GENERALIZED LEGENDRIAN RACKS: KNOT COLORING INVARIANTS, MEDIALITY, AND TABULATION

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Abstract. Generalized Legendrian racks, also called GL-racks or bi-Legendrian racks, are a type of nonassociative algebraic structure that can distinguish between Legendrian links in $\mathbb{R}^3$. In this article, we confirm several conjectures in Legendrian knot theory using GL-racks, study the category of medial GL-racks, and classify GL-racks of orders $n \leq 7$ up to isomorphism. First, we distinguish between Legendrian representatives of knot types 6_2 and 8_{10} using GL-rack coloring numbers. Then, we show that the GL-rack of a Legendrian link recovers the fundamental group of the link complement in $\mathbb{R}^3$. We also propose a medial GL-rack-valued invariant of Legendrian links and exhibit a symmetric monoidal closed structure on the category of medial GL-racks. From an additional functorial construction, we obtain a group-theoretic sufficient condition for any two GL-racks or quandles to be isomorphic. Finally, we provide algorithms that tabulate medial and nonmedial GL-racks and GL-quandles of small orders up to isomorphism and compute GL-rack coloring numbers. We also state a conjecture relating isomorphism classes of racks and GL-quandles.

1. Introduction

In 1980, Joyce [22] introduced algebraic structures called *quandles* as a means of capturing the topological structure of knots, links, and symmetric spaces. Since then, quandles and slightly more general algebraic objects called *racks* have enjoyed significant study as link invariants among geometric topologists and in their own right among quantum algebraists. In 2017, Karmakar and Prathamesh [29] introduced rack-theoretic invariants of Legendrian links in $\mathbb{R}^3$. In 2021, Ceniceros et al. [5] refined these invariants by introducing *Legendrian racks*. In 2023, Karmakar et al. [23] and Kimura [25] independently strengthened these constructions by introducing *generalized Legendrian racks*, which are also called *GL-racks* or *bi-Legendrian racks*.

In this article, we study the category GLR of GL-racks and their homomorphisms, extend several known results about quandles to GL-racks, and apply GL-racks to confirm several conjectures about Legendrian links. Along with a classification of GL-racks of orders $n \leq 7$ up to isomorphism in Appendix A, the main results of this paper are as follows.

Theorem 1.1. *The two Legendrian knots with* $(\mathrm{tb}, \mathrm{rot}) = (-7, 2)$ *and underlying smooth knot type* 6_2 *given in* [8] *are distinguishable by GL-rack coloring numbers.*

Theorem 1.2. *The two Legendrian knots with* $(\mathrm{tb}, \mathrm{rot}) = (-8, 3)$ *and underlying smooth knot type* 8_{10} *given in* [3] *are distinguishable by GL-rack coloring numbers.*

Theorem 1.3. *Let* $\Lambda \subset \mathbb{R}^3$ *be an oriented Legendrian link, let* $\mathcal{G}(\Lambda)$ *be the GL-rack of* Λ *as defined in Definition 3.2, and let* $\mathrm{Env}_{\mathsf{GLR}}(\mathcal{G}(\Lambda))$ *be its enveloping group as defined in Definition 2.16. Then there exists a group isomorphism*

$$\mathrm{Env}_{\mathsf{GLR}}(\mathcal{G}(\Lambda)) \cong \pi_1(\mathbb{R}^3 \setminus \Lambda).$$

2020 *Mathematics Subject Classification.* Primary 57K12; Secondary 18B99, 57K10, 57K33.

Key words and phrases. Enumeration, Legendrian knot, link coloring, medial, quandle, quantum algebra, rack.

Theorem 1.4. *Let R_1 and R_2 be GL-racks. If R_2 is medial, then $\mathrm{Hom}_{\mathsf{GLR}}(R_1, R_2)$ has a canonical medial GL-rack structure. If in addition R_2 is a GL-quandle, then so is $\mathrm{Hom}_{\mathsf{GLR}}(R_1, R_2)$.*

Theorem 1.5. *The full subcategory of* GLR *whose objects are medial is symmetric monoidal closed.*

Inspired by the homogeneous representations of GL-racks constructed in [24, Section 5], we also construct a category GrpTup satisfying the following.

