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Enumeration of Virtual Quandles up to Isomorphism

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Abstract

Virtual racks and virtual quandles are nonassociative algebraic structures based on the Reidemeister moves of virtual knots. In this note, we enumerate virtual dihedral quandles and several families of virtual permutation racks and virtual conjugation quandles up to isomorphism. We also classify virtual racks and virtual quandles up to order 8 using a computer search. These classifications are based on the conjugacy class structures of rack automorphism groups. In particular, we compute class numbers of holomorphs of finite cyclic groups, which may be of independent interest.

1 Introduction

In this note, we enumerate virtual dihedral quandles and other families of virtual racks up to isomorphism. These classifications are based on the conjugacy class structures of the automorphism groups of the underlying racks. Using a computer search, we also classify virtual racks and virtual quandles up to order 8. We provide our code and data in a GitHub repository [28].

1.1 Motivations

In 1992, Fenn and Rourke [9] introduced nonassociative algebraic structures called *racks* to construct complete invariants of irreducible framed links in connected 3-manifolds. Racks generalize algebraic structures called *quandles*, which Joyce [11] and Matveev [22] independently introduced in 1982 to construct complete invariants of links in $\mathbb{R}^3$ and S^3, and *kei*, which Takasaki [29] introduced in 1943 to study Riemannian symmetric spaces. Racks, quandles, and kei have enjoyed significant study as knot invariants in geometric topology and in their own rights in quantum algebra and group theory. We refer the reader to a survey of Nelson [23] and the book of Elhamdadi and Nelson [7] for accessible introductions to quandle theory, the book of Nosaka [24] for a reference on racks as they concern low-dimensional topology, and an article of Elhamdadi [5] for a survey of the algebraic state of the art.

In 2002, Manturov [21] introduced *virtual racks*, which are racks equipped with a distinguished automorphism. Virtual racks generalize *virtual quandles*, which define invariants of virtual links in thickened surfaces [14, 21], links in certain lens spaces [2], and long virtual links [20]. As shown in [26], virtual racks also generalize *GL-racks*, which are used to distinguish Legendrian links in $\mathbb{R}^3$ or S^3 with the standard contact structure [12, 16, 27]. More abstractly, virtual racks model braided objects in symmetric categories and actions of virtual braid groups [18]. Recent papers have further generalized virtual racks to construct invariants of multi-virtual links, which generalize virtual links [13, 15].

Finite virtual quandles are particularly important because they define counting invariants and cohomological invariants of virtual links [3, 14, 21]. In particular, various authors have used *virtual dihedral quandles* to study the Kauffman–Harary conjecture and Fox n-coloring invariants of virtual links [4, 8, 31]. The classification of finite virtual quandles is therefore a natural question that extends the classification problems for finite quandles [19, 30] and finite GL-racks [12, Sec. 3].

1.2 Structure of the paper

In Section 2, we give definitions and examples of virtual racks and virtual quandles.

In Section 3, we record a key observation relating virtual rack isomorphism classes to conjugacy classes of rack automorphism groups. As an application, we classify virtual racks and virtual quandles up to order 8. As another application, we introduce an integer-valued rack invariant $v(R)$. We compute $v(R)$ for certain permutation racks and conjugation quandles.

In Section 4, we classify virtual dihedral quandles up to isomorphism. In particular, we obtain the following enumeration.

Theorem 1. *Let $n \in \mathbb{Z}^+$ be a positive integer, let R_n be the dihedral quandle of order n, and let φ denote Euler's totient function. Then the number of isomorphism classes of virtual quandles whose underlying quandles are isomorphic to R_n is*

$$v(R_n) = \varphi(n) \sum_{d \mid n} \frac{1}{\varphi(d)}. \tag{1}$$

Remark 2. The integer sequence $(v(R_n))_{n\geq 1}$ is sequence A069208 from the *On-Line Encyclopedia of Integer Sequences* (OEIS) [25]. Our proof of Theorem 1 shows that $(v(R_n))_{n\geq 1}$ is also the sequence of class numbers of the holomorphs $\mathbb{Z}/n\mathbb{Z} \rtimes (\mathbb{Z}/n\mathbb{Z})^\times$ of finite cyclic groups; see Theorem 23.

