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**CONNECTED QUANDLES ASSOCIATED
WITH POINTED ABELIAN GROUPS**

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A quandle is a self-distributive algebraic structure that appears in quasi-group and knot theories. For each abelian group A and $c \in A$, we define a quandle $G(A, c)$ on $\mathbb{Z}_3 \times A$. These quandles are generalizations of a class of nonmedial Latin quandles defined by V. M. Galkin, so we call them *Galkin quandles*. Each $G(A, c)$ is connected but not Latin unless A has odd order. $G(A, c)$ is nonmedial unless $3A = 0$. We classify their isomorphism classes in terms of pointed abelian groups and study their various properties. A family of symmetric connected quandles is constructed from Galkin quandles, and some aspects of knot colorings by Galkin quandles are also discussed.

1. Introduction

Sets with certain self-distributive operations called *quandles* have been studied since the 1940s in various areas. They have been studied, for example, as an algebraic system for symmetries [Takasaki 1943], as quasigroups [Galkin 1988], and in relation to modules [Nelson 2003]. The *fundamental quandle* was defined in a manner similar to the fundamental group [Joyce 1982; Matveev 1982], which made quandles an important tool in knot theory. Algebraic homology theories for quandles were defined [Carter et al. 2003b; Fenn et al. 1995] and developed and investigated ([Litherland and Nelson 2003; Mochizuki 2011; Niebrzydowski and Przytycki 2009; 2011; Nosaka 2011], for example), and extensions of quandles by cocycles have been studied [Andruskiewitsch and Graña 2003; Carter et al. 2003a; Eisermann 2007b] and applied to various properties of knots and knotted surfaces (see [Carter et al. 2004] and references therein).

Before algebraic theories of extensions were developed, Galkin [1988] defined a family of quandles that are extensions of the 3-element connected quandle R_3 , and we call them *Galkin quandles*. Even though the definition of Galkin quandles is a

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special case of a cocycle extension described in [Andruskiewitsch and Graña 2003], they have curious properties such as the explicit and simple defining formula, close connections to dihedral quandles, and the fact that they appear in the list of small connected quandles.

In this paper, we generalize Galkin's definition and define a family of quandles that are extensions of R_3 , characterize their isomorphism classes, and study their properties. The definition is given in Section 3 after a brief review of necessary materials in Section 2. Isomorphism classes are characterized by pointed abelian groups in Section 4. Various algebraic properties of Galkin quandles are investigated in Section 5, and their knot colorings are studied in Section 6.

2. Preliminaries

In this section we briefly review some definitions and examples of quandles. More details can be found, for example, in [Andruskiewitsch and Graña 2003; Carter et al. 2004; Fenn et al. 1995].

A *quandle* X is a set with a binary operation $(a, b) \mapsto a * b$ satisfying the following conditions.

- | | | |
|-----|-----------------------------|---|
| (1) | (Idempotency) | For any $a \in X$, $a * a = a$. |
| (2) | (Invertibility) | For any $b, c \in X$, there is a unique $a \in X$ such that $a * b = c$. |
| (3) | (Right self-distributivity) | For any $a, b, c \in X$, we have $(a * b) * c = (a * c) * (b * c)$. |

A *quandle homomorphism* between two quandles X, Y is a map $f : X \rightarrow Y$ such that $f(x *_X y) = f(x) *_Y f(y)$, where $*_X$ and $*_Y$ denote the quandle operations of X and Y , respectively. A *quandle isomorphism* is a bijective quandle homomorphism, and two quandles are *isomorphic* if there is a quandle isomorphism between them.

Typical examples of quandles include the following.

- Any nonempty set X with the operation $x * y = x$ for any $x, y \in X$ is a quandle called the *trivial* quandle.
- A group $X = G$ with the operation of n -fold conjugation, $a * b = b^{-n} a b^n$, is a quandle.
- Let n be a positive integer. For $a, b \in \mathbb{Z}_n$ (integers modulo n), define

$$a * b \equiv 2b - a \pmod{n}.$$

Then $*$ defines a quandle structure called the *dihedral quandle* R_n . This set can be identified with the set of reflections of a regular n -gon with conjugation as the quandle operation.

- Any $\mathbb{Z}[T, T^{-1}]$ -module M is a quandle with $a * b = Ta + (1 - T)b$ for $a, b \in M$. This is called an *Alexander quandle*. An Alexander quandle is also regarded as a pair (M, T) , where M is an abelian group and $T \in \text{Aut}(M)$.

Let X be a quandle. The *right translation* $\mathcal{R}_a : X \rightarrow X$ by $a \in X$ is defined by $\mathcal{R}_a(x) = x * a$ for $x \in X$. Similarly, the *left translation* \mathcal{L}_a is defined by $\mathcal{L}_a(x) = a * x$. Then \mathcal{R}_a is a permutation of X by Axiom (2). The subgroup of $\text{Sym}(X)$ generated by the permutations $\mathcal{R}_a, a \in X$, is called the *inner automorphism group* of X and is denoted by $\text{Inn}(X)$. We list some definitions of commonly known properties of quandles below.

- A quandle is *connected* if $\text{Inn}(X)$ acts transitively on X .
- A *Latin quandle* is a quandle such that for each $a \in X$, the left translation \mathcal{L}_a is a bijection. That is, the multiplication table of the quandle is a Latin square.
- A quandle is *faithful* if the mapping $a \mapsto \mathcal{R}_a$ is an injection from X to $\text{Inn}(X)$.
- A quandle X is *involutory*, or a *kei*, if the right translations are involutions: $\mathcal{R}_a^2 = \text{id}$ for all $a \in X$.
- The operation $\bar{*}$ on X defined by $a \bar{*} b = \mathcal{R}_b^{-1}(a)$ is a quandle operation, and $(X, \bar{*})$ is called the *dual* quandle of $(X, *)$. If $(X, \bar{*})$ is isomorphic to $(X, *)$, then $(X, *)$ is called *self-dual*.
- A quandle X is *medial* if $(a * b) * (c * d) = (a * c) * (b * d)$ for all $a, b, c, d \in X$. It is also called *abelian*. It is known and easily seen that every Alexander quandle is medial.

A *coloring* of an oriented knot diagram by a quandle X is a map $\mathcal{C} : \mathcal{A} \rightarrow X$ from the set of arcs \mathcal{A} of the diagram to X such that the image of the map satisfies the relation depicted in Figure 1 at each crossing. More details can be found in [Carter et al. 2004; Eisermann 2007a], for example. A coloring that assigns the same element of X for all the arcs is called trivial, and otherwise nontrivial. The number of colorings of a knot diagram by a finite quandle is known to be independent of the choice of a diagram, and hence is a knot invariant. A coloring by a dihedral quandle R_n for a positive integer $n > 1$ is called an n -coloring. If a knot is nontrivially colored by a dihedral quandle R_n for a positive integer $n > 1$, then it is called *n-colorable*. In Figure 2, a nontrivial 3-coloring of the trefoil knot (3_1 in a common notation in a knot table [Cha and Livingston 2011]) is indicated. This is presented

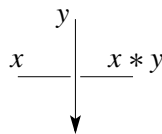


Figure 1. A coloring rule at a crossing.

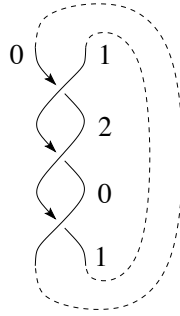


Figure 2. Trefoil as the closure of σ_1^3 .

in a closed braid form. Each crossing corresponds to a standard generator σ_1 of the 2-strand braid group, and σ_1^3 represents three crossings together as in the figure. The dotted line indicates the closure; see [Rolfsen 1976] for more details of braids.

The fundamental quandle is defined in a manner similar to the fundamental group [Joyce 1982; Matveev 1982]. A *presentation* of a quandle is defined in a manner similar to groups as well, and a presentation of the fundamental quandle is obtained from a knot diagram (see, for example, [Fenn and Rourke 1992]), by assigning generators to arcs of a knot diagram, and relations corresponding to crossings. The set of colorings of a knot diagram K by a quandle X is then in one-to-one correspondence with the set of quandle homomorphisms from the fundamental quandle of K to X .

3. Definition and notation for Galkin quandles

Let A be an abelian group, also regarded naturally as a \mathbb{Z} -module. Let $\mu : \mathbb{Z}_3 \rightarrow \mathbb{Z}$, $\tau : \mathbb{Z}_3 \rightarrow A$ be functions. These functions μ and τ need not be homomorphisms. Define a binary operation on $\mathbb{Z}_3 \times A$ by

$$(x, a) * (y, b) = (2y - x, -a + \mu(x - y)b + \tau(x - y)), \quad x, y \in \mathbb{Z}_3, \quad a, b \in A.$$

Proposition 3.1. *For any abelian group A , the operation $*$ defines a quandle structure on $\mathbb{Z}_3 \times A$ if $\mu(0) = 2$, $\mu(1) = \mu(2) = -1$, and $\tau(0) = 0$.*

Galkin [1988, p. 950] gave this definition for $A = \mathbb{Z}_p$. The proposition generalizes his result to any abelian group A . For the proof, we examine the axioms.

Lemma 3.2. (A) *The operation is idempotent — that is, it satisfies Axiom (1) — if and only if $(\mu(0) - 2)a = 0$ for any $a \in A$, and $\tau(0) = 0$.*

(B) *The operation as a right action is invertible — that is, it satisfies Axiom (2).*

Proof. Direct calculations. □

Lemma 3.3. *The operation $*$ on $\mathbb{Z}_3 \times A$ is right self-distributive — that is, it satisfies Axiom (3) — if and only if μ, τ satisfy the following conditions for any $X, Y \in \mathbb{Z}_3$ and $b, c \in A$:*

$$(4) \quad \mu(-X)b = \mu(X)b,$$

$$(5) \quad (\mu(X + Y) + \mu(X - Y))c = (\mu(X)\mu(Y))c,$$

$$(6) \quad \tau(X + Y) + \tau(Y - X) = \tau(X) + \tau(-X) + \mu(X)\tau(Y).$$

Proof. Right self-distributivity, that is,

$$((x, a) * (y, b)) * (z, c) = ((x, a) * (z, c)) * ((y, b) * (z, c))$$

for $x, y, z \in \mathbb{Z}_3$ and $a, b, c \in A$, is satisfied if and only if

$$\begin{aligned} \mu(x - y)b &= \mu(y - x)b, \\ \mu(2y - x - z)c &= (-\mu(x - z) + \mu(y - x)\mu(y - z))c, \\ -\tau(x - y) + \tau(2y - x - z) &= -\tau(x - z) + \mu(y - x)\tau(y - z) + \tau(y - x). \end{aligned}$$

This is seen by equating the coefficients of b and c and the constant term. For the equivalence of the first equation with (4), set $X = x - y$. For the equivalence of the second with (5), set $X = y - x$ and $Y = z - y$. For the equivalence of the last with (6), set $X = y - x$ and $Y = y - z$. \square

Proof of Proposition 3.1. Assume the conditions stated. By Lemma 3.2, Axioms (1) and (2) are satisfied under the specifications $\mu(0) = 2, \mu(1) = \mu(2) = -1$, and $\tau(0) = 0$.