Theorem 1.6. *There exists an essentially surjective functor $\mathcal{F} : \mathsf{GrpTup} \twoheadrightarrow \mathsf{GLR}$. This functor induces a group-theoretic sufficient condition for any two GL-racks or quandles to be isomorphic.*

The structure of this article is as follows. In Section 2, we give an overview of the questions in Legendrian knot theory motivating the study of GL-racks and quandles. We define these algebraic structures abstractly and discuss related groups, categories, and functors in the literature.

In Section 3, we discuss how to assign a GL-rack to an oriented Legendrian link, give several worked examples, and discuss related invariants of Legendrian links. Then, we prove Theorems 1.1, 1.2, and 1.3, which we state as Theorems 3.8, 3.11, and 3.13, respectively. Our approach to the first result offers a simpler algebraic alternative to Dynnikov and Prasolov's proof in [10, Proposition 2.3] and gives a positive answer to a question posed in [25, Section 4], which we state as Corollary 3.9 and strengthen in Proposition A.3. The second result confirms a conjecture of Bhattacharyya et al. in [3], and the third result confirms an empirical observation from the original version of [23, Remark 8.2].

In Section 4, we define *medial* or *abelian* GL-racks and tensor products of GL-racks. Using Theorem 1.4, which we state as Theorem 4.3, we propose a medial GL-rack-valued invariant of Legendrian links with suggestions for future research. Then, we prove Theorem 1.5, which we state as Theorem 4.5. These results extend Crans and Nelson's analogous results for medial quandles in [9, Theorems 3 and 12] to medial GL-racks.

In Section 5, we define GrpTup using objects constructed from collections of left cosets of groups. Karmakar et al. originally employed these objects in [24, Theorem 5.2] to produce a homogeneous representation of any GL-rack. Then, we prove Theorem 1.6, the first part of which we state as Theorem 5.1 and the second part of which we discuss afterward.

In Appendix A, we describe algorithms that can classify GL-racks of orders $n \leq 11$ up to isomorphism, building upon the work of Vojtěchovský and Yang in [42]. We provide a link to our implementations of these algorithms in `GAP` [19] and the data we were able to compute and enumerate for all $n \leq 7$. Our findings motivate us to state a conjecture relating rack isomorphism classes to GL-quandle isomorphism classes. We also provide an algorithm that computes the GL-rack coloring number of any oriented Legendrian link with respect to all GL-racks of a given order $1 \leq n \leq 7$.

In Appendix B, we tabulate all GL-racks of orders $2 \leq n \leq 4$ up to isomorphism.

Acknowledgments. This article was written in partial fulfillment of the senior requirements for the mathematics major at Yale. I thank Sam Raskin for serving as my senior thesis advisor even while on academic leave and as I dove into unfamiliar subjects. I also thank Patrick Devlin, Miki Havlíčková, Kati Hubley, Matthew King, Andrew Neitzke, and Carol Rutschman for their mentorship and support. I especially thank Samantha Pezzimenti for her mentorship, support, and introducing me to mathematics research, Legendrian knot theory, and the UnKnot V conference. I also thank Peyton Wood for their support and helpful discussions about Legendrian racks. Finally, I thank Jose Ceniceros for helpful discussions about the category of quandles at UnKnot V.

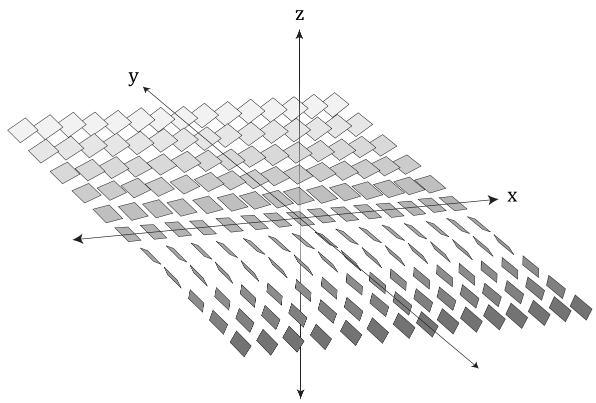

FIGURE 1. The standard contact structure ξ_{std} on $\mathbb{R}^3$. Reprinted from [28, Figure 1].

