion $G_a/G' \hookrightarrow G/G'$. One can assemble everything in a commutative diagram, where all arrows but p_a are group morphisms, and the three squares commute:

$$\begin{array}{ccc}
 G & \xrightarrow{p_a} & Q_{2;i} \\
 \downarrow & \searrow & \swarrow \\
 G/G' & & G_a \xrightarrow{p'_a} H_{2;i} \\
 & \swarrow & \downarrow \\
 & G_a/G' \xrightarrow{\bar{p}'_a} H_{2;i}/T_i
 \end{array}$$

Here all the maps \rightarrow and \hookrightarrow are the obvious quotients and inclusions. In what follows they will all be abusively denoted by π and ι respectively.

We will now prove that \bar{p}'_a is injective, hence a group isomorphism. This will give the short exact sequence

$$0 \rightarrow T_i \rightarrow H_{2;i} \rightarrow G_a/G' \rightarrow 0.$$

The group G_a/G' is a subgroup of $G/G' = G_{\text{ab}} \cong \mathbb{Z}^r$ (cf. the proof of Theorem 3.2). As a result, $G_a/G' \cong \mathbb{Z}^{r'}$ for some $r' \leq r$. Our short exact sequence becomes

$$0 \rightarrow T_i \rightarrow H_{2;i} \rightarrow \mathbb{Z}^{r'} \rightarrow 0.$$

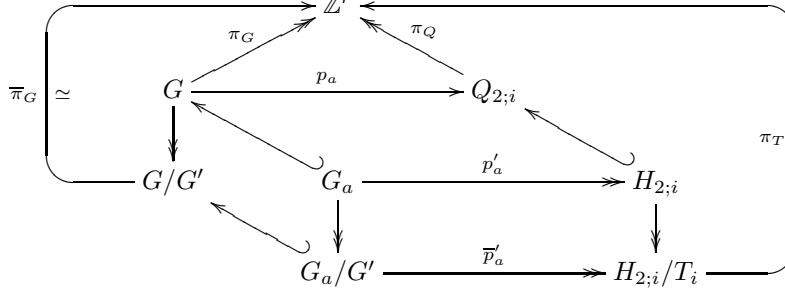
Since $\mathbb{Z}^{r'}$ is free abelian, the sequence splits: $H_{2;i} \cong \mathbb{Z}^{r'} \oplus T_i$. The group T_i being finite, we have $\text{rk}(H_{2;i}) = r'$. From [EG03] (or from a direct inspection of the orbit $O_i = G(M^{(i)})$), we get $\text{rk}(H_{2;i}) = r$, hence $r = r'$, and $H_{2;i} \cong \mathbb{Z}^r \oplus T_i$ as desired.

To prove the injectivity of \bar{p}'_a , we need the group isomorphism $\bar{\pi}_G: G/G' = G_{\text{ab}} \xrightarrow{\sim} \mathbb{Z}^r = \bigoplus_{j=1}^r \mathbb{Z}e_j$ induced by the map $\pi_G: G \rightarrow \mathbb{Z}^r$ sending g_b to e_j for all b from the orbit O_j (cf. the proof of Theorem 3.2). Similarly, the assignment $(a', b) \mapsto e_j$ for $b \in O_j$ induces a map $\pi_Q: Q_{2;i} \rightarrow \mathbb{Z}^r$; indeed, π_Q sends boundaries $d_3(a', b, c) = (a' \triangleleft b, c) - (a', c) - (a' \triangleleft c, b \triangleleft c) + (a', b)$ to 0. Recalling the definition of the path map p_a , one sees that it intertwines π_G and π_Q : $\pi_G = \pi_Q p_a$. Finally, the group $T_i = p'_a(G')$ is generated by (the classes of) the loops of the form

$$\begin{array}{ccc}
 a \triangleleft c & \xrightarrow{b} & (a \triangleleft b) \triangleleft c \\
 \uparrow c & & \uparrow c \\
 a & \xrightarrow{b} & a \triangleleft b
 \end{array}$$

The map π_Q sends them to 0, and thus induces a map $\pi_T: H_{2;i}/T_i \rightarrow \mathbb{Z}^r$. One can now extend the above commutative diagram by two triangles and one square, all

of which commute:



From this diagram, one reads

$$\pi_T \bar{p}'_a \pi = \pi_T \pi p'_a = \pi_Q \iota p'_a = \pi_Q p_a \iota = \pi_G \iota = \bar{\pi}_G \pi \iota = \bar{\pi}_G \iota \pi.$$

Since π is surjective, this implies $\pi_T \bar{p}'_a = \bar{\pi}_G \iota$. Both $\bar{\pi}_G$ and ι being injective, so is \bar{p}'_a , as desired. \square

Let us now see how the torsion groups T_i look like in particular cases.

Proposition 7.4. *The 2nd homology group of a 2-orbit abelian quandle $U_{m,n}$ is*

$$H_2(U_{m,n}) \cong \mathbb{Z}^4 \oplus (G'(U_{m,n}))^2 \cong \mathbb{Z}^4 \oplus \mathbb{Z}_{\gcd(m,n)}^2.$$

In Section 3 we have seen that $G'(U_{m,n}) \cong \mathbb{Z}_{\gcd(m,n)}$. So, in this case both torsion groups T_1 and T_2 coincide with the whole parameter group G' .

Proof. Put $d = \gcd(m, n)$, $O_1 = \{x_0, x_1, \dots, x_{m-1}\}$, $O_2 = \{y_0, y_1, \dots, y_{n-1}\}$. We will construct a map $\varphi: Q_{2;1} \rightarrow \mathbb{Z}_d$ sending (the class of) $(x_0, x_1) - (x_0, x_0)$ to 1. Here we used the description (1.1) of $U_{m,n}$. This shows that the order of $(x_0, x_1) - (x_0, x_0)$ is at least d . In the proof of Theorem 2.3 we saw that $g_{x_0}^{-1} g_{x_0 \triangleleft y_0} = g_{x_0}^{-1} g_{x_1}$ generates the parameter group $G' \cong \mathbb{Z}_d$, therefore $\bar{p}'_{x_0}(g_{x_0}^{-1} g_{x_1}) = -(x_0, x_0) + (x_0, x_1)$ generates T_1 . Hence $T_1 \cong \mathbb{Z}_d$. Similarly, $T_2 \cong \mathbb{Z}_d$. Theorem 7.1 allows us to conclude.

To describe the map φ , we need the map

$$\begin{aligned} \bar{\bullet}: U_{m,n} &\rightarrow \mathbb{Z}_d, \\ x_i &\mapsto i \pmod{d}, \\ y_k &\mapsto -k \pmod{d}. \end{aligned}$$

We have

$$\overline{a \triangleleft b} = \begin{cases} \bar{a} + 1 & \text{if } a \in O_1, b \in O_2, \\ \bar{a} - 1 & \text{if } a \in O_2, b \in O_1, \\ \bar{a} & \text{otherwise.} \end{cases}$$

Further, extend the assignment

$$(a, b) \mapsto \bar{b} - \bar{a}$$

to a map $\psi: C_{2,1} \rightarrow \mathbb{Z}_d$ by linearisation. Let us check that it induces a map $\varphi: Q_{2,1} \rightarrow \mathbb{Z}_d$. We have

$$\begin{aligned}\psi(d_3(a, b, c)) &= \psi((a \triangleleft b, c) - (a, c) - (a \triangleleft c, b \triangleleft c) + (a, b)) \\ &= \bar{c} - \overline{a \triangleleft b} - \bar{c} + \bar{a} - \overline{b \triangleleft c} + \overline{a \triangleleft c} + \bar{b} - \bar{a} \\ &= -\overline{a \triangleleft b} - \overline{b \triangleleft c} + \overline{a \triangleleft c} + \bar{b}.\end{aligned}$$

Testing all possibilities for the orbits of a, b and c , one sees that $\psi(d_3(a, b, c))$ always vanishes, so ψ indeed survives in the quotient $Q_{2,1}$. Further, as announced,

$$\psi((x_0, x_1) - (x_0, x_0)) = (1 - 0) - (0 - 0) = 1. \quad \square$$

To construct examples where a T_i is smaller than the whole G' , we need

Proposition 7.5. *Given a finite abelian quandle, the order of any element in the torsion group T_i divides the square of the size of the orbit O_i .*