If $X = 0$ or $Y = 0$, then (5) (together with (4)) becomes a tautology. If $X - Y = 0$ or $X + Y = 0$, then (5) reduces to $\mu(2X) + 2 = \mu(X)^2$, which is satisfied by the above specifications. For R_3 , if $X + Y \neq 0$ and $X - Y \neq 0$, then either $X = 0$ or $Y = 0$. Hence (5) is satisfied. For (6), it is checked similarly, for the two cases $[X = 0 \text{ or } Y = 0]$ and $[X - Y = 0 \text{ or } X + Y = 0]$. \square

Definition 3.4. Let A be an abelian group. The quandle defined by $*$ on $\mathbb{Z}_3 \times A$ by Proposition 3.1,

$$(x, a) * (y, b) = (2y - x, -a + \mu(x - y)b + \tau(x - y)), \quad x, y \in \mathbb{Z}_3, \quad a, b \in A,$$

with $\mu(0) = 2, \mu(1) = \mu(2) = -1$, and $\tau(0) = 0$, is called the *Galkin quandle* and denoted by $G(A, \tau)$.

Since τ is specified by the values $\tau(1) = c_1$ and $\tau(2) = c_2$ where $c_1, c_2 \in A$, we also denote it by $G(A, c_1, c_2)$.

Example 3.5. The Galkin quandle $G(\mathbb{Z}_2, 0, 1)$ is $\mathbb{Z}_3 \times \mathbb{Z}_2$ as a set with the quandle operation defined as above with $\mu(0) = 2, \mu(1) = \mu(2) = -1, \tau(0) = \tau(1) = 0$, and

$\tau(2) = 1$. Thus, $(0, 1) * (1, 0) = (2, -1 + \mu(2)0 + \tau(2)) = (2, 0)$ and $(2, 0) * (1, 1) = (0, 0 + \mu(1)1 + \tau(1)) = (0, 1)$, for example.

Lemma 3.6. *For any abelian group A and $c_1, c_2 \in A$, the quandles $G(A, c_1, c_2)$ and $G(A, 0, c_2 - c_1)$ are isomorphic.*

Proof. Let $c = c_2 - c_1$. Define $\eta : G(A, c_1, c_2) \rightarrow G(A, 0, c)$, as a map on $\mathbb{Z}_3 \times A$, by $\eta(x, a) = (x, a + \beta(x))$ where $\beta(0) = \beta(1) = 0$ and $\beta(2) = -c_1$. This η is a bijection, and we show that it is a quandle homomorphism. We compute $\eta((x, a) * (y, b))$ and $\eta(x, a) * \eta(y, b)$ for $x, y \in \mathbb{Z}_3$ and $a, b \in A$.

If $x = y$, then $\mu(x - y) = 2$ and $\tau(x - y) = 0$ for both $G(A, c_1, c_2)$ and $G(A, 0, c)$, so that

$$\begin{aligned} \eta((x, a) * (x, b)) &= \eta(x, 2b - a) = (x, 2b - a + \beta(x)), \\ \eta(x, a) * \eta(x, b) &= (x, a + \beta(x)) * (x, b + \beta(x)) = (x, 2(b + \beta(x)) - (a + \beta(x))) \\ &= (x, 2b - a + \beta(x)), \end{aligned}$$

as desired.

If $x - y = 1 \in \mathbb{Z}_3$, then $\mu(x - y) = -1$ for both $G(A, c_1, c_2)$ and $G(A, 0, c)$ and $\tau(x - y) = c_1$ for $G(A, c_1, c_2)$ but $\tau(x - y) = 0$ for $G(A, 0, c)$, so that

$$\begin{aligned} \eta((x, a) * (y, b)) &= \eta(2y - x, -a - b + c_1) = (2y - x, -a - b + c_1 + \beta(2y - x)), \\ \eta(x, a) * \eta(y, b) &= (x, a + \beta(x)) * (y, b + \beta(y)) \\ &= (2y - x, -(a + \beta(x)) - (b + \beta(y))). \end{aligned}$$

The two expressions are equal if and only if $\beta(x) + \beta(y) + \beta(2y - x) = -c_1$, which is true since $x \neq y$ implies that exactly one of $x, y, 2y - x$ is $2 \in \mathbb{Z}_3$.

If $x - y = 2 \in \mathbb{Z}_3$, then $\mu(x - y) = -1$ for both $G(A, c_1, c_2)$ and $G(A, 0, c)$ and $\tau(x - y) = c_2$ for $G(A, c_1, c_2)$ but $\tau(x - y) = c_2 - c_1 = c$ for $G(A, 0, c)$, so that

$$\begin{aligned} \eta((x, a) * (y, b)) &= \eta(2y - x, -a - b + c_2) = (2y - x, -a - b + c_2 + \beta(2y - x)), \\ \eta(x, a) * \eta(y, b) &= (x, a + \beta(x)) * (y, b + \beta(y)) \\ &= (2y - x, -(a + \beta(x)) - (b + \beta(y)) + c_2 - c_1) \\ &= (2y - x, -a - b - \beta(x) - \beta(y) + (c_2 - c_1)), \end{aligned}$$

and again these are equal for the same reason as above. \square

Notation. Since, by Lemma 3.6, any Galkin quandle is isomorphic to $G(A, 0, c)$ for an abelian group A and $c \in A$, we denote $G(A, 0, c)$ by $G(A, c)$ for short.

Any finite abelian group is a product $\mathbb{Z}_{n_1} \times \cdots \times \mathbb{Z}_{n_k}$, where the positive integers n_j satisfy $n_j | n_{j+1}$ for $j = 1, \dots, k - 1$. In this case, any element $c \in A$ is written in a vector form $[c_1, \dots, c_k]$, where $c_j \in \mathbb{Z}_{n_j}$. Then the corresponding Galkin quandle is denoted by $G(A, [c_1, \dots, c_k])$.

Remark 3.7. We note that the definition of Galkin quandles induces a functor. Let \mathbf{Ab}_0 denote the category of pointed abelian groups; its objects are pairs (A, c) , where A is an abelian group and $c \in A$, and its morphisms $f : (A, c) \rightarrow (B, d)$ are group homomorphisms $f : A \rightarrow B$ such that $f(c) = d$. Let \mathbf{Q} be the category of quandles consisting of quandles as objects and quandle homomorphisms as morphisms.

Then the correspondence $(A, c) \mapsto G(A, c)$ defines a functor $\mathcal{F} : \mathbf{Ab}_0 \rightarrow \mathbf{Q}$. It is easy to verify that if a morphism $f : (A, c) \rightarrow (B, d)$ is given, then the mapping $\mathcal{F}(f)(x, a) = (x, f(a))$ with $(x, a) \in G(A, c) = \mathbb{Z}_3 \times A$ is a homomorphism from $G(A, c)$ to $G(B, d)$ and satisfies $\mathcal{F}(gf) = \mathcal{F}(g)\mathcal{F}(f)$ and $\mathcal{F}(\text{id}_{(A,c)}) = \text{id}_{G(A,c)}$.

Remark 3.8. A reader will wonder to what extent Definition 3.4 of a Galkin quandle can be generalized. We tried several generalizations. For example, if one attempts to replace 3 by an arbitrary prime p in Definition 3.4, then Lemma 3.3 still holds. In this case for $p > 3$, we prove in Lemma 5.14 that $\mu(x) = 2$ for all $x \in \mathbb{Z}_p$, and computer experiments indicate that one almost always obtains a quandle if and only if $\tau = 0$, in which case the quandle obtained is simply a product of dihedral quandles. We have also attempted to replace $-x + 2y$ by the Alexander quandle operation $tx + (1 - t)y$ in both the left and right coordinates, but have neither been successful in finding interesting new quandles, nor been able to prove that no such generalizations exist. We note that if a generalization for $p > 3$ exists, then any such quandles will be less dense than Galkin quandles, since multiples of 3 are more numerous than multiples of p when $p > 3$.

4. Isomorphism classes

In this section we classify isomorphism classes of Galkin quandles.

Lemma 4.1. *Let A be an abelian group, and let $h : A \rightarrow A'$ be a group isomorphism. Then Galkin quandles $G(A, \tau)$ and $G(A', h\tau)$ are isomorphic as quandles.*

Proof. Define $f : G(A, \tau) \rightarrow G(A', h\tau)$, as a map from $\mathbb{Z}_3 \times A$ to $\mathbb{Z}_3 \times A'$, by $f(x, a) = (x, h(a))$. This f is a bijection, and we show that it is a quandle homomorphism by computing $f((x, a) * (y, b))$ and $f(x, a) * f(y, b)$ for $x, y \in \mathbb{Z}_3$ and $a, b \in A$:

$$\begin{aligned} f((x, a) * (y, b)) &= f(2y - x, -a + \mu(x - y)b + \tau(x - y)) \\ &= (2y - x, h(-a + \mu(x - y)b + \tau(x - y))), \end{aligned}$$

$$\begin{aligned} f(x, a) * f(y, b) &= (x, h(a)) * (y, h(b)) \\ &= (2y - x, -h(a) + \mu(x - y)h(b) + h\tau(x - y)). \end{aligned}$$

The equality $f((x, a) * (y, b)) = f(x, a) * f(y, b)$ follows from the facts that h is a group homomorphism and $\mu(x - y)$ is an integer. \square

Lemma 4.2. *Let c, d, n be positive integers. If $\gcd(c, n) = d$, then $G(\mathbb{Z}_n, c)$ is isomorphic to $G(\mathbb{Z}_n, d)$.*

Proof. If $A = \mathbb{Z}_n$, then $\text{Aut}(A) = \mathbb{Z}_n^* =$ units of \mathbb{Z}_n , and the divisors of n are representatives of the orbits of \mathbb{Z}_n^* acting on \mathbb{Z}_n . \square

Thus we may choose the divisors of n for the values of c for representing isomorphism classes of $G(\mathbb{Z}_n, c)$.

Corollary 4.3. *If A is a vector space (elementary p -group), then there are exactly two isomorphism classes of Galkin quandles $G(A, \tau)$.*

Proof. If A is a vector space containing nonzero vectors c_1 and c_2 , then there is a nonsingular linear transformation h of A such that $h(c_1) = c_2$. That $G(A, 0)$ is not isomorphic to $G(A, c)$ if $c \neq 0$ follows from Lemma 4.5. \square

For distinguishing isomorphism classes, cycle structures of the right action are useful, and we use the following lemmas.