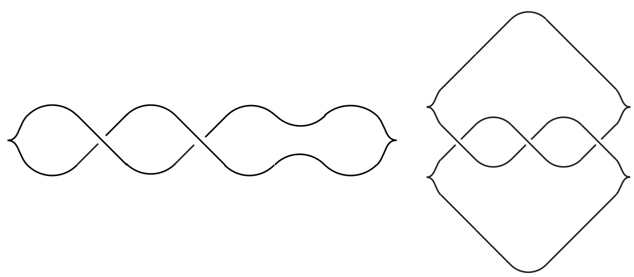

FIGURE 2. Unoriented front projections of a Legendrian unknot and a Legendrian trefoil. Adapted from [28, Figures 6 and 15].

2. Preliminaries

In this section, we discuss motivations and establish pertinent definitions for the study of GL-racks. In particular, we discuss the crossing and cusp relations afforded by Legendrian Reidemeister moves, which motivate the axioms of GL-racks. After stating some preliminary results, we discuss several functors relating to the category of GL-racks.

2.1. **Motivations: Legendrian knots and links.**

In this subsection, we discuss how the development of Legendrian link invariants in contact geometry motivates the study of GL-racks. (For an accessible introduction to Legendrian knot theory, we refer the reader to [36]. For a more detailed survey of the field, we refer the reader to [16].)

Definition 2.1. A *knot* is a smooth embedding of the circle S^1 into $\mathbb{R}^3$, and a *link* is a disjoint union of a finite number of knots. A link Λ is called *Legendrian* if it lies everywhere tangent to the *standard contact structure* $\xi_{\mathrm{std}} := \ker(dz - y\,dx)$ on $\mathbb{R}^3$, which is depicted in Figure 1. That is, $T_x\Lambda \in \xi_{\mathrm{std}}$ for all $x \in \Lambda$, where $T_x\Lambda$ denotes the tangent space of Λ at x. A *front projection* or *front diagram* $D(\Lambda)$ is the projection of Λ to the xz-plane. Finally, two Legendrian links are called *equivalent* or *Legendrian isotopic* if there exists a smooth homotopy between them that preserves the condition of being Legendrian at every stage.

When discussing Legendrian links alongside general links, we will call the latter *smooth links* or *topological links*. Also, we will denote the underlying smooth link of a Legendrian link Λ by L.

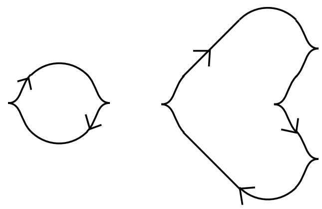

FIGURE 3. Front projections of distinct oriented Legendrian unknots.

Central to contact geometry is the question of how to distinguish Legendrian links up to Legendrian isotopy. To this end, knot theorists typically study Legendrian links Λ through their front projections, which follow several restrictions thanks to the tangency condition on Λ. For one, at every crossing in $D(\Lambda)$, the strand with the more negative slope is always the overstrand. For two, $D(\Lambda)$ has cusps in place of vertical tangencies. Note that the numbers of crossings and cusps in a Legendrian front projection are finite due to smoothness. Moreover, $D(\Lambda)$ can be viewed as a *link diagram* of L, denoted by $D(L)$, by "ignoring" all cusps. For example, Figure 2 depicts unoriented front projections of a Legendrian unknot and a Legendrian trefoil, and Figure 3 depicts oriented front projections of two distinct Legendrian unknots.

In fact, one can use the tangency condition to show that the geometric structure of an oriented Legendrian link can be recovered entirely from its front projection; see [16]. Indeed, many *invariants* of Legendrian links, which are constructed to be invariant under Legendrian isotopy, can be recovered from front projections. In particular, the *classical invariants* of a Legendrian link Λ, called the *Thurston-Bennequin number* and *rotation number* and denoted respectively by $\mathrm{tb}(\Lambda)$ and $\mathrm{rot}(\Lambda)$, can be defined as the integers

$$\mathrm{tb}(\Lambda) = P - N - \frac{1}{2}(D + U), \quad \mathrm{rot}(\Lambda) = \frac{1}{2}(D - U),$$

where P, N, D, and U are the numbers of positively oriented crossings, negatively oriented crossings, downward-oriented cusps, and upward-oriented cusps in $D(\Lambda)$, respectively. It is well-known that two Legendrian links are equivalent only if their classical invariants are equal. The main challenge in distinguishing between Legendrian links is that the converse only holds within certain topological link types, which are called *Legendrian simple*; see [16, Section 5]. For example, Theorem 1.2 shows that the topological knot type 8_{10} is not Legendrian simple.