We use the following notation throughout this paper. We denote the composition of functions $\chi : X \to Y$ and $\psi : Y \to Z$ by $\psi\chi$. That is, $\psi\chi(x) := \psi(\chi(x))$ for all $x \in X$. Given a set X, let S_X be the symmetric group of X. Given a group G, let $Z(G)$ denote the center of G. Given an element $g \in G$, let $C_G(g)$ denote the centralizer of g in G. For all positive integers $n \in \mathbb{Z}^+$, let $\mathbb{Z}/n\mathbb{Z}$ denote the cyclic group of order n, and let $(\mathbb{Z}/n\mathbb{Z})^\times$ denote its multiplicative group of units.

2 Preliminaries

2.1 Racks

Definition 3. Let X be a set, let $s : X \to S_X$ be a map, and write $s_x := s(x)$ for all elements $x \in X$. We call the pair $R := (X, s)$ a *rack* if

$$s_x s_y = s_{s_x(y)} s_x$$

for all $x, y \in X$. If in addition $s_x(x) = x$ for all $x \in X$, then we say that R is a *quandle*. The *order* of R is the cardinality of X.

Remark 4. Some authors define racks and quandles as sets X with a right-distributive nonassociative binary operation $\triangleright : X \times X \to X$ satisfying certain axioms. These two definitions are equivalent [2, 5] via the formula

$$s_y(x) = x \triangleright y.$$

Example 5. [7, Ex. 99] Let X be a set, and fix a permutation $\sigma \in S_X$. Define $s : X \to S_X$ by $x \mapsto \sigma$, so that $s_x(y) = \sigma(y)$ for all $x, y \in X$. Then $(X, \sigma)_{\text{perm}} := (X, s)$ is a rack called a *permutation rack*, *cyclic rack*, or *constant action rack*.

Note that $(X, \sigma)_{\text{perm}}$ is a quandle if and only if σ is the identity map id_X. In this case, we call $(X, \mathrm{id}_X)_{\text{perm}}$ a *trivial quandle*.

Example 6. [24, Ex. 2.13] Let X be a union of conjugacy classes in a group G, and define $c : X \to S_X$ by sending any element $x \in X$ to the conjugation map

$$c_x := [y \mapsto xyx^{-1}].$$

Then $\operatorname{Conj} X := (X, c)$ is a quandle called a *conjugation quandle* or *conjugacy quandle*. Note that $\operatorname{Conj} G$ is a trivial quandle if and only if G is abelian.

Example 7. [7, Ex. 54] Let G be an abelian additive group. Define $s : G \to S_G$ by setting

$$s_g(h) := 2h - g$$

for all elements $g, h \in G$. Then $T(G) := (G, s)$ is a quandle called a *Takasaki kei*.

In particular, if $n \in \mathbb{Z}^+$ and $G = \mathbb{Z}/n\mathbb{Z}$, then we call $T(\mathbb{Z}/n\mathbb{Z})$ the *dihedral quandle* of order n. We denote $T(\mathbb{Z}/n\mathbb{Z})$ by R_n.

2.2 Virtual racks

Virtual racks are racks equipped with a rack automorphism.

Definition 8. Given two racks (X, s) and (Y, t), we say that a map $\psi : X \to Y$ is a *rack homomorphism* if

$$\psi s_x = t_{\psi(x)}\psi$$

for all $x \in X$. A *rack isomorphism* is a bijective rack homomorphism. *Automorphisms* of racks are isomorphisms from a rack to itself. We denote the *automorphism group* of a rack R by $\operatorname{Aut} R$.

Definition 9. A *virtual rack* is a pair (R, f) where R is a rack and $f \in \operatorname{Aut} R$ is a rack automorphism. We say that f is a *virtual structure* on R. If in addition R is a quandle, then we call (R, f) a *virtual quandle*. We say that R is the *underlying rack* (resp. *underlying quandle*) of (R, f).