This directly implies

Corollary 7.6. *Given a finite abelian quandle with a 1-element orbit O_i , its torsion group T_i is trivial.*

Example 7.7. Extend the quandle $U_{m,n}$ by adding an element z , and putting

$$(7.2) \quad a \triangleleft b = a \quad \text{whenever } a = z \text{ or } b = z.$$

One gets a 3-orbit abelian quandle, denoted by $U_{m,n}^*$. Its parameter matrix is

$$\begin{pmatrix} m & \cdot & \cdot \\ \cdot & 1 & 1 \\ -n & \cdot & \cdot \\ \cdot & -1 & \cdot \\ \cdot & \cdot & -1 \end{pmatrix},$$

so its parameter group is $G'(U_{m,n}^*) \cong \mathbb{Z}_{\gcd(m,n)}$. By Corollary 7.6, its torsion group T_3 is trivial. However, the remaining torsion groups are $T_1 \cong T_2 \cong \mathbb{Z}_{\gcd(m,n)}$. To see this, one can extend the map ψ from the proof of Proposition 7.4 from $U_{m,n}$ to $U_{m,n}^*$ by putting $\psi(a, b) = 0$ whenever $a = z$ or $b = z$. Summarising, we have

$$H_2(U_{m,n}^*) \cong \mathbb{Z}^9 \oplus (G'(U_{m,n}^*))^2 \cong \mathbb{Z}^9 \oplus \mathbb{Z}_{\gcd(m,n)}^2.$$

In particular, $U_{m,n}$ and $U_{m,n}^*$ have the same torsion in H_2 .

Proof of Proposition 7.5. Fix an $a' \in O_i$, and put $n := \#O_i$. As seen in the proof of Theorem 2.3, the elements $g_b^{-1}g_{b \triangleleft c}$ generate G' , therefore the elements $\bar{p}'_{a'}(g_b^{-1}g_{b \triangleleft c}) = -(a, b) + (a, b \triangleleft c)$, where $a = a' \triangleleft b$, generate T_i . Thus it suffices to show that $n^2(-(a, b) + (a, b \triangleleft c)) = 0$ in $Q_{2,i}$ for all $a \in O_i, b, c \in X$. Again by the proof of Theorem 2.3, the element $g_b^{-1}g_{b \triangleleft c}$ of G' depends only on the orbits of b and c . This yields

$$(g_b^{-1}g_{b \triangleleft c})^n = (g_b^{-1}g_{b \triangleleft c})(g_{b \triangleleft c}^{-1}g_{(b \triangleleft c) \triangleleft c}) \cdots (g_{b \triangleleft c}^{-1}g_{b \triangleleft c}) = g_b^{-1}g_{b \triangleleft c^n},$$

where $b \triangleleft c^k$ stands for $(\cdots((b \triangleleft c) \triangleleft c) \cdots) \triangleleft c$, with k occurrences of c . Since $g_b^{-1}g_{b \triangleleft c}$ is central in G , so is $g_b^{-1}g_{b \triangleleft c^n}$, and we get

$$(g_b^{-1}g_{b \triangleleft c})^{n^2} = (g_b^{-1}g_{b \triangleleft c^n})^n = g_b^{-n}g_{b \triangleleft c^n}^n.$$

Further, the defining relations of the structure group yield

$$g_{b \triangleleft c^n} = g_c^{-1}g_{b \triangleleft c^{n-1}}g_c = \cdots = g_c^{-n}g_b g_c^n,$$

so $(g_b^{-1}g_{b\triangleleft c})^{n^2} = g_b^{-n}g_c^{-n}g_b^n g_c^n$. As shown in the proof of Theorem 2.3, the right translation $- \triangleleft b$ divides O_i into cycles of equal length, which has to divide $n = \#O_i$. Hence g_b^n stabilises $a \in O_i$: $g_b^n \in G_a$. The same holds for g_c^n . Then