A celebrated theorem of Świątkowski in 1992 offers a method of comparing Legendrian links using only their front projections.

Proposition 2.2. [38, Theorem B] *Two Legendrian links are Legendrian isotopic if and only if their front projections are related by a finite sequence of planar isotopies and the three* Legendrian Reidemeister moves *depicted in Figures 5–7.*

Example 2.3. Let Λ_1 and Λ_2 be the oriented Legendrian unknots depicted on the left and right of Figure 3, respectively. Although Λ_1 and Λ_2 share the same underlying smooth knot type, they are not Legendrian isotopic because $\mathrm{tb}(\Lambda_1) = -1 \neq -2 = \mathrm{tb}(\Lambda_2)$ and $\mathrm{rot}(\Lambda_1) = 0 \neq 1 = \mathrm{rot}(\Lambda_2)$. Proposition 2.2 asserts that the two front projections in Figure 3 cannot be related by any sequence of Legendrian Reidemeister moves.

There are in fact infinitely many examples of distinct Legendrian links having the same underlying smooth link type, making distinguishing between Legendrian links significantly more difficult than distinguishing between smooth links. This has motivated the development of numerous

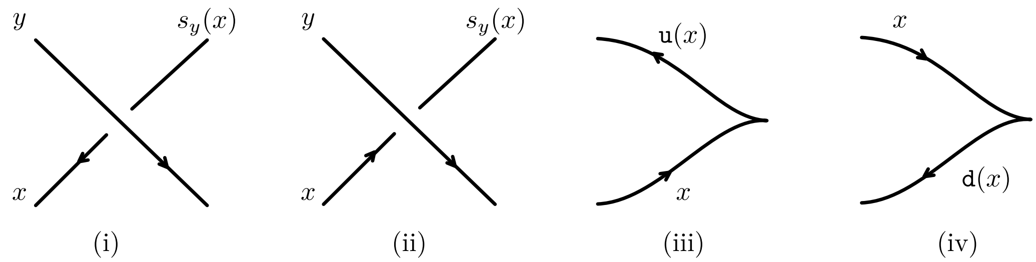

FIGURE 4. Crossing and cusp relations. Adapted from [24, Figure 4] under CC BY 4.0.

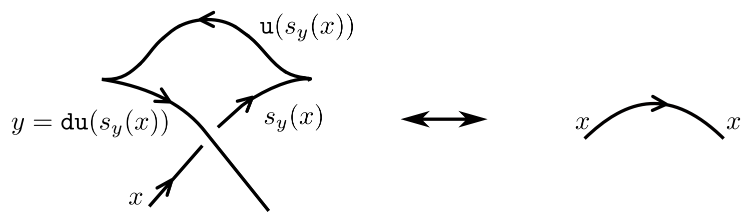

FIGURE 5. Crossing and cusp relations in one possible orientation of the first Legendrian Reidemeister move. Adapted from [24, Figure 5] under CC BY 4.0.

nonclassical invariants of Legendrian links, including the Chekanov-Eliashberg differential graded algebra and associated polynomial-valued invariants [16, 33], various (co)homology theories [18], and the mosaic number [28, 35]. GL-racks and quandles have also been used to define algebro-combinatorial and cohomological invariants of both Legendrian links and topological links. These include fundamental quandles and their Legendrian analogues [5, 22, 24], GL-rack and quandle coloring numbers [5, 24, 25], cocycle invariants [6, 26], and state-sum invariants [15, 23], many of which have elegant categorifications and enhancements (see, e.g., [4, 6, 7, 14]). These invariants motivate the study of GL-racks as a category.