Lemma 4.4. *For any abelian group A , the Galkin quandle $G(A, \tau)$ is connected.*

Proof. Recall that the operation is defined by the formula

$$(x, a) * (y, b) = (2y - x, -a + \mu(x - y)b + \tau(x - y)),$$

with $\mu(0) = 2$, $\mu(1) = \mu(2) = -1$, and $\tau(0) = 0$. If $x \neq y$, then $(x, a) * (y, b) = (2y - x, -a - b + c_i) = (z, c)$, where $i = 1$ or 2 and $x, y \in \mathbb{Z}_3$ and $a, b \in A$. Note that $\{x, y, 2y - x\} = \mathbb{Z}_3$ if $x \neq y$. In particular, for any (x, a) and (z, c) with $x \neq z$, there is (y, b) such that $(x, a) * (y, b) = (z, c)$.

For any (x, a_1) and (x, a_2) where $x \in \mathbb{Z}_3$ and $a_1, a_2 \in A$, take $(z, c) \in \mathbb{Z}_3 \times A$ such that $z \neq x$. Then there are $(y, b_1), (y, b_2)$ such that $x \neq y \neq z$ and $(x, a_1) * (y, b_1) = (z, c)$ and $(z, c) * (y, b_2) = (x, a_2)$. Hence $G(A, \tau)$ is connected. \square

Lemma 4.5. *The cycle structure of a right translation in $G(A, \tau)$, where $\tau(0) = \tau(1) = 0$ and $\tau(2) = c$, consists of 1-cycles, 2-cycles, and $2k$ -cycles, where k is the order of c in the group A .*

Since isomorphic quandles have the same cycle structure of right translations, $G(A, c)$ and $G(A, c')$ for $c, c' \in A$ are not isomorphic unless the orders of c and c' coincide.

Proof. Let $\tau(0) = 0$, $\tau(1) = 0$, and $\tau(2) = c$. Then by Lemma 4.4, the cycle structure of each column is the same as the cycle structure of the right translation by $(0, 0)$, that is, of the permutation $f(x, a) = (x, a) * (0, 0) = (-x, -a + \tau(x))$.

We show that this permutation has cycles of length only 1, 2 and twice the order of c in A . Since $f(0, a) = (0, -a)$ for $a \in A$, $a \neq 0$, we have $f^2(0, a) = (0, a)$, so that $(0, a)$ generates a 2-cycle, or a 1-cycle if $2a = 0$. Now from $f(1, a) = (2, -a)$ and $f(2, a) = (1, -a + c)$ for $a \in A$, by induction it is easy to see that for $k > 0$,

$f^{2k}(1, a) = (1, a + kc)$ and $f^{2k}(2, a) = (2, a - kc)$. In the case of $(1, a)$, $a \neq 0$, the cycle closes when $a + kc = a$ in A . The smallest k for which this holds is the order of c , in which case the cycle is of length $2k$. A cycle beginning at $(2, a)$ similarly has this same length. \square

Proposition 4.6. *Let n be a positive integer. Let $A = \mathbb{Z}_n$ and $c_i, c'_i \in \mathbb{Z}_n$ for $i = 1, 2$. Two Galkin quandles $G(A, c_1, c_2)$ and $G(A, c'_1, c'_2)$ are isomorphic if and only if $\gcd(c_1 - c_2, n) = \gcd(c'_1 - c'_2, n)$.*

Proof. If $\gcd(c_1 - c_2, n) = \gcd(c'_1 - c'_2, n)$, then they are isomorphic by Lemmas 3.6 and 4.2. The cycle structures are different if $\gcd(c_1 - c_2, n) \neq \gcd(c'_1 - c'_2, n)$ by Lemma 4.5, and hence they are not isomorphic. \square

Remark 4.7. The cycle structure is not sufficient for noncyclic groups A . For example, let $A = \mathbb{Z}_2 \times \mathbb{Z}_4$. Then $G(A, [1, 0])$ and $G(A, [0, 2])$ have the same cycle structure for right translations, with cycle lengths $\{2, 2, 4, 4, 4, 4\}$ in a multiset notation, yet they are known not to be isomorphic. (In the notation of Example 4.12 below, $G(A, [1, 0]) = C[24, 29]$ and $G(A, [0, 2]) = C[24, 31]$.) We note that there is no automorphism of A carrying $[1, 0]$ to $[0, 2]$.

More generally, the isomorphism classes of Galkin quandles are characterized as follows.

Theorem 4.8. *Suppose A, A' are finite abelian groups. Two Galkin quandles $G(A, \tau)$ and $G(A', \tau')$ are isomorphic if and only if there exists a group isomorphism $h : A \rightarrow A'$ such that $h\tau = \tau'$.*

One implication in the proof of Theorem 4.8 is Lemma 4.1. For the other, first we prove the following two lemmas. We will use a well known description of the automorphisms of a finite abelian group, which can be found in [Hillar and Rhea 2007; Ranum 1907].

Lemma 4.9. *Let A be a finite abelian p -group and let $f : pA \rightarrow pA$ be an automorphism. Then f can be extended to an automorphism of A .*

Proof. Let $A = \mathbb{Z}_{p^{n_1}} \times \cdots \times \mathbb{Z}_{p^{n_k}}$. Then

$$(7) \quad f \left(\begin{bmatrix} px_2 \\ \vdots \\ px_k \end{bmatrix} \right) = P \begin{bmatrix} px_2 \\ \vdots \\ px_k \end{bmatrix}, \quad \begin{bmatrix} x_2 \\ \vdots \\ x_k \end{bmatrix} \in \mathbb{Z}_{p^2}^{n_2} \times \cdots \times \mathbb{Z}_{p^k}^{n_k},$$

where

$$(8) \quad P = \begin{bmatrix} P_{22} & P_{23} & \cdots & P_{2k} \\ pP_{32} & P_{33} & \cdots & P_{3k} \\ \vdots & \vdots & & \vdots \\ p^{k-2}P_{k2} & p^{k-3}P_{k3} & \cdots & P_{kk} \end{bmatrix},$$

$P_{ij} \in M_{n_i \times n_j}(\mathbb{Z})$, $\det P_{ii} \not\equiv 0 \pmod{p}$. Entries of the vectors are elements of finite groups as specified, and entries of the block matrices are integers. Define $g : A \rightarrow A$ by

$$g \left(\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix} \right) = \begin{bmatrix} I & \\ & P \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix}, \quad \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix} \in \mathbb{Z}_{p^1}^{n_1} \times \mathbb{Z}_{p^2}^{n_2} \times \cdots \times \mathbb{Z}_{p^k}^{n_k}.$$

Then $g \in \text{Aut}(A)$ and $g|_{pA} = f$. \square

Lemma 4.10. *Let A be a finite abelian p -group and let $a, b \in A \setminus pA$. If there exists an automorphism $f : pA \rightarrow pA$ such that $f(pa) = pb$, then there exists an automorphism $g : A \rightarrow A$ such that $g(a) = b$.*

Proof. Let $A = \mathbb{Z}_{p^1}^{n_1} \times \cdots \times \mathbb{Z}_{p^k}^{n_k}$ and let f be defined by (7) and (8). Write

$$a = \begin{bmatrix} a_1 \\ \vdots \\ a_n \end{bmatrix}, \quad b = \begin{bmatrix} b_1 \\ \vdots \\ b_n \end{bmatrix}, \quad a_i, b_i \in \mathbb{Z}_{p^i}^{n_i}.$$

Since $f(pa) = pb$, we have

$$p \left(P \begin{bmatrix} a_2 \\ \vdots \\ a_n \end{bmatrix} - \begin{bmatrix} b_2 \\ \vdots \\ b_n \end{bmatrix} \right) = 0,$$

that is,

$$(9) \quad P \begin{bmatrix} a_2 \\ \vdots \\ a_n \end{bmatrix} - \begin{bmatrix} b_2 \\ \vdots \\ b_n \end{bmatrix} = \begin{bmatrix} pc_2 \\ \vdots \\ p^{k-1}c_k \end{bmatrix}, \quad c_i \in \mathbb{Z}_{p^i}^{n_i}, \quad 2 \leq i \leq k.$$

Case 1. Assume that $\begin{bmatrix} a_2 \\ \vdots \\ a_n \end{bmatrix} \in pA$. Then by (9), $\begin{bmatrix} b_2 \\ \vdots \\ b_n \end{bmatrix} \in pA$. So $a_1 \neq 0$ and $b_1 \neq 0$.

Then we have

$$\begin{bmatrix} pc_2 \\ \vdots \\ p^{k-1}c_k \end{bmatrix} = \begin{bmatrix} pQ_2 \\ \vdots \\ p^{k-1}Q_k \end{bmatrix} a_1$$

for some $Q_i \in M_{n_i \times n_1}(\mathbb{Z})$ with $2 \leq i \leq k$. Also, there exists $P_{11} \in M_{n_1 \times n_1}(\mathbb{Z})$ such

that $\det P_{11} \not\equiv 0 \pmod{p}$ and $P_{11}a_1 = b_1$. Let $g \in \text{Aut}(A)$ be defined by

$$g \left(\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix} \right) = \begin{bmatrix} P_{11} & 0 \\ -pQ_2 & \\ \vdots & P \\ -p^{k-1}Q_k & \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix}, \quad x_i \in \mathbb{Z}_{p^i}^{n_i}.$$

Then $g(a) = b$.

Case 2. Assume that $\begin{bmatrix} a_2 \\ \vdots \\ a_n \end{bmatrix} \notin pA$. Then there exists $2 \leq s \leq k$ such that $a_s \notin p\mathbb{Z}_{p^s}^{n_s}$.