$$\begin{aligned} n^2(-(a, b) + (a, b \triangleleft c)) &= \overline{p}'_{a'}((g_b^{-1}g_{b\triangleleft c})^{n^2}) = \overline{p}'_{a'}(g_b^{-n}g_c^{-n}g_b^n g_c^n) \\ &= -\overline{p}'_{a'}(g_b^n) - \overline{p}'_{a'}(g_c^n) + \overline{p}'_{a'}(g_b^n) + \overline{p}'_{a'}(g_c^n) = 0, \end{aligned}$$

as desired. \square

Remark 7.8. Along the same lines, one shows that $a \triangleleft b^n = a \triangleleft c^m = a$ for some (equivalently, any) $a \in O_i$, $b \in O_j$, $c \in O_k$ implies that the order of the generator $\overline{p}'_a(x_{k-j}^{(j)})$ in T_i divides mn . The optimal choice for m and n is the order of $x_{j-i}^{(i)}$ and $x_{k-i}^{(i)}$ in $G(M^{(i)})$ respectively.

We finish with explicit computations for one more family of abelian quandles. In particular we obtain two 3-orbit quandles $(U_{2,2}^*$ and $U_{2,2}^*$) having the same parameter group G' but different homology groups H_2 .

Example 7.9. Extend the quandle $U_{m,n}$ by two elements z_0 and z_1 , with

$$\begin{aligned} a \triangleleft z_s &= a \quad \text{for all } a, \\ z_s \triangleleft x_i &= z_s \triangleleft y_k = z_{s+1}. \end{aligned}$$

Here and below $s \in \{0, 1\}$, and the index $s + 1$ is taken modulo 2. One gets a 3-orbit abelian quandle, denoted by $U_{m,n}^*$. Its parameter matrix is

$$\begin{pmatrix} m & \cdot & \cdot \\ \cdot & 1 & 1 \\ -n & \cdot & \cdot \\ \cdot & -2 & \cdot \\ \cdot & -1 & -1 \end{pmatrix},$$

so its parameter group is $G'(U_{m,n}^*) \cong \mathbb{Z}_{\gcd(m,n)}$, which is the same as $G'(U_{m,n}^*)$. We will prove that its torsion groups are $T_1 \cong T_2 \cong \mathbb{Z}_{\gcd(m,n)}$, and $T_3 \cong \mathbb{Z}_{\gcd(m,n,2)}$. This yields

$$H_2(U_{m,n}^*) \cong \mathbb{Z}^9 \oplus \mathbb{Z}_{\gcd(m,n)}^2 \oplus \mathbb{Z}_{\gcd(m,n,2)}.$$

For T_1 and T_2 , the proof we gave for $U_{m,n}^*$ repeats verbatim. For T_3 , we need to compute the order t of $\overline{p}'_{z_0}(g_{x_0}^{-1}g_{x_0\triangleleft y_0})$ in H_2 . We know that t divides the order of $g_{x_0}^{-1}g_{x_0\triangleleft y_0} = g_{x_0}^{-1}g_{x_1}$ in G' , which is $\gcd(m, n)$. On the other hand, in G we have

$$g_y g_x g_y g_y = g_y g_y g(y \triangleleft y) \triangleleft y g(x \triangleleft y) \triangleleft y = g_y g_y g_y g(x \triangleleft y) \triangleleft y,$$

where $x := x_0$ and $y := y_0$. Since $g_y g_x$, $g_y g_y$ and $g_y g(x \triangleleft y) \triangleleft y$ stabilise z_0 , this yields

$$\overline{p}'_{z_0}(g_y g_x) + \overline{p}'_{z_0}(g_y g_y) = \overline{p}'_{z_0}(g_y g_y) + \overline{p}'_{z_0}(g_y g(x \triangleleft y) \triangleleft y),$$

hence $\overline{p}'_{z_0}(g_y g_x) = \overline{p}'_{z_0}(g_y g(x \triangleleft y) \triangleleft y)$, and

$$\begin{aligned} 0 &= \overline{p}'_{z_0}((g_y g_x)^{-1}(g_y g(x \triangleleft y) \triangleleft y)) = \overline{p}'_{z_0}(g_x^{-1}g_{(x \triangleleft y) \triangleleft y}) \\ &= \overline{p}'_{z_0}((g_x^{-1}g_{x \triangleleft y})(g_{x \triangleleft y}^{-1}g_{(x \triangleleft y) \triangleleft y})) = \overline{p}'_{z_0}(g_x^{-1}g_{x \triangleleft y}) + \overline{p}'_{z_0}(g_{x \triangleleft y}^{-1}g_{(x \triangleleft y) \triangleleft y}) \\ &= 2\overline{p}'_{z_0}(g_x^{-1}g_{x \triangleleft y}). \end{aligned}$$