In light of Proposition 2.2, the axioms of GL-racks are motivated by the *crossing* and *cusp relations* induced between strands of a Legendrian front projection modulo the relations afforded by the Legendrian Reidemeister moves. (Note that planar isotopies do not affect crossings or cusps, so they do not induce any such relations.) In Figure 4, (i) and (ii) depict crossing relations between strands in a Legendrian front projection, and (iii) and (iv) depict cusp relations. Note that $\mathtt{u}$ and $\mathtt{d}$ correspond to the relations induced by upward- and downward-oriented cusps, respectively. Figures 5–7 depict the crossing and cusp relations in one possible orientation of each of the three Legendrian Reidemeister moves. For a complete list of all possible orientations and their induced crossing and cusp relations, we refer the reader to [25, Figures 6–8].

In Subsection 3.1, we discuss how to assign a GL-rack to any oriented Legendrian link Λ using the cusp and crossing relations in $D(\Lambda)$. This assignment is independent of the choice of front projection of Λ, making it an invariant of Legendrian links [24, Theorem 4.3].

2.2. **GL-racks and quandles.** In this subsection, we define GL-racks and quandles abstractly by translating the crossing and cusp relations in Subsection 2.1 into the language of *rack symmetries*. Henceforth, we will denote the group of all bijections from a set X to itself by $\mathrm{Sym}(X)$.

Although racks and quandles are often defined as sets X endowed with binary operations $\triangleright, \triangleright^{-1} : X \times X \to X$, they may also be characterized in terms of symmetries $s_x \in \mathrm{Sym}(X)$ assigned to each element $x \in X$; cf. [12, Section 2; 22, Definition 1.1; 39, Definition 2.7]. One may translate

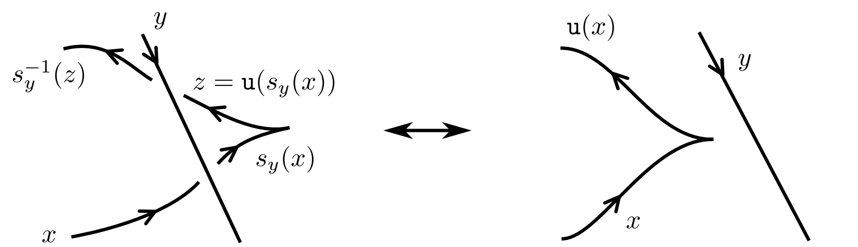

FIGURE 6. Crossing and cusp relations in one possible orientation of the second Legendrian Reidemeister move. Adapted from [24, Figure 6] under CC BY 4.0.

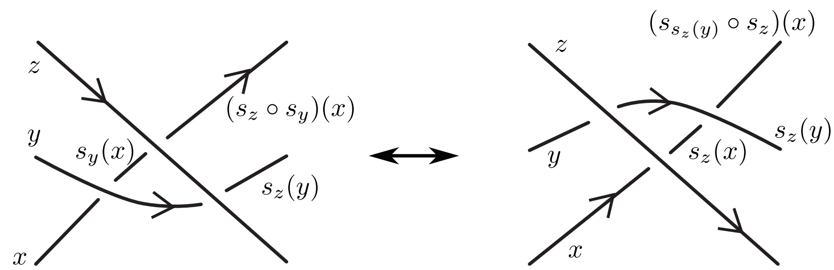

FIGURE 7. Crossing and cusp relations in one possible orientation of the third Legendrian Reidemeister move. Adapted from [24, Figure 3] under CC BY 4.0.

between the two conventions via the formulas $s_x(y) = y \triangleright x$ and $s_x^{-1}(y) = y \triangleright^{-1} x$. In this article, we adopt the definitions using symmetries due to their convenience for abstract proofs and exhaustive search algorithms; we have (re)written all crossing relations in Figures 4–7 in this notation. We refer the reader to [13, 32] for accessible introductions to quandle theory, [13, 34] for references on racks and quandles as they concern low-dimensional topology, and [11] for a survey of modern algebraic research on racks and quandles.

The rack and quandle axioms encapsulate the crossing relations depicted in Figures 5-7.

Definition 2.4. Let X be a set, and let $s : X \to \mathrm{Sym}(X)$ be a map defined by $x \mapsto s_x$. We call the pair (X, s) a *rack* or a *wrack* if, for all $x, y \in X$, we have $s_x \circ s_y = s_{s_x(y)} \circ s_x$. We say that s_x is the *symmetry at* x, and we say that $|X|$ is the *order* of (X, s). If in addition $s_x(x) = x$ for all $x \in X$, then we say that (X, s) is a *quandle*. Finally, if $Y \subset X$ and $s_y(z) \in Y$ for all $y, z \in Y$, then we say that $(Y, s|_Y)$ is a *subrack* of (X, s).