Then we have

$$\begin{bmatrix} c_2 \\ \vdots \\ p^{k-2}c_k \end{bmatrix} = \begin{bmatrix} Q_2 \\ \vdots \\ p^{k-2}Q_k \end{bmatrix} a_s$$

for some $Q_i \in M_{n_i \times n_s}(\mathbb{Z})$ with $2 \leq i \leq k$. Put

$$Q = \begin{bmatrix} 0 & \cdots & 0 & Q_2 & 0 & \cdots & 0 \\ \vdots & & \vdots & \vdots & \vdots & & \vdots \\ 0 & \cdots & 0 & p^{k-2}Q_k & 0 & \cdots & 0 \end{bmatrix},$$

where the (i, j) block is of size $n_i \times n_j$ and Q_2 is in the $(1, s)$ block. Then

$$Q \begin{bmatrix} a_2 \\ \vdots \\ a_k \end{bmatrix} = \begin{bmatrix} c_2 \\ \vdots \\ p^{k-2}c_k \end{bmatrix}.$$

Also, there exist $U \in M_{n_1 \times (n_2 + \cdots + n_k)}(\mathbb{Z})$ such that

$$U \begin{bmatrix} a_2 \\ \vdots \\ a_k \end{bmatrix} = b_1 - a_1.$$

Now define $g \in \text{Aut}(A)$ by

$$g \left(\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix} \right) = \begin{bmatrix} I & U \\ 0 & P - pQ \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix}, \quad x_i \in \mathbb{Z}_{p^i}^{n_i}.$$

Then $g(a) = b$. □

Proof of Theorem 4.8. We assume that $|3A'| \leq |3A|$. Since $G(A', c')$ is connected, there exists an isomorphism $\phi : G(A, c) \rightarrow G(A', c')$ such that $\phi(0, 0) = (0, 0)$. Write

$$\phi(x, a) = (\alpha(x, a), \beta(x, a)), \quad (x, a) \in \mathbb{Z}_3 \times A.$$

Define $t : \mathbb{Z}_3 \rightarrow \mathbb{Z}$ by

$$t(x) = \begin{cases} 1 & \text{if } x = 2, \\ 0 & \text{if } x \neq 2, \end{cases}$$

so that for $(x, a), (y, b) \in \mathbb{Z}_3 \times A$, the operation on $G(A, c)$ is written by

$$(x, a) * (y, b) = (-x - y, -a + \mu(x - y)b + t(x - y)c).$$

Then $\phi((x, a) * (y, b)) = \phi(x, a) * \phi(y, b)$ is equivalent to

$$(10) \quad \alpha(-x - y, -a + \mu(x - y)b + t(x - y)c) = -\alpha(x, a) - \alpha(y, b),$$

$$(11) \quad \begin{aligned} \beta(-x - y, -a + \mu(x - y)b + t(x - y)c) \\ = -\beta(x, a) + \mu(\alpha(x, a) - \alpha(y, b))\beta(y, b) + t(\alpha(x, a) - \alpha(y, b))c'. \end{aligned}$$

Claim 1. *The map $\alpha(0, \cdot) : A \rightarrow \mathbb{Z}_3$ is a homomorphism.*

Proof. Setting $x = y = 0$ in (10), we have

$$(12) \quad \alpha(0, -a + 2b) = -\alpha(0, a) - \alpha(0, b).$$

Setting $b = 0$ in (12), we have

$$(13) \quad \alpha(0, -a) = -\alpha(0, a).$$

By the symmetry of the right-hand side of (12), we also have

$$(14) \quad \alpha(0, -a + 2b) = \alpha(0, -b + 2a), \quad a, b \in A.$$

Now we have

$$\begin{aligned} \alpha(0, a + b) &= \alpha(0, a - b + 2b) \\ &= \alpha(0, -b + 2(b - a)) && \text{(by (14))} \\ &= \alpha(0, b - 2a) \\ &= -\alpha(0, -b) - \alpha(0, -a) && \text{(by (12))} \\ &= \alpha(0, a) + \alpha(0, b) && \text{(by (13)).} \end{aligned} \quad \square$$

Claim 2. *There exists $u \in \mathbb{Z}_3$ such that*

$$(15) \quad \alpha(x, a) = \alpha(0, a) + ux, \quad (x, a) \in \mathbb{Z}_3 \times A.$$

Proof. Setting $x = 1$ and $y = 0$ in (10), we have

$$(16) \quad \alpha(-1, -a - b) = -\alpha(1, a) - \alpha(0, b).$$

Setting $b = 0$ in (16) gives

$$(17) \quad \alpha(-1, -a) = -\alpha(1, a).$$

Letting $a = 0$ in (16) and using (17), we get

$$(18) \quad \alpha(1, b) = \alpha(0, b) + \alpha(1, 0), \quad b \in A.$$

Equations (16) and (13) also imply that

$$(19) \quad \alpha(-1, -b) = \alpha(0, -b) - \alpha(1, 0), \quad b \in A.$$

Let $u = \alpha(1, 0)$. Then

$$\alpha(x, a) = \alpha(0, a) + ux, \quad (x, a) \in \mathbb{Z}_3 \times A. \quad \square$$

Claim 3. $\alpha(0, c) = 0$.

Proof. Substituting (15) in (10), we get

$$(20) \quad \alpha(0, -a + \mu(x - y)b + t(x - y)c) = -\alpha(0, a) - \alpha(0, b).$$

Setting $x - y = 2$, we have $\alpha(0, c) = 0$. \square

The rest of the proof of Theorem 4.8 is divided into two cases according to whether u is zero or nonzero in (15).

Case A. Assume $u = 0$ in (15).

We have $\alpha(x, a) = \alpha(0, a)$ for all $(x, a) \in \mathbb{Z}_3 \times A$. We write $\alpha(a)$ for $\alpha(0, a)$. Then (11) becomes

$$(21) \quad \begin{aligned} \beta(-x - y, -a + \mu(x - y)b + t(x - y)c) \\ = -\beta(x, a) + \mu(\alpha(a - b))\beta(y, b) + t(\alpha(a - b))c'. \end{aligned}$$

Step A-1. We claim that $c = 0$.

Equation (21) with $x = 1, y = 0, a = b = 0$ yields

$$\beta(-1, 0) = -\beta(1, 0),$$

and with $x = -1, y = 0, a = b = 0$, it yields

$$\beta(1, c) = -\beta(-1, 0).$$

Thus $\beta(1, c) = \beta(1, 0)$. Since $\alpha(1, c) = 0 = \alpha(1, 0)$, we have $\phi(1, c) = \phi(1, 0)$.

Thus $c = 0$.

Step A-2. We claim that $c' = 0$.

The homomorphism $\alpha : A \rightarrow \mathbb{Z}_3$ must be onto. (Otherwise ϕ is not onto.) Choose $d \in A$ such that $\alpha(d) = -1$. Equation (21) with $x = y = 0$, $a = d$, $b = 0$ gives

$$\beta(0, -d) = -\beta(0, d) + c',$$

and with $x = y = 0$, $a = -d$, $b = 0$, it gives

$$\beta(0, d) = -\beta(0, -d).$$

Therefore $c' = 0$.

Step A-3. Now (21) becomes

$$(22) \quad \beta(-x - y, -a + \mu(x - y)b) = -\beta(x, a) + \mu(\alpha(a - b))\beta(y, b).$$

Setting $y = 0$ and $b = 0$ in (22), we have

$$(23) \quad \beta(-x, -a) = -\beta(x, a).$$

Step A-4. We claim that $\beta(0, \cdot) : 3A \rightarrow A'$ is a one-to-one homomorphism.

Note that $3A \subset \ker \alpha$. Let $a, b \in 3A$, and $x = -1$, $y = 1$ in (22). We have

$$(24) \quad \beta(0, -a - b) = -\beta(-1, a) + 2\beta(1, b).$$

Setting $b = 0$ and $a = 0$, respectively, in (24) and using (23), we have

$$(25) \quad \beta(0, -a) = -\beta(-1, a) + 2\beta(1, 0) = \beta(1, -a) + 2\beta(1, 0),$$

$$(26) \quad \beta(0, -b) = -\beta(-1, 0) + 2\beta(1, b) = \beta(1, 0) + 2\beta(1, b).$$

Setting $a = b = 0$ in (24), we have

$$(27) \quad 3\beta(1, 0) = 0.$$

Combining (24)–(27), we have

$$\beta(0, -a - b) = \beta(0, -a) + \beta(0, -b).$$

If $a \in 3A$ such that $\beta(0, a) = 0$, then $\phi(0, a) = (0, 0)$, so $a = 0$. Thus

$$\beta(0, \cdot) : 3A \rightarrow A'$$

is one-to-one.

Step A-5. We claim that $\beta(0, 3b) \in 3A'$ for all $b \in A$.

Let $x = y = 0$ and $a = -b$ in (22). We have

$$\begin{aligned} \beta(0, 3b) &= -\beta(0, -b) + \mu(\alpha(-2b))\beta(0, b) \\ &= \beta(0, b) + \mu(\alpha(b))\beta(0, b) \\ &\equiv 0 \pmod{3A'} \quad (\text{since } \mu(\alpha(b)) \equiv -1 \pmod{3}). \end{aligned}$$

Step A-6. Now $\beta(0, \cdot) : 3A \rightarrow 3A'$ is a one-to-one homomorphism. It is therefore an isomorphism, since $|3A'| \leq |3A|$. Since $|A| = |A'|$, we have $A \cong A'$. We are done in Case A.

Case B. Assume $u \neq 0$ in (15).

By the proofs of Lemma 4.5 above and Proposition 5.11 below, the map $(x', a') \mapsto (-x', a' - t(-x')c')$ is an isomorphism from $G(A', c')$ to $G(A', -c')$. Thus we may assume $u = 1$ in (15). We have $\alpha(x, a) = \alpha(0, a) + x$ for all $(x, a) \in \mathbb{Z}_3 \times A$.

Step B-1. We claim that $\beta(0, \cdot) : \ker \alpha(0, \cdot) \rightarrow A'$ is a one-to-one homomorphism.

In (11) let $a, b \in \ker \alpha(0, \cdot)$ and $x = -1, y = 1$. We have

$$(28) \quad \beta(0, -a - b) = -\beta(-1, a) - \beta(1, b).$$

Equation (28) with $a = -b$ yields

$$(29) \quad \beta(-1, -b) = -\beta(1, b).$$

So

$$(30) \quad \beta(0, -a - b) = \beta(1, -a) - \beta(1, b).$$

Letting $b = 0$ and $a = 0$ in (30), respectively, we have

$$\begin{aligned} \beta(0, -a) &= \beta(1, -a) - \beta(1, 0), \\ \beta(0, -b) &= \beta(1, 0) - \beta(1, b). \end{aligned}$$

Thus

$$\begin{aligned} \beta(0, -a) + \beta(0, -b) &= \beta(1, -a) - \beta(1, b) \\ &= \beta(0, -a - b) \quad (\text{by (30)}). \end{aligned}$$

If $a \in \ker \alpha(0, \cdot)$ such that $\beta(0, a) = 0$, then $\phi(0, a) = (0, 0)$, so $a = 0$. Hence $\beta(0, \cdot) : \ker \alpha(0, \cdot) \rightarrow A'$ is one-to-one.

Step B-2. We claim that $\beta(0, 3a) \in 3A'$ for all $a \in A$.

Setting $x = y = 0$ in (11), we have

$$(31) \quad \begin{aligned} \beta(0, -a + 2b) &= -\beta(0, a) + \mu(\alpha(0, a - b))\beta(0, b) + t(\alpha(0, a - b))c' \\ &\equiv -\beta(0, a) - \beta(0, b) + t(\alpha(0, a - b))c' \pmod{3A'}. \end{aligned}$$

By (31),

$$\beta(0, 3a) = \beta(0, -a + 2(2a)) \equiv -\beta(0, a) - \beta(0, 2a) + t(\alpha(0, -a))c' \pmod{3A'}$$

and

$$\beta(0, 2a) = \beta(0, 0 + 2a) \equiv -\beta(0, a) + t(\alpha(0, -a))c' \pmod{3A'}.$$

Thus $\beta(0, 3a) \equiv 0 \pmod{3A'}$.