So, t divides 2, and hence $\gcd(m, n, 2)$. It remains to show that, if m and n are both even, then $t = 2$. For this we will construct a map $\theta: Q_{2,3} \rightarrow \mathbb{Z}_2$ not vanishing

on (the class of) $\overline{p}'_{z_0}(g_x^{-1}g_{x \triangleleft y}) = (z_1, x_1) - (z_1, x_0)$. Put

$$\begin{aligned}\overline{\bullet}: U_{m,n}^* &\rightarrow \mathbb{Z}_2, \\ x_i &\mapsto i \pmod{2}, \\ y_k &\mapsto k \pmod{2}, \\ z_s &\mapsto 0.\end{aligned}$$

For $a \in O_i$ and $b \in O_j$, we have

$$\overline{a \triangleleft b} = \begin{cases} \overline{a} + 1 & \text{if } \{i, j\} = \{1, 2\}, \\ \overline{a} & \text{otherwise.} \end{cases}$$

Further, put

$$\varepsilon(a, b) = \begin{cases} 1 & \text{if } a = z_0, b \in O_1, \\ 0 & \text{otherwise,} \end{cases}$$

and extend the assignment $(a, b) \mapsto \varepsilon(a, b) + \overline{b}$ to a map $\psi: C_{2,3} \rightarrow \mathbb{Z}_2$ by linearisation. Let us check that it induces a map $\theta: Q_{2,3} \rightarrow \mathbb{Z}_2$. We have

$$\begin{aligned}\psi(d_3(a, b, c)) &= \psi((a \triangleleft b, c) - (a, c) - (a \triangleleft c, b \triangleleft c) + (a, b)) \\ &= \overline{a \triangleleft b} + \overline{b} + \varepsilon(a \triangleleft b, c) + \varepsilon(a, c) + \varepsilon(a \triangleleft c, b) + \varepsilon(a, b).\end{aligned}$$

The part $\overline{a \triangleleft b} + \overline{b}$ vanishes unless $\{i, j\} = \{1, 2\}$; the part $\varepsilon(a \triangleleft b, c) + \varepsilon(a, c)$ vanishes unless $c \in O_1$ and $b \in O_1 \cup O_2$; similarly, $\varepsilon(a \triangleleft c, b) + \varepsilon(a, b)$ vanishes unless $b \in O_1$ and $c \in O_1 \cup O_2$. The sum of these three parts is zero in any case. Further, as announced,