Example 2.5. [39, Definition 2.11] Let Ω be a union of conjugacy classes in a group G, and define $s : \Omega \to \mathrm{Sym}(\Omega)$ by $\alpha \mapsto s_\alpha := [\omega \mapsto \alpha\omega\alpha^{-1}]$. Then (Ω, s) is a quandle called a *conjugation quandle*, and we denote it by $\mathrm{Conj}(\Omega)$.

Example 2.6. [13, Example 99] Let X be a set, and fix $\sigma \in \mathrm{Sym}(X)$. Define $s : X \to \mathrm{Sym}(X)$ by $x \mapsto \sigma$, so that $s_x(y) = \sigma(y)$ for all $x, y \in X$. Then (X, s) is a rack called a *permutation rack* or *constant action rack*, and we denote it by $(X, \sigma)_p$.

In 2023, Karmakar et al. [23] and Kimura [25] independently introduced *GL-racks* to generalize the *Legendrian racks* introduced by Kulkarni and Prathamesh [29] in 2017 and refined by Ceniceros et al. [5] in 2021. The GL-rack axioms encode the crossing and cusp relations induced by the Legendrian Reidemeister moves in Figures 5-7. Once again, we translate the original definition into the language of rack symmetries.

Definition 2.7. [23, Definition 3.1] A *GL-rack*, also called a *generalized Legendrian rack* or a *bi-Legendrian rack*, is a quadruple $(X, s, \mathtt{u}, \mathtt{d})$ in which (X, s) is a rack, $\mathtt{u}, \mathtt{d} : X \to X$ are maps, and the following axioms hold for all $x \in X$:

(L1) $(\mathtt{ud} \circ s_x)(x) = x = (\mathtt{du} \circ s_x)(x)$.
(L2) $\mathtt{u} \circ s_x = s_x \circ \mathtt{u}$ and $\mathtt{d} \circ s_x = s_x \circ \mathtt{d}$.
(L3) $s_{\mathtt{u}(x)} = s_x = s_{\mathtt{d}(x)}$.

We call the ordered pair $(\mathtt{u}, \mathtt{d})$ a *GL-structure* on (X, s). If in addition (X, s) is a quandle, we say that $(X, s, \mathtt{u}, \mathtt{d})$ is a *GL-quandle*.

Example 2.8. [25, Example 3.6] Let G be a group, let $z \in Z(G)$, and define $f : G \to G$ by $g \mapsto zg$. Then $(\mathrm{Conj}(G), f, f^{-1})$ is a GL-quandle.

Example 2.9. [25, Example 3.7] Let $(X, \sigma)_p$ be a permutation rack, and let $\mathtt{u}, \mathtt{d} : X \to X$ be maps. Then $(\mathtt{u}, \mathtt{d})$ defines a GL-structure on $(X, \sigma)_p$ if and only if $\mathtt{ud} = \sigma^{-1} = \mathtt{du}$. In this case, we say that $((X, \sigma)_p, \mathtt{u}, \mathtt{d})$ is a *permutation GL-rack* or *constant action GL-rack*, and we denote it by $(X, \sigma, \mathtt{u}, \mathtt{d})_p$.

Example 2.10. [24, Example 3.4] Any GL-rack of the form $(X, s, \mathrm{id}_X, \mathrm{id}_X)$ is called a *trivial GL-rack*. In particular, any quandle (Q, s) can be identified with the trivial GL-rack $(Q, s, \mathrm{id}_Q, \mathrm{id}_Q)$; cf. Lemma 2.14. In other words, GL-racks generalize quandles.

We define homomorphisms of these algebraic structures as follows.