Step B-3. By the argument in Step A-6, $\beta(0, \cdot) : 3A \rightarrow 3A'$ is an isomorphism and $A \cong A'$.

Step B-4. We claim that $\beta(0, c) = c'$.

Equation (11) with $x = 1, y = -1, a = b = 0$ yields

$$\begin{aligned}\beta(0, c) &= -\beta(1, 0) - \beta(-1, 0) + c' \\ &= c' \quad (\text{by (29)}).\end{aligned}$$

Step B-5. Now we complete the proof in Case B. Write $A = A_1 \oplus A_2$ and $A' = A'_1 \oplus A'_2$, where neither $|A_1|$ nor $|A'_1|$ is a multiple of 3, and $|A_2|$ and $|A'_2|$ are powers of 3. Write $c = c_1 + c_2$, where $c_1 \in A_1, c_2 \in A_2$. Then $c_1 \in A_1 \subset \ker \alpha(0, \cdot)$, so $c_2 = c - c_1 \in \ker \alpha(0, \cdot)$. Since $\beta(0, \cdot) : \ker \alpha(0, \cdot) \rightarrow A'$ is a homomorphism, we have

$$c' = \beta(0, c_1) + \beta(0, c_2) = c'_1 + c'_2,$$

where $c'_1 = \beta(0, c_1) \in A'_1$ and $c'_2 = \beta(0, c_2) \in A'_2$. By Step B-3, $\beta(0, \cdot) : A_1 \rightarrow A'_1$ is an isomorphism. So it suffices to show that there is an isomorphism $f : A_2 \rightarrow A'_2$ such that $f(c_2) = c'_2$.

First assume $c_2 \in 3A_2$. Then $c'_2 \in 3A'_2$. By Lemma 4.9, the isomorphism $\beta(0, \cdot) : 3A \rightarrow 3A'$ can be extended to an isomorphism $f : A_2 \rightarrow A'_2$ and we are done.

Now assume that $c_2 \in A_2 \setminus 3A_2$. We claim that $c_2 \in A'_2 \setminus 3A'_2$. Assume to the contrary that $c'_2 \in 3A'_2$. By Step B-3, there exists $d \in A_2$ such that $\beta(0, 3d) = c'_2 = \beta(0, c_2)$. By Step B-1, $c_2 = 3d$, which is a contradiction.

Note that $\beta(0, \cdot) : 3A_2 \rightarrow 3A'_2$ is an isomorphism and

$$\begin{aligned}\beta(0, 3c_2) &= 3\beta(0, c_2) \quad (\text{by Step B-1}) \\ &= 3c'_2.\end{aligned}$$

By Lemma 4.10, there exists an isomorphism $f : A_2 \rightarrow A'_2$ such that $f(c_2) = c'_2$. \square

Remark 4.11. The numbers of isomorphism classes of order $3n$, from $n = 1$ to $n = 100$, are as follows: 1, 2, 2, 5, 2, 4, 2, 10, 5, 4, 2, 10, 2, 4, 4, 20, 2, 10, 2, 10, 4, 4, 2, 20, 5, 4, 10, 10, 2, 8, 2, 36, 4, 4, 4, 25, 2, 4, 4, 20, 2, 8, 2, 10, 10, 4, 2, 40, 5, 10, 4, 10, 2, 20, 4, 20, 4, 4, 2, 20, 2, 4, 10, 65, 4, 8, 2, 10, 4, 8, 2, 50, 2, 4, 10, 10, 4, 8, 2, 40, 20, 4, 2, 20, 4, 4, 4, 20, 2, 20, 4, 10, 4, 4, 4, 72, 2, 10, 10, 25.

In [Clark and Hou 2013] it is shown that the number $N(n)$ of isomorphism classes of Galkin quandles of order n is multiplicative, that is, if $\gcd(n, m) = 1$, then $N(nm) = N(n)N(m)$, so it suffices to find $N(q^n)$ for all prime powers q^n . Clark and Hou established that

$$N(q^n) = \sum_{0 \leq m \leq n} p(m)p(n-m),$$

where $p(m)$ is the number of partitions of the integer m . In particular, $N(q^n)$ is independent of the prime q . The sequence $n \mapsto N(q^n)$ appears in the *On-Line Encyclopedia of Integer Sequences* [Sloane 2011] as sequence A000712.

Example 4.12. In [Vendramin 2011], connected quandles are listed up to order 35. For a positive integer $n > 1$, let $q(n)$ be the number of isomorphism classes of connected quandles of order n . For a positive integer $n > 1$, if $q(n) \neq 0$, then we denote by $C[n, i]$ the i -th quandle of order n in their list ($1 < n \leq 35, i = 1, \dots, q(n)$). We note that $q(n) = 0$ for $n = 2, 14, 22, 26$, and 34 (for $1 < n \leq 35$). The quandle $C[n, i]$ is denoted by $Q_{n,i}$ in [Vendramin 2012] (and they are left-distributive in that work, so the matrix of $C[n, i]$ is the transpose of the matrix of $Q_{n,i}$). Isomorphism classes of Galkin quandles are identified with those in their list in Table 1.

The 4-digit numbers to the right of each row in Table 1 indicate the numbers of knots that are colored nontrivially by these Galkin quandles, out of total 2977 knots in the table [Cha and Livingston 2011] with 12 crossings or less. See Section 6 for more on this.

5. Properties of Galkin quandles

In this section, we investigate various properties of Galkin quandles.

Lemma 5.1. *The Galkin quandle $G(A, \tau)$ is Latin if and only if $|A|$ is odd.*

Proof. To show that it is Latin if n is odd, first note that R_3 is Latin. Suppose that $(x, a) * (y, b) = (x, a) * (y', b')$. Then we have the equations

$$(32) \quad -x + 2y = -x + 2y',$$

$$(33) \quad -a + \mu(x - y)b + \tau(x - y) = -a + \mu(x - y')b' + \tau(x - y').$$

From (32) it follows that $y = y'$, and it follows from (33) that $\mu(x - y)b = \mu(x - y)b'$. Now since $|A|$ is odd, the left module action of 2 on A is invertible, and hence $b = b'$. If $|A|$ is even, there is a nonzero element b of order 2, and hence $(0, 0) * (0, b) = (0, 0) * (0, 0)$, so the quandle is not Latin. \square

Lemma 5.2. *Any Galkin quandle is faithful.*

Proof. We show that if $(x, a) * (y, b) = (x, a) * (y', b')$ holds for all (x, a) , then $(y, b) = (y', b')$. We have $y = y'$ immediately. From the second factor

$$-a + \mu(x - y)b + \tau(x - y) = -a + \mu(x - y)b' + \tau(x - y),$$

we have $\mu(x - y)b = \mu(x - y)b'$ for any x . Pick x such that $x \neq y$; then we have $\mu(x - y) = -1$, and hence $b = b'$. \square

Lemma 5.3. *If A' is a subgroup of A and c' is in A' , then $G(A', c')$ is a subquandle of $G(A, c')$.*

Proof. Immediate. \square

Lemma 5.4. *Any Galkin quandle $G(A, \tau)$ consists of three disjoint subquandles $\{x\} \times A$ for $x \in \mathbb{Z}_3$, and each is a product of dihedral quandles.*

Proof. Immediate. □

We note the following somewhat curious quandles from Lemma 5.4: For a positive integer k , $G(\mathbb{Z}_2^k, [0, \dots, 0])$ is a connected quandle that is a disjoint union of three trivial subquandles of order 2^k .

Lemma 5.5. *The Galkin quandle $G(A, \tau)$ has R_3 as a subquandle if and only if $\tau = 0$ or 3 divides $|A|$.*

Proof. If A is any group and $\tau = 0$, then $(x, 0) * (y, 0) = (2y - x, 0)$ for any $x, y \in \mathbb{Z}_3$, so that $\mathbb{Z}_3 \times \{0\}$ is a subquandle isomorphic to R_3 . If 3 divides $|A|$, then A has a subgroup B isomorphic to \mathbb{Z}_3 . In the subquandle $\{0\} \times B$, we have $(0, a) * (0, b) = (0, -a + 2b)$ for $a, b \in B$, so that $\{0\} \times B$ is a subquandle isomorphic to R_3 .

| Rig notation | Galkin notation | N.C. | Rig notation | Galkin notation | N.C. |
|--------------|---|------|--------------|--|------|
| $C[6, 1]$ | $G(\mathbb{Z}_2, [0])$ | 1084 | $C[24, 28]$ | $G(\mathbb{Z}_8, [4])$ | 1084 |
| $C[6, 2]$ | $G(\mathbb{Z}_2, [1])$ | 1084 | $C[24, 29]$ | $G(\mathbb{Z}_2 \times \mathbb{Z}_4, [1, 0], [1, 2])$ | 1084 |
| $C[9, 2]$ | $G(\mathbb{Z}_3, [0])$ | 1084 | $C[24, 30]$ | $G(\mathbb{Z}_2 \times \mathbb{Z}_4, [0, 0])$ | 1084 |
| $C[9, 6]$ | $G(\mathbb{Z}_3, [1])$ | 1084 | $C[24, 31]$ | $G(\mathbb{Z}_2 \times \mathbb{Z}_4, [0, 2])$ | 1084 |
| $C[12, 5]$ | $G(\mathbb{Z}_4, [2])$ | 1084 | $C[24, 32]$ | $G(\mathbb{Z}_8, [1])$ | 1051 |
| $C[12, 6]$ | $G(\mathbb{Z}_4, [0])$ | 1084 | $C[24, 33]$ | $G(\mathbb{Z}_2 \times \mathbb{Z}_4, [0, 1], [1, 1])$ | 1051 |
| $C[12, 7]$ | $G(\mathbb{Z}_4, [1])$ | 1051 | $C[24, 38]$ | $G(\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2, [0, 0, 1])$ | 1084 |
| $C[12, 8]$ | $G(\mathbb{Z}_2 \times \mathbb{Z}_2, [0, 0])$ | 1084 | $C[24, 39]$ | $G(\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2, [0, 0, 0])$ | 1084 |
| $C[12, 9]$ | $G(\mathbb{Z}_2 \times \mathbb{Z}_2, [1, 0])$ | 1084 | $C[27, 2]$ | $G(\mathbb{Z}_3 \times \mathbb{Z}_3, [0, 0])$ | 1084 |
| $C[15, 5]$ | $G(\mathbb{Z}_5, [1])$ | 1440 | $C[27, 12]$ | $G(\mathbb{Z}_9, [3])$ | 1084 |
| $C[15, 6]$ | $G(\mathbb{Z}_5, [0])$ | 1512 | $C[27, 13]$ | $G(\mathbb{Z}_9, [0])$ | 1084 |
| $C[18, 1]$ | $G(\mathbb{Z}_2 \times \mathbb{Z}_3, [0, 0])$ | 1084 | $C[27, 23]$ | $G(\mathbb{Z}_3 \times \mathbb{Z}_3, [1, 0])$ | 1084 |
| $C[18, 4]$ | $G(\mathbb{Z}_2 \times \mathbb{Z}_3, [1, 0])$ | 1084 | $C[27, 55]$ | $G(\mathbb{Z}_9, [1])$ | 1084 |
| $C[18, 5]$ | $G(\mathbb{Z}_2 \times \mathbb{Z}_3, [1, 1])$ | 1084 | $C[30, 12]$ | $G(\mathbb{Z}_2 \times \mathbb{Z}_5, [0, 1])$ | 1440 |
| $C[18, 8]$ | $G(\mathbb{Z}_2 \times \mathbb{Z}_3, [0, 1])$ | 1084 | $C[30, 13]$ | $G(\mathbb{Z}_2 \times \mathbb{Z}_5, [0, 0])$ | 1512 |
| $C[21, 7]$ | $G(\mathbb{Z}_7, [1])$ | 1339 | $C[30, 14]$ | $G(\mathbb{Z}_2 \times \mathbb{Z}_5, [1, 1])$ | 1440 |
| $C[21, 8]$ | $G(\mathbb{Z}_7, [0])$ | 1386 | $C[30, 15]$ | $G(\mathbb{Z}_2 \times \mathbb{Z}_5, [1, 0])$ | 1512 |
| $C[24, 26]$ | $G(\mathbb{Z}_8, [2])$ | 1071 | $C[33, 10]$ | $G(\mathbb{Z}_{11}, [0])$ | 1260 |
| $C[24, 27]$ | $G(\mathbb{Z}_8, [0])$ | 1084 | $C[33, 11]$ | $G(\mathbb{Z}_{11}, [1])$ | 1220 |