Example 10. Let $P = (X, \sigma)_{\mathrm{perm}}$ be a permutation rack. Evidently, $\operatorname{Aut} P = C_{S_X}(\sigma)$, so a virtual structure on P is precisely a permutation of X that commutes with σ.

Example 11. Let G be a group. We consider several virtual structures on $\operatorname{Conj} G$. Fix an element $g \in G$.

- Consider the left-multiplication map $m_g := [h \mapsto gh]$. Then $(\operatorname{Conj} G, m_g)$ is a virtual quandle if and only if $g \in Z(G)$ [16, Ex. 3.6].
- Consider the conjugation map $c_g := [h \mapsto ghg^{-1}]$. Then $(\operatorname{Conj} G, c_g)$ is a virtual quandle [21, Lemma 1]. More generally, given any rack $R = (X, s)$ and any element $x \in X$, the pair (R, s_x) is a virtual rack.

Example 12. Let $n \in \mathbb{Z}^+$ be a positive integer, and let R_n be the dihedral quandle of order n. A result of Elhamdadi, Macquarrie, and Restrepo [6, Thm. 2.3] states that $\operatorname{Aut} R_n$ is the group of affine transformations of $\mathbb{Z}/n\mathbb{Z}$, which is isomorphic to the holomorph $\mathbb{Z}/n\mathbb{Z} \rtimes (\mathbb{Z}/n\mathbb{Z})^\times$ of $\mathbb{Z}/n\mathbb{Z}$. Hence, virtual structures on R_n are precisely affine transformations

$$T_{a,u} := [x \mapsto a + ux]$$

with $a \in \mathbb{Z}/n\mathbb{Z}$ and $u \in (\mathbb{Z}/n\mathbb{Z})^\times$.

Definition 13. Let $V_1 = (R_1, f_1)$ and $V_2 = (R_2, f_2)$ be virtual racks. A *virtual rack homomorphism* from V_1 to V_2 is a rack homomorphism ψ from R_1 to R_2 that intertwines the virtual structures:

$$\psi f_1 = f_2\psi.$$

Virtual rack isomorphisms are bijective virtual rack homomorphisms.

3 Enumeration results

3.1 Key observation

The following is immediately evident from Definition 13.

Proposition 14. *Let f_1, f_2 be two virtual structures on a rack R. Then $(R, f_1) \cong (R, f_2)$ if and only if f_1 and f_2 are conjugate in* $\operatorname{Aut} R$.

In other words, classifying virtual structures on a given rack up to isomorphism is equivalent to characterizing the conjugacy classes of the rack's automorphism group.

3.2 Applications of Proposition 14

3.2.1 A library of virtual racks

Using the computer algebra system `GAP` [10], we implemented an algorithm that exhaustively searches for conjugacy relations in automorphism groups of finite racks. By Proposition 14, this search classifies finite virtual racks and virtual quandles up to isomorphism. Our implementation uses Vojtěchovský and Yang's library of racks and quandles [30] in a way similar to the author's previous classification of GL-racks up to order 8 [26, Appendix A].

We were able to complete this search for virtual racks and virtual quandles up to order 8. We provide our `GAP` code and tabulate our data in a GitHub repository [28]. We also enumerate our data in OEIS sequences A385040 and A385041 [25]; see Table 1.

Order	0	1	2	3	4	5	6	7	8
Virtual racks	1	1	4	15	71	350	2372	18543	199491
Virtual quandles	1	1	2	8	26	104	467	2540	18419

Table 1: Enumeration of isomorphism classes of virtual racks and quandles up to order 8.

3.2.2 Class numbers as rack invariants

We use the following notation for the remainder of this paper. For all racks R, let $v(R)$ denote the number of isomorphism classes of virtual racks whose underlying rack is isomorphic to R. Given a group G, let $k(G)$ be the class number of G, that is, the number of conjugacy classes of G.