Definition 2.11. Let (X, s) and (Y, t) be racks. A map $\varphi : X \to Y$ is called a *rack homomorphism* if $\varphi \circ s_x = t_{\varphi(x)} \circ \varphi$ for all $x \in X$. If in addition $(\mathtt{u}_1, \mathtt{d}_2)$ and $(\mathtt{u}_2, \mathtt{d}_2)$ are GL-structures on (X, s) and (Y, t), we say that a φ is also a *GL-rack homomorphism* if $\varphi \circ \mathtt{u}_1 = \mathtt{u}_2 \circ \varphi$ and $\varphi \circ \mathtt{d}_1 = \mathtt{d}_2 \circ \varphi$. A *(GL-)rack isomorphism* is simply a bijective (GL-)rack homomorphism. If R is a GL-rack, we denote its group of GL-rack automorphisms by $\mathrm{Aut}_{\mathsf{GLR}}(R)$.

Evidently, we have the following; the final sentence is from [24, Proposition 3.2].

Proposition 2.12. *Let (X, s) be a rack with maps $\mathtt{u}, \mathtt{d} : X \to X$ satisfying axioms (L1) and (L3) of Definition 2.7. Then $R := (X, s, \mathtt{u}, \mathtt{d})$ is a GL-rack if and only if $\mathtt{u}$ and $\mathtt{d}$ are endomorphisms of the underlying rack (X, s). In this case, we actually have $\mathtt{u}, \mathtt{d} \in \mathrm{Aut}_{\mathsf{GLR}}(R)$.*

Axiom (L1) immediately yields the following.

Proposition 2.13. *Let $(X, s, \mathtt{u}, \mathtt{d})$ be a GL-rack. Then the underlying rack (X, s) is a quandle if and only if $\mathtt{ud} = \mathrm{id}_X = \mathtt{du}$, that is, $\mathtt{d} = \mathtt{u}^{-1}$ as GL-rack automorphisms.*

2.3. **Functors of interest in the literature.** In this subsection, we define several categories and functors appearing in the literature on GL-racks, quandles, and their relationships with groups.

We begin by defining several categories. Let Set and Grp be the categories of sets with functions and groups with group homomorphisms, respectively. Let Rack be the category of racks with rack homomorphisms, let Qnd be the full subcategory of Rack whose objects are quandles, and let GLR be the category of GL-racks with GL-rack homomorphisms.

By Example 2.10 and Proposition 2.13, we have the following.

Lemma 2.14. *The correspondence $(Q, s) \mapsto (Q, s, \mathrm{id}_Q, \mathrm{id}_Q)$ defines a canonical isomorphism from Qnd to the full subcategory of GLR whose objects are trivial GL-racks.*

In the sense of universal algebra, GLR is an equational algebraic category, so it is complete and cocomplete; see [1, Corollary 1.2, Theorem 4.5]. Thus, we can express GL-racks in terms of generators and relations using quotients of *free GL-racks*, which we define as follows.

Definition 2.15. [24, Section 4] Let X be a set. We define the *free GL-rack on X*, denoted by $\mathrm{FGLR}(X)$, as follows. If $X = \emptyset$, let $\mathrm{FGLR}(X)$ be the trivial GL-rack with one element. Else, define the *universe of words generated by* X to be the set $W(X)$ such that $X \subset W(X)$ and $s_y(x)$, $s_y^{-1}(x)$, $\mathtt{u}(x)$, $\mathtt{d}(x) \in W(X)$ for all $x, y \in W(X)$. Let $F(X)$ be the set of equivalence classes of elements of $W(X)$ modulo the equivalence relation generated by the following relations for all $x, y, z \in W(X)$:

(1) $s_y^{-1}(s_y(x))y \sim x \sim s_y(s_y^{-1}(x))$.
(2) $s_z(s_y(x)) \sim s_{s_z(y)}(s_z(x))$.
(3) $\mathtt{u}(\mathtt{d}(s_x(x))) \sim x \sim \mathtt{d}(\mathtt{u}(s_x(x)))$.
(4) $\mathtt{u}(s_y(x)) \sim s_y(\mathtt{u}(x))$ and $\mathtt{d}(s_y(x)) \sim s_y(\mathtt{d}(x))$.
(5) $s_{\mathtt{u}(y)}(x) \sim s_y(x)$ and $s_{\mathtt{d}(y)}(x) \sim s_y(x)$.