Table 1. Galkin quandles in the Rig table [Vendramin 2011]. The columns headed N.C. show the number of knots with at most 12 crossings that can be nontrivially colored by the quandle.

Conversely, let $S = \{(x, a), (y, b), (z, d)\}$ be a subquandle of $G(A, c)$ isomorphic to R_3 . Note that the quandle operation of R_3 is commutative, and the product of any two distinct elements is equal to the third. We examine two cases.

Case 1. $x = y = z$. In this case we have

$$\begin{aligned}(x, a) * (x, b) &= (x, -a + 2b) = (x, d), \\ (x, b) * (x, a) &= (x, -b + 2a) = (x, d).\end{aligned}$$

Hence we have $-a + 2b = -b + 2a$, so that $3(a - b) = 0$. If there are no elements of order 3 in A , then we have $a - b = 0$, and so $b = a$. This is a contradiction to the fact that S contains 3 elements, so there is an element of order 3 in A ; hence 3 divides $|A|$.

Case 2. x, y and z are all distinct (if two are distinct then all three are). In this case consider $S = \{(0, a), (1, b), (2, d)\}$. Now we have

$$\begin{aligned}(2, d) * (0, a) &= (1, -d - a + c) = (1, b), \\ (0, a) * (2, d) &= (1, -a - d) = (1, b).\end{aligned}$$

Hence we have $-d - a + c = -a - d$, so that $c = 0$, and we have $\tau = 0$. \square

Lemma 5.6. *The Galkin quandle $G(A, \tau)$ is left-distributive if and only if $3A = 0$, that is, every element of A has order 3.*

Proof. Let $\tau(1) = c_1$, $\tau(2) = c_2$. Let $a = (0, 0)$, $b = (0, \alpha)$ and $c = (1, 0)$ for $\alpha \in A$. Then we get $a * (b * c) = (1, \alpha - c_2 + c_1)$ and $(a * b) * (a * c) = (1, -2\alpha - c_2 + c_1)$. If these are equal, then $3\alpha = 0$ for any $\alpha \in A$.

Conversely, suppose that every element of A has order 3. Then we have $\mu(x)a = 2a$ for any $x \in \mathbb{Z}_3$, $a \in A$. Then one computes

$$(34) \quad (x, a) * [(y, b) * (z, c)] = (x * (y * z), -a + b + c - \tau(y - z) + \tau(x - y * z)),$$

$$(35) \quad [(x, a) * (y, b)] * [(x, a) * (z, c)] \\ = ((x * y) * (x * z), -a + b + c - \tau(x - y) - \tau(x - z) + \tau(x * y - x * z)).$$

If all x, y, z are distinct, then $x - y = 1$ or $x - y = 2$, and $x * y = z$, $x * z = y$, $y * z = x$. If $x - y = 1$, then $z = x + 1$ and $y - z = 1$, $x - z = 2$, and one computes that (34) = $(-x + y + z, -a + b + c - c_1) = (35)$. If $x - y = 2$, then one computes (34) = $(-x + y + z, -a + b + c - c_2) = (35)$. The other cases for x, y, z are checked similarly. \square

Proposition 5.7. *The Galkin quandle $G(A, \tau)$ is Alexander if and only if $3A = 0$.*

Proof. If $G(A, \tau)$ is Alexander then it is left-distributive, and hence Lemma 5.6 implies $3A = 0$. Conversely, suppose $3A = 0$. Then $A = \mathbb{Z}_3^k$ for some positive integer k , and is an elementary 3-group. By Corollary 4.3, there are two isomorphism classes,

$G(\mathbb{Z}_3^k, [0, \dots, 0])$ and $G(\mathbb{Z}_3^k, [0, \dots, 0, 1])$. The quandle $G(\mathbb{Z}_3, 1) = C[9, 6]$ is isomorphic to $\mathbb{Z}_3[t]/(t+1)^2$ by a direct comparison. Hence the two classes are isomorphic to the Alexander quandles R_3^k and $R_3^{k-2} \times \mathbb{Z}_3[t]/(t+1)^2$, respectively. \square

Proposition 5.8. *The Galkin quandle $G(A, c)$ is medial if and only if $3A = 0$.*

Proof. We have seen that if $3A = 0$, then $G(A, c)$ is Alexander and hence is medial. Suppose $3b \neq 0$ for some $b \in A$. Then consider the products

$$\begin{aligned} X &= ((0, 0) * (1, b)) * ((1, 0) * (0, 0)) = (-1, b - \tau(-1)), \\ Y &= ((0, 0) * (1, 0)) * ((1, b) * (0, 0)) = (-1, -\tau(-1) - 2b). \end{aligned}$$

Since $3b \neq 0$, we have $X \neq Y$ and so $G(A, c)$ is not medial. \square

Remark 5.9. The fact that the same condition appeared in Lemma 5.6 and Propositions 5.7 and 5.8 is explained as follows. Alexander quandles are left-distributive and medial. It is easy to check that, for a finite Alexander quandle (M, T) with $T \in \text{Aut}(M)$,

(M, T) is connected $\iff (1-T)$ is an automorphism of $M \iff (M, T)$ is Latin.

It was also proved by Toyoda [1941] that a Latin quandle is Alexander if and only if it is medial. As noted by Galkin, $G(\mathbb{Z}_5, 0)$ and $G(\mathbb{Z}_5, 1)$ are the smallest nonmedial Latin quandles and hence the smallest non-Alexander Latin quandles.

We note that medial quandles are left-distributive (by idempotency). We show in Theorem 5.10 that any left-distributive connected quandle is Latin. This implies, by Toyoda's theorem, that every medial connected quandle is Alexander and Latin. The smallest Latin quandles that are not left-distributive are the Galkin quandles of order 15.

It is known that the smallest left-distributive Latin quandle that is not Alexander is of order 81. This is due to V. D. Belousov. See, for example, [Pflugfelder 1990; Galkin 1988, Section 5].

Theorem 5.10. *Every finite left-distributive connected quandle is Latin.*

Proof. Let $(X, *)$ be a finite, connected, and left-distributive quandle. For each $a \in X$, let $X_a = \{a * x : x \in X\}$.

Step 1. We claim that $|X_a| = |X_b|$ for all $a, b \in X$. For any $a, y \in X$, we have

$$|X_a| = |X_a * y| = |\{(a * x) * y : x \in X\}| = |\{(a * y) * (x * y) : x \in X\}| = |X_{a*y}|.$$

Since X is connected, we have $|X_a| = |X_b|$ for all $a, b \in X$.

Step 2. Fix $a \in X$. If $|X_a| = |X|$, by Step 1, $X_b = X$ for all $b \in X$ and we are done. So assume $|X_a| < |X|$. Clearly, $(X_a, *)$ is a left-distributive quandle. Since

$(X, *)$ is connected and $x \mapsto a * x$ is an onto homomorphism from $(X, *)$ to $(X_a, *)$, $(X_a, *)$ is also connected. Using induction, we may assume that $(X_a, *)$ is Latin.

Step 3. For each $y \in Y$, we claim that $X_{a*y} = X_a$. In fact,

$$\begin{aligned} X_{a*y} &\supset (a * y) * X_a \\ &= X_a \quad (\text{since } X_a \text{ is Latin}). \end{aligned}$$

Since $|X_{a*y}| = |X_a|$, we must have $X_{a*y} = X_a$.

Step 4. Since $(X, *)$ is connected, by Step 3, $X_b = X_a$ for all $b \in X$. Thus $X = \bigcup_{b \in X} X_b = X_a$, which is a contradiction. \square

Proposition 5.11. *Any Galkin quandle is self-dual, that is, isomorphic to its dual.*

Proof. The dual quandle structure of $G(A, \tau) = G(A, c_1, c_2)$ is written by

$$(x, a) \bar{*} (y, b) = (x \bar{*} y, -a + \mu(y - x)b + \tau(y - x))$$

for $(x, a), (y, b) \in G(A, \tau)$. Note that $\mu(x - y) = \mu(y - x)$ and $\tau(y - x) = c_{-i}$ if $\tau(x - y) = c_i$ for any $x, y \in X$ and $i \in \mathbb{Z}_3$. Hence its dual is $G(A, c_2, c_1)$. The isomorphism is $f : \mathbb{Z}_3 \times A \rightarrow \mathbb{Z}_3 \times A$, defined by $f(x, a) = (-x, a)$. \square

Corollary 5.12. *A Galkin quandle $G(A, c_1, c_2)$ is involutory (kei) if and only if $c_1 = c_2 \in A$.*

Proof. A quandle is a kei if and only if it is the same as its dual, that is, the identity map is an isomorphism between the dual quandle and itself. Hence this follows from Proposition 5.11. \square

A good involution [Kamada 2007; Kamada and Oshiro 2010] ρ on a quandle $(X, *)$ is an involution $\rho : X \rightarrow X$ (a map with $\rho^2 = \text{id}$) such that $x * \rho(y) = x \bar{*} y$ and $\rho(x * y) = \rho(x) * y$ for any $x, y \in X$. A quandle with a good involution is called a *symmetric* quandle. A kei is a symmetric quandle with $\rho = \text{id}$ (in this case ρ is said to be trivial). Symmetric quandles have been used for unoriented knots and nonorientable surface-knots.