Proposition 14 implies that for all racks R,

$$v(R) = k(\operatorname{Aut} R). \tag{2}$$

In particular, $v(R)$ is a rack invariant. The rest of this note is dedicated to using Equation (2) to compute $v(R)$ for various families of racks.

For all nonnegative integers $n \geq 0$, let $p(n)$ denote the number of partitions of n [25, A000041].

Example 15. Let $P = (X, \sigma)_{\text{perm}}$ be a permutation rack. By Example 10 and Equation (2),

$$v(P) = k(\operatorname{Aut} P) = k(C_{S_X}(\sigma)).$$

For example, let X be a finite set of cardinality $n \in \mathbb{Z}^+$. If P is a trivial quandle, then $\operatorname{Aut} P = S_X$, so $v(P) = p(n)$. If, instead, $\sigma \in S_n$ is an n-cycle, then $C_{S_X}(\sigma) = \langle \sigma \rangle \cong \mathbb{Z}/n\mathbb{Z}$, so $v(P) = n$.

Remark 16. Example 15 coincides with the classification of GL-racks whose underlying racks are permutation racks [26, Subsec. 4.2].

3.2.3 Virtual conjugation quandles

The following result of Bardakov, Nasybullov, and Singh [1, Cor. 2] gives a simple way to compute $v(\operatorname{Conj} G)$ when G is a centerless group.

Lemma 17. *Let G be a group, and let $\operatorname{Aut}_{\mathsf{Grp}}(G)$ denote its automorphism group. Then $Z(G) = 1$ if and only if*

$$\operatorname{Aut}_{\mathsf{Grp}}(G) = \operatorname{Aut}(\operatorname{Conj} G).$$

Example 18. Let $n \in \mathbb{Z}^+$ be a positive integer, and let S_n denote the symmetric group on n letters. We compute $v(\operatorname{Conj} S_n)$ as follows. Since $\operatorname{Conj} S_2$ is a trivial quandle, Example 15 yields $v(\operatorname{Conj} S_2) = p(2) = 2$. If $n \neq 2$, then $Z(S_n) = 1$, so Lemma 17 implies that

$$\operatorname{Aut}(\operatorname{Conj} S_n) = \begin{cases} S_n, & \text{if } n \neq 6; \\ S_6 \rtimes \mathbb{Z}/2\mathbb{Z}, & \text{if } n = 6. \end{cases}$$

Since $k(S_n) = p(n)$ for all $n \in \mathbb{Z}^+$ and $k(S_6 \rtimes \mathbb{Z}/2\mathbb{Z}) = 13$, Equation (2) and the above discussion yield

$$v(\operatorname{Conj} S_n) = \begin{cases} p(n), & \text{if } n \neq 6; \\ 13, & \text{if } n = 6. \end{cases}$$

Example 19. Let $n \in \mathbb{Z}^+$ be a positive integer, and let A_n denote the alternating group on n letters. An argument similar to that of Example 18 yields

$$v(\operatorname{Conj} A_n) = \begin{cases} p(n), & \text{if } n \neq 2, 6; \\ 1, & \text{if } n = 2, \\ 13, & \text{if } n = 6. \end{cases}$$

Example 20. For all odd primes $p \geq 3$, the projective special linear group $\mathrm{PSL}(2, p)$ is centerless, and its automorphism group is isomorphic to the projective linear group $\mathrm{PGL}(2, p)$. Hence, Lemma 17 and Equation (2) yield

$$v(\operatorname{Conj} \mathrm{PSL}(2, p)) = k(\mathrm{PGL}(2, p)) = (p - 1)(p + 1).$$

See OEIS sequence A084920 [25].

4 Virtual dihedral quandles

In this section, we classify virtual dihedral quandles up to isomorphism. In particular, we prove Theorem 1.

For the remainder of the paper, let $n \in \mathbb{Z}^+$ be a positive integer, let $A := \mathbb{Z}/n\mathbb{Z}$, and let $G := A \rtimes A^\times$ be the holomorph of A.