Thus, we have maps $s : F(X) \to \mathrm{Sym}(F(X))$ defined by $x \mapsto s_x := [y \mapsto s_x(y)]$ and $\mathtt{u}, \mathtt{d} : F(X) \to F(X)$ defined by $x \mapsto \mathtt{u}(x)$ and $x \mapsto \mathtt{d}(x)$. We define $\mathrm{FGLR}(X)$ to be the GL-rack $(F(X), s, \mathtt{u}, \mathtt{d})$. The *free quandle on* X is defined similarly; in the sense of Lemma 2.14, it is simply $\mathrm{FGLR}(X)$ modulo the relations $\mathtt{u}(x) \sim x \sim \mathtt{d}(x)$ for all $x \in W(X)$.

To rephrase [24, Proposition 4.2], the forgetful functor $\mathsf{GLR} \to \mathsf{Set}$ has a left adjoint defined by $X \mapsto \mathrm{FGLR}(X)$, as one might expect.

Another functor of interest in Subection 3.3 assigns an *enveloping group* to each GL-rack. By [23, Proposition 8.4], it has a right adjoint that results from taking $\Omega = G$ in Example 2.5.

Definition 2.16. [23, Section 8] Given a GL-rack $R = (X, s, \mathtt{u}, \mathtt{d})$, its *enveloping group* is

$$\mathrm{Env}_{\mathsf{GLR}}(R) := \langle e_x,\ x \in X \mid e_{s_x(y)} = e_x^{-1} e_y e_x,\ e_{\mathtt{u}(x)} = e_x,\ e_{\mathtt{d}(x)} = e_x,\ x, y \in X \rangle.$$

By taking $\mathtt{u} = \mathrm{id}_X = \mathtt{d}$, we can also define the enveloping group of a quandle (Q, s) to be

$$\mathrm{Env}_{\mathsf{Qnd}}(Q, s) := \langle e_x,\ x \in Q \mid e_{s_x(y)} = e_x^{-1} e_y e_x,\ x, y \in Q \rangle.$$

Proposition 2.17. [23, Proposition 8.4] *There exists a functor* $\mathrm{Env}_{\mathsf{GLR}} : \mathsf{GLR} \to \mathsf{Grp}$ *that sends a GL-rack to its enveloping group and sends any GL-rack homomorphism* $\psi : (X, s, \mathtt{u}_1, \mathtt{d}_1) \to (Y, t, \mathtt{u}_2, \mathtt{d}_2)$ *to the group homomorphism* $\widetilde{\psi} : \mathrm{Env}_{\mathsf{GLR}}(X, s, \mathtt{u}_1, \mathtt{d}_1) \to \mathrm{Env}_{\mathsf{GLR}}(Y, t, \mathtt{u}_2, \mathtt{d}_2)$ *defined by* $e_x \mapsto e_{\psi(x)}$ *for all* $x \in X$. *Also,* $\mathrm{Env}_{\mathsf{GLR}}$ *is left adjoint to a functor sending a group G to the GL-rack* $(\mathrm{Conj}(G), \mathrm{id}_G, \mathrm{id}_G)$*, which is isomorphic to* $\mathrm{Conj}(G)$ *in the sense of Lemma 2.14.*

Thus, some authors denote the enveloping group of a GL-rack or quandle R by $\mathrm{Adconj}(R)$ or $\mathrm{As}(R)$ and call it the *associated group of* R; see, e.g., [22, Section 6; 34, Definition 2.19]. For an example of how to compute the enveloping group of a GL-rack, see Example 3.6 in Subsection 3.2.

3. On rack-theoretic invariants of Legendrian links

In this section, we begin by defining the GL-rack of an oriented Legendrian link Λ and the fundamental quandle of its underlying smooth link L, both of which are invariant under Legendrian isotopy. After a few worked examples, we give short algebraic proofs of several conjectures relating to Legendrian links and their invariants.

3.1. The GL-rack of a Legendrian link.

In this subsection, we discuss how to assign a GL-rack to a Legendrian link in a way invariant under Legendrian isotopy. We begin with several definitions.

Definition 3.1. Given a front projection $D(\Lambda)$ of an oriented Legendrian link Λ, define a *cusped strand* of $D(\Lambda)$ to be a maximal (with respect to inclusion) connected segment in $D(\Lambda)$. Also, define an *uncusped strand* of $D(\Lambda)$ to be a maximal (with respect to inclusion) connected subset of a cusped strand of $D(\Lambda)