Symmetric quandles with nontrivial good involution have been hard to find. Other than computer calculations, very few constructions have been known. In [Kamada 2007; Kamada and Oshiro 2010], nontrivial good involutions were defined on dihedral quandles of even order, which are not connected. Infinitely many symmetric connected quandles were constructed in [Carter et al. 2010] as extensions of odd order dihedral quandles: For each odd $2n + 1$ ($n \in \mathbb{Z}, n > 0$), a symmetric connected quandle of order $(2n + 1)2^{2n+1}$ was given that is not a kei. Here we use Galkin quandles to construct more symmetric quandles.

Proposition 5.13. *For any positive integer n , there exists a symmetric connected quandle of order $6n$ that is not involutory.*

Proof. We show that if an abelian group A has an element $c \in A$ of order 2, then $G(A, c)$ is a symmetric quandle. Note that $G(A, c)$ is not involutory by Corollary 5.12.

Define the map $\rho : \mathbb{Z}_3 \times A \rightarrow \mathbb{Z}_3 \times A$ by $\rho(x, a) = (x, a + c)$, where $c \in A$ is a fixed element of order 2 and $x \in \mathbb{Z}_3, a \in A$. The map ρ is an involution. It satisfies the required conditions, as we show below. For $x, y \in \mathbb{Z}_3$, we have

$$\begin{aligned} (x, a) * \rho(y, b) &= (x, a) * (y, b + c) \\ &= (2y - x, -a + \mu(x - y)(b + c) + \tau(x - y)), \\ (x, a) \bar{*}(y, b) &= (2y - x, -a + \mu(y - x)b + \tau(y - x)), \end{aligned}$$

where the last equality follows from the proof of Proposition 5.11. If $x = y$, then $\mu(x - y) = 2 = \mu(y - x)$ and $\tau(x - y) = 0 = \tau(y - x)$, and the above two terms are equal. If $x \neq y$, then $\mu(x - y) = -1 = \mu(y - x)$, and exactly one of $\tau(x - y)$ and $\tau(y - x)$ is c and the other is 0, so that the equality holds.

Next we compute

$$\begin{aligned} \rho((x, a) * (y, b)) &= \rho(2y - x, -a + \mu(x - y)b + \tau(x - y)) \\ &= (2y - x, -a + \mu(x - y)b + \tau(x - y) + c), \\ \rho(x, a) * (y, b) &= (x, a + c) * (y, b) \\ &= (2y - x, -a - c + \mu(x - y)b + \tau(x - y)), \end{aligned}$$

and these are equal. □

For the equations in Lemma 3.3, we have the following for \mathbb{Z}_p .

Lemma 5.14. *Let $p > 3$ be a prime and let $\mu : \mathbb{Z}_p \rightarrow \mathbb{Z}$ be a function satisfying $\mu(0) = 2$ and*

$$(36) \quad \mu(x + y) + \mu(x - y) = \mu(x)\mu(y)$$

for any $x, y \in \mathbb{Z}_p$. Then $\mu(x) = 2$ for all $x \in \mathbb{Z}_p$.

Proof. Let

$$S = \sum_{x \in \mathbb{Z}_p} \mu(x).$$

Summing (36) as y runs over \mathbb{Z}_p , we have $2S = S\mu(x)$. So if $S \neq 0$, we have $\mu(x) = 2$ for all $x \in \mathbb{Z}_p$. Hence we only need to prove that $S \neq 0$.

Assume to the contrary that $S = 0$. Since $\mu(kx)\mu(x) = \mu((k+1)x) + \mu((k-1)x)$, it is easy to see by induction that

$$(37) \quad \mu(x)^k = \frac{1}{2} \sum_{0 \leq i \leq k} \binom{k}{i} \mu((k-2i)x).$$

(Here we also use the fact that $\mu(-x) = \mu(x)$, which follows from the fact that $\mu(x - y) = \mu(x)\mu(y) - \mu(x + y)$ is symmetric in x and y .) In particular,

$$\mu(x)^{2p} = \frac{1}{2} \sum_{0 \leq i \leq 2p} \binom{2p}{i} \mu(2(p - i)x).$$

Since $\sum_{x \in \mathbb{Z}_p} \mu(x) = 0$, we have

$$\sum_{x \in \mathbb{Z}_p} \mu(x)^{2p} = \left[2 + \binom{2p}{p} \right] p.$$

Since $\mu(x) = \mu\left(\frac{x}{2}\right)^2 - 2$, we have $\mu(x) = -2, -1, 2, 7, \dots$

Case 1. Assume that there exists $0 \neq x \in \mathbb{Z}_p$ such that $\mu(x) \geq 7$. Then

$$\left[2 + \binom{2p}{p} \right] p = \sum_{x \in \mathbb{Z}_p} \mu(x)^{2p} \geq 7^{2p},$$

which is not possible.

Case 2. Assume that $\mu(x) \in \{-2, -1, 2\}$ for all $x \in \mathbb{Z}_p$. Let $a_i = |\mu^{-1}(i)|$. Since $\sum_{x \in \mathbb{Z}_p} \mu(x) = 0$ and $\sum_{x \in \mathbb{Z}_p} \mu(x)^3 = 0$, where the second equation follows from (37), we have

$$\begin{cases} -2a_{-2} - a_{-1} + 2a_2 = 0, \\ -8a_{-2} - a_{-1} + 8a_2 = 0. \end{cases}$$

So $a_{-1} = 0$, that is, $\mu(x) = \pm 2$ for all $x \in \mathbb{Z}_p$. Then

$$\sum_{x \in \mathbb{Z}_p} \mu(x) \equiv 2p \equiv 2 \pmod{4},$$

which is a contradiction. □

6. Knot colorings by Galkin quandles

In this section we investigate knot colorings by Galkin quandles. Recall from Lemma 5.4 that any Galkin quandle $G(A, \tau)$ consists of three disjoint subquandles $\{x\} \times A$ for $x \in \mathbb{Z}_3$, and each is a product of dihedral quandles. Also any Galkin quandle has R_3 as a quotient. Thus we look at relations between colorings by dihedral quandles and those by Galkin quandles. For a positive integer n , a knot is called n -colorable if its diagram is colored nontrivially by the dihedral quandle R_n .

First we present the numbers of n -colorable knots (for odd n) with 12 crossings or less out of 2977 knots in the knot table from [Cha and Livingston 2011], for comparison with Table 1. These are for dihedral quandles and their products that

may be of interest and relevant for comparisons.

$$R_3 : 1084, \quad R_5 : 670, \quad R_7 : 479, \quad R_{11} : 285, \quad R_{15} : 1512, \quad R_{17} : 192,$$

$$R_{19} : 159, \quad R_{21} : 1386, \quad R_{23} : 128, \quad R_{29} : 97, \quad R_{31} : 87, \quad R_{33} : 1260.$$

Remark 6.1. We note that many Rig Galkin quandles in Table 1 have the same number (1084) of nontrivially colorable knots as the number of 3-colorable knots. We make a few observations on these Galkin quandles.

By Lemma 5.5, a Galkin quandle has R_3 as a subquandle if $\tau = 0$ or 3 divides $|A|$, and among Rig Galkin quandles with the number 1084, 17 of them satisfy this condition. Hence any 3-colorable knot is nontrivially colored by these Galkin quandles. The converse is not necessarily true: $G(\mathbb{Z}_5, 0)$ has $\tau = 0$ but has the number 1512. See Corollary 6.5 for more on these quandles.

The remaining 7 Rig Galkin quandles with the number 1084 have $C[6, 2]$ as a subquandle:

$$C[12, 5], \quad C[12, 9], \quad C[24, 28], \quad C[24, 29], \quad C[24, 31], \quad C[24, 38].$$

It was conjectured [Carter et al. 2010] that if a knot is 3-colorable, then it is nontrivially colored by $C[6, 2]$ (\tilde{R}_3 in their notation). It is also seen that any nontrivial coloring by $C[6, 2]$ descends to a nontrivial 3-coloring via the surjection $C[6, 2] \rightarrow R_3$, so if the conjecture is true, then any knot is nontrivially colored by these quandles if and only if it is 3-colorable. See also Remarks 6.6 and 6.7.

The *determinant* of a knot is a well known knot invariant related to n -colorability; see [Fox 1962; Rolfsen 1976] for example, for the definition.

Proposition 6.2. *Let K be a knot with a prime determinant $p > 3$. Then K is nontrivially colored by a finite Galkin quandle $G(A, \tau)$ if and only if p divides $|A|$.*

Proof. By Fox's theorem [1962], for any prime p , a knot is p -colorable if and only if its determinant is divisible by p . Let K be a knot with the determinant that is a prime $p > 3$. Then K is p -colorable and not 3-colorable.

Let $G(A, \tau)$ be any Galkin quandle and let $\mathcal{C} : \mathcal{A} \rightarrow G(A, \tau)$ be a coloring, where \mathcal{A} is the set of arcs of a knot diagram of K . By the surjection $r : G(A, \tau) \rightarrow R_3$, the coloring \mathcal{C} induces a coloring $r \circ \mathcal{C} : \mathcal{A} \rightarrow R_3$. Since K is not 3-colorable, it is a trivial coloring, and therefore $\mathcal{C}(\mathcal{A}) \subset r^{-1}(x)$ for some $x \in R_3$. The subquandle $r^{-1}(x)$ for any $x \in R_3$ is an Alexander quandle $\{x\} \times A$ with the operation

$$(x, a) * (x, b) = (x, 2b - a),$$

so that it is a product of dihedral quandles $\{x\} \times A = R_{q_1} \times \cdots \times R_{q_k}$ for some positive integer k and prime powers q_j , $j = 1, \dots, k$ (Lemma 5.4). It is known that the number of colorings by a product quandle $X_1 \times \cdots \times X_k$ is the product of numbers of colorings by X_i for $i = 1, \dots, k$. It is also seen that a knot is nontrivially

colored by R_{p^k} for a prime p if and only if it is p -colorable. Hence K is nontrivially colored by $\{x\} \times A$ if and only if one of q_1, \dots, q_k is a power of p . \square

A *2-bridge knot* is a knot that can be put into a position with two maxima and two minima with respect to some height function in space (see [Rolfsen 1976], for example, for its definition and properties).

Corollary 6.3. *For any positive integer n not divisible by 3 and any finite Galkin quandle $G(A, \tau)$, all 2-bridge knots with the determinant n have the same number of colorings by $G(A, \tau)$.*

Proof. Let K be a two-bridge knot with the determinant $n = p_1^{m_1} \dots p_\ell^{m_\ell}$ (in the prime decomposition form), where $p_i \neq 3$ for $i = 1, \dots, \ell$, and let $A = R_{q_1} \times \dots \times R_{q_k}$ be the decomposition for prime powers, as a quandle. By Fox’s theorem [1962], for a prime p , K is p -colorable if and only if p divides the determinant of K . Hence K is p_i -colorable for $i = 1, \dots, \ell$ and not 3-colorable. By the proof of Proposition 6.2, the number of colorings by a Galkin quandle $G(A, \tau)$ of K is determined by the number of colorings by the dihedral quandles R_{q_j} that are factors of A .