$$\theta((z_1, x_1) - (z_1, x_0)) = 1 - 0 = 1.$$

REFERENCES

- [AG03] Nicolás Andruskiewitsch and Matías Graña. From racks to pointed Hopf algebras. *Adv. Math.*, 178(2):177–243, 2003.
- [BCW18] Marco Bonatto, Alissa S. Crans, and Glen T. Whitney. On the Structure of Hom Quandles. *arXiv e-prints*, page arXiv:1808.01738, Aug 2018.
- [BN19] Valeriy Bardakov and Timur Nasybullov. On embeddings of quandles into groups. *arXiv e-prints*, page arXiv:1902.02154, Feb 2019.
- [CJK⁺03] J. Scott Carter, Daniel Jelsovsky, Seiichi Kamada, Laurel Langford, and Masahico Saito. Quandle cohomology and state-sum invariants of knotted curves and surfaces. *Trans. Amer. Math. Soc.*, 355:3947–3989, 2003.
- [Cla10] F. J. B. J. Clauwens. The adjoint group of an Alexander quandle. *arXiv e-prints*, page arXiv:1011.1587, Nov 2010.
- [EG03] P. Etingof and M. Graña. On rack cohomology. *J. Pure Appl. Algebra*, 177(1):49–59, 2003.
- [ESS99] Pavel Etingof, Travis Schedler, and Alexandre Soloviev. Set-theoretical solutions to the quantum Yang–Baxter equation. *Duke Math. J.*, 100(2):169–209, 1999.
- [FRS95] Roger Fenn, Colin Rourke, and Brian Sanderson. Trunks and classifying spaces. *Appl. Categ. Structures*, 3(4):321–356, 1995.
- [FRS07] Roger Fenn, Colin Rourke, and Brian Sanderson. The rack space. *Trans. Amer. Math. Soc.*, 359(2):701–740 (electronic), 2007.
- [GIV17] Agustín García Iglesias and Leandro Vendramin. An explicit description of the second cohomology group of a quandle. *Math. Z.*, 286(3-4):1041–1063, 2017.
- [GIVdB98] Tatiana Gateva-Ivanova and Michel Van den Bergh. Semigroups of I -type. *J. Algebra*, 206(1):97–112, 1998.
- [Joy82] David Joyce. A classifying invariant of knots, the knot quandle. *J. Pure Appl. Algebra*, 23(1):37–65, 1982.

- [JPSZD15] Přemysl Jedlička, Agata Pilitowska, David Stanovský, and Anna Zamojska-Dzienio. The structure of medial quandles. *J. Algebra*, 443:300–334, 2015.
- [JPZD18] Přemysl Jedlička, Agata Pilitowska, and Anna Zamojska-Dzienio. Subdirectly irreducible medial quandles. *Comm. Algebra*, 46(11):4803–4829, 2018.
- [LN03] R. A. Litherland and Sam Nelson. The Betti numbers of some finite racks. *J. Pure Appl. Algebra*, 178(2):187–202, 2003.
- [LV17] Victoria Lebed and Leandro Vendramin. Homology of left non-degenerate set-theoretic solutions to the Yang-Baxter equation. *Adv. Math.*, 304:1219–1261, 2017.
- [LV19] Victoria Lebed and Leandro Vendramin. On Structure Groups of Set-Theoretic Solutions to the Yang–Baxter Equation. *Proc. Edinb. Math. Soc. (2)*, 62(3):683–717, 2019.
- [LYZ00] Jiang-Hua Lu, Min Yan, and Yong-Chang Zhu. On the set-theoretical Yang–Baxter equation. *Duke Math. J.*, 104(1):1–18, 2000.
- [Mat82] S. V. Matveev. Distributive groupoids in knot theory. *Mat. Sb. (N.S.)*, 119(161)(1):78–88, 160, 1982.
- [NP11] Maciej Niebrzydowski and Józef H. Przytycki. The second quandle homology of the Takasaki quandle of an odd abelian group is an exterior square of the group. *J. Knot Theory Ramifications*, 20(1):171–177, 2011.
- [PIM⁺18] Rhea Palak Bakshi, Dionne Ibarra, Sujoy Mukherjee, Takefumi Nosaka, and Józef H. Przytycki. Schur Multipliers and Second Quandle Homology. *arXiv e-prints*, page arXiv:1812.04704, Dec 2018.
- [Pł85] J. Płonka. On k -cyclic groupoids. *Math. Japon.*, 30(3):371–382, 1985.
- [RR89] A. Romanowska and B. Roszkowska. Representations of n -cyclic groupoids. *Algebra Universalis*, 26(1):7–15, 1989.
- [Sol00] Alexander Soloviev. Non-unitary set-theoretical solutions to the quantum Yang–Baxter equation. *Math. Res. Lett.*, 7(5-6):577–596, 2000.

LMNO, UNIVERSITÉ DE CAEN–NORMANDIE, BP 5186, 14032 CAEN CEDEX, FRANCE
E-mail address: lebed@unicaen.fr

LMNO, UNIVERSITÉ DE CAEN–NORMANDIE, BP 5186, 14032 CAEN CEDEX, FRANCE
E-mail address: arnaud.mortier@unicaen.fr