4.1 Classification

First, we recall Example 12: Virtual structures on the dihedral quandle R_n of order n are precisely the affine transformations $T_{a,u} : A \to A$ defined by

$$x \mapsto a + ux$$

with $a \in A$ and $u \in A^\times$. Indeed, the mapping $T_{a,u} \mapsto (a, u)$ defines a group isomorphism from $\operatorname{Aut} R_n$ to G [6, Thm. 2.3].

In the following, we classify virtual dihedral quandles up to isomorphism.

Proposition 21. *Let $n \in \mathbb{Z}^+$ be a positive integer, and let $T_{a,u}, T_{b,v}$ be virtual structures on the dihedral quandle R_n of order n. Then $(R_n, T_{a,u}) \cong (R_n, T_{b,v})$ if and only if $u = v$ and*

$$b = ya + (1 - u)x$$

for some element $(x, y) \in G$.

By Proposition 14, Proposition 21 is equivalent to the following.

Proposition 22. *For all $u \in A^\times$, define the group*

$$A_u := (1 - u)A \leq A. \tag{3}$$

Then two elements $(a, u), (b, v) \in G$ are conjugate if and only if (i) $u = v$ and (ii) a and b lie in the same orbit under the action of $A^\times$ on A/A_u.

Proof. Conjugation in G is given by

$$(x, y)(a, u)(x, y)^{-1} = (x + ya, yu)(-y^{-1}x, y^{-1}) = (ya + (1 - u)x, u).$$

The claim follows immediately from this computation. $\square$

4.2 Enumeration

Finally, we prove Theorem 1. By Equation (2), Theorem 1 is equivalent to the following.

Theorem 23. *Let φ denote Euler's totient function. If $A = \mathbb{Z}/n\mathbb{Z}$ and $G = A \rtimes A^\times$, then*

$$k(G) = \varphi(n) \sum_{d \mid n} \frac{1}{\varphi(d)}.$$

Proof. For all elements $u \in A^\times$, define the group A_u as in Equation (3), and let $\psi(u)$ denote the number of orbits of the action of $A^\times$ on A/A_u. By Proposition 22,

$$k(G) = \sum_{u \in A^\times} \psi(u).$$

We compute the right-hand side. For each element $u \in A^\times$, consider the integer

$$d_u := \gcd(n, 1-u).$$

By construction,

$$A/A_u \cong \mathbb{Z}/d_u\mathbb{Z}. \tag{4}$$

Let $\tau(d_u)$ be the number of divisors of d_u. By Equation (4) and a standard result of group theory [17, Lemma 1.3], the number of orbits of the action of $(A/A_u)^\times$ on A/A_u equals $\tau(d_u)$. Since $A^\times$ projects onto $(A/A_u)^\times$, it follows that $\psi(u) = \tau(d_u)$. Therefore,

$$k(G) = \sum_{u \in A^\times} \tau(d_u) = \sum_{u \in A^\times} \sum_{d \mid d_u} 1 = \sum_{d \mid n} \sum_{\substack{u \in A^\times \\ d \mid d_u}} 1, \tag{5}$$

where in the last equality we have used the fact that the sums are finite.

Note that if $d \mid n$ and $u \in A^\times$, then $d \mid d_u$ if and only if $u \equiv 1 \pmod{d}$; the latter condition holds if and only if u lies in the kernel of the projection $\pi_d : A^\times \twoheadrightarrow (\mathbb{Z}/d\mathbb{Z})^\times$. In other words, the rightmost sum in Equation (5) equals the cardinality of $\ker \pi_d$. By the first isomorphism theorem, this cardinality equals

$$|\ker \pi_d| = \frac{|A^\times|}{|(\mathbb{Z}/d\mathbb{Z})^\times|} = \frac{\varphi(n)}{\varphi(d)}.$$

Hence,

$$k(G) = \sum_{d \mid n} |\ker \pi_d| = \sum_{d \mid n} \frac{\varphi(n)}{\varphi(d)}.$$

□

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