The double branched cover $M_2(K)$ of the 3-sphere \mathbb{S}^3 along a 2-bridge knot K is a lens space ([Rolfsen 1976], for example), and its first homology group $H_1(M_2(K), \mathbb{Z})$ is cyclic. If the determinant of K is n , then it is isomorphic to \mathbb{Z}_n ([Lickorish 1997], for example). It is known [Przytycki 1998] that the number of colorings by R_{q_j} is equal to the order of the group $(\mathbb{Z} \oplus H_1(M_2(K), \mathbb{Z})) \otimes \mathbb{Z}_{q_j}$, which is determined by n and q_j alone. \square

Example 6.4. Among knots with up to 8 crossings, the following sets of knots have the same numbers of colorings by all finite Galkin quandles from Corollary 6.3: $\{4_1, 5_1\}$ (determinant 5), $\{5_2, 7_1\}$ (7), $\{6_2, 7_2\}$ (11), $\{6_3, 7_3, 8_1\}$ (13), $\{7_5, 8_2, 8_3\}$ (17), $\{7_6, 8_4\}$ (19), $\{8_6, 8_7\}$ (23), $\{8_8, 8_9\}$ (25), $\{8_{12}, 8_{13}\}$ (29). See [Cha and Livingston 2011] for notations of knots in the table. This exhausts such sets of knots up to 8 crossings.

Computer calculations show that the set of knots up to 8 crossings with determinant 9 is $\{6_1, 8_{20}\}$, and these have different numbers of colorings by some Galkin quandles. The determinant was looked up at KnotInfo [Cha and Livingston 2011].

There are two knots (7_4 and 8_{21} , up to 8 crossings) with determinant 15. They can be distinguished by the numbers of colorings by some Galkin quandles, according to computer calculations.

Corollary 6.5. *Let p be an odd prime. Then a knot K is nontrivially colored by the Galkin quandle $G(\mathbb{Z}_p, 0)$ if and only if it is $3p$ -colorable.*

Proof. Suppose it is $3p$ -colorable; then it is nontrivially colored by R_{3p} , which is isomorphic to $R_3 \times R_p$, so that it is either 3-colorable or p -colorable. If K is 3-colorable, then K is nontrivially colored by $G(\mathbb{Z}_p; 0)$, since $G(\mathbb{Z}_p; 0)$ has R_3 as

a subquandle by Lemma 5.5. If K is p -colorable, then K is nontrivially colored by $G(\mathbb{Z}_p; 0)$, since $G(\mathbb{Z}_p; 0)$ has $\{0\} \times R_p$ as a subquandle by Lemma 5.4.

Suppose that a knot K is nontrivially colored by $G(\mathbb{Z}_p, 0)$, where p is an odd prime. If K is 3-colorable, then it is $3p$ -colorable, and we are done. By the proof of Proposition 6.2, if K is not 3-colorable, then K is nontrivially colored by $\{x\} \times R_p$, where $x \in \mathbb{Z}_3$. Hence K is p -colorable, and so $3p$ -colorable. \square

Remark 6.6. According to computer calculations, the following sets of Galkin quandles (in the numbering of Table 1) have the same numbers of colorings for all 2977 knots with 12 crossings or less. Thus we conjecture that it is the case for all knots. If a Galkin quandle does not appear in the list, then it means that it has different numbers of colorings for some knots, compared to other Galkin quandles. The numbers of colorings are distinct for distinct sets listed below as well.

$$\begin{aligned} & \{C[6, 1], C[6, 2]\}, \{C[12, 5], C[12, 6]\}, \{C[12, 8], C[12, 9]\}, \\ & \{C[18, 1], C[18, 4]\}, \{C[18, 5], C[18, 8]\}, \{C[24, 27], C[24, 28]\}, \\ & \{C[24, 29], C[24, 30], C[24, 31]\}, \{C[24, 38], C[24, 39]\}, \\ & \{C[30, 12], C[30, 14]\}, \{C[30, 13], C[30, 15]\}. \end{aligned}$$

We wish to acknowledge the use of the programs GAP [2008], Maple15 (Magma package) [Maplesoft 2011], and Prover9 and Mace4 [McCune 2009] in our computations. Computational results are posted at [Clark and Yeatman 2011].

Remark 6.7. In contrast to the preceding remark, if we relax the requirement of coloring the same number of times, and instead consider two quandles equivalent if each colors the same knots nontrivially (among these 2977 knots), then we get the following 4 equivalence classes:

$$\begin{aligned} & \{C[3, 1], C[6, 1], C[6, 2], C[9, 2], C[9, 6], C[12, 5], C[12, 6], C[12, 8], C[12, 9], \\ & C[18, 1], C[18, 4], C[18, 5], C[18, 8], C[24, 27], C[24, 28], C[24, 29], C[24, 30], \\ & C[24, 31], C[24, 38], C[24, 39], C[27, 2], C[27, 12], C[27, 13], C[27, 23], C[27, 55]\}, \\ & \{C[12, 7], C[24, 32], C[24, 33]\}, \\ & \{C[15, 5], C[30, 12], C[30, 14]\}, \\ & \{C[15, 6], C[30, 13], C[30, 15]\}. \end{aligned}$$

Thus we conjecture that it is the case for all knots. Of these, the first family with many elements consists of quandles with $C[3, 1]$, $C[6, 1]$ or $C[6, 2]$ as a subquandle. Hence, in fact, the conjecture about this family follows from the conjecture about $\{C[6, 1], C[6, 2]\}$ in the preceding remark.

Remark 6.8. Also in contrast to Remark 6.6, there exists a virtual knot K (see, for example, [Kauffman 1999]) such that the numbers of colorings by $C[6, 1]$ and

$C[6, 2]$ are distinct. A virtual knot K with the following property was given in [Carter et al. 2010, Remark 4.6]: K is 3-colorable, but does not have a nontrivial coloring by $C[6, 2]$. Since $C[6, 1]$ has R_3 as a subquandle, this virtual knot K has a nontrivial coloring by $C[6, 1]$. Hence the numbers of colorings by $C[6, 1]$ and $C[6, 2]$ are distinct for K . Thus we might conjecture that for any pair of nonisomorphic Galkin quandles, there is a virtual knot with different numbers of colorings.

Remark 6.9. For any finite Galkin quandle $G(A, \tau)$, there is a knot K with a surjection $\pi_Q(K) \rightarrow G(A, \tau)$ from the fundamental quandle $\pi_Q(K)$. In fact, a connected sum of trefoils can be taken as K as follows (see, for example, [Rolfsen 1976] for connected sum).

First we take a set of generators of $G(A, \tau)$ as follows. Let $A = \mathbb{Z}_{n_1} \times \cdots \times \mathbb{Z}_{n_k}$, where k, n_1, \dots, n_k are positive integers such that n_i divides n_{i+1} for $i = 1, \dots, k$. Let $S = \{(x, e_i) \mid x \in \mathbb{Z}_3, i = 0, \dots, k\}$, where $e_0 = 0 \in A$ and $e_i \in A$ ($i = 1, \dots, k$) is an elementary vector $[0, \dots, 0, 1, 0, \dots, 0] \in \mathbb{Z}_{n_1} \times \cdots \times \mathbb{Z}_{n_k}$ with a single 1 at the i -th position. Note that R_n is generated by $0, 1$ as $0 * 1 = 2, 1 * 2 = 3$, and inductively, $i * (i + 1) = i + 2$ for $i = 0, \dots, n - 2$. Since $\{x\} \times A$ is isomorphic to a product of dihedral quandles for each $x \in \mathbb{Z}_3$, S generates $G(A, \tau)$.

For a 2-string braid σ_1^3 whose closure is trefoil (see Figure 2), we note that if $x \neq y \in \mathbb{Z}_3$, then for any $a, b \in A$, the pair of colors $(x, a), (y, b) \in G(A, \tau)$ at top arcs extends to the bottom, that is, the bottom arcs receive the same pair. This can be computed directly.

For the copies of the trefoil, we assign pairs $[(0, e_0), (x, e_i)]$ as colors where $x = 1, 2$ and $i = 0, \dots, k$, and take connected sums on the portion of the arcs with the common color $(0, e_0)$. Further we take pairs $[(0, e_j), (1, e_0)]$ for $j = 1, \dots, k$, for example, and take connected sums on the arcs with the common color $(1, e_0)$, to obtain a connected sum of trefoils with all elements of S used as colors, as indicated in Figure 3. Such a coloring gives rise to a quandle homomorphism $\pi_Q(K) \rightarrow G(A, \tau)$ whose image contains generators S ; hence it defines a surjective homomorphism.

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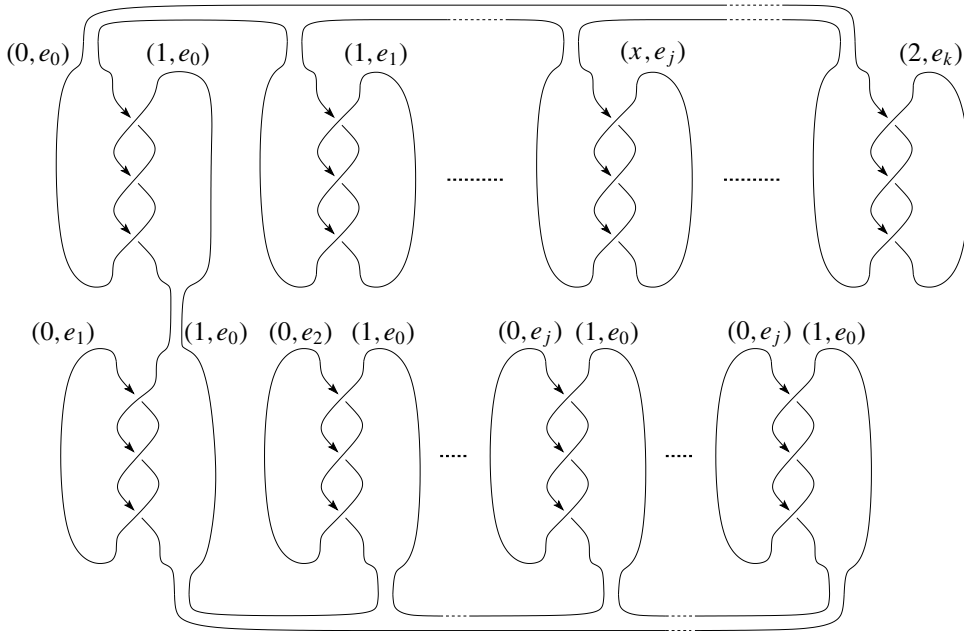


Figure 3. A coloring of a connected sum of trefoils.

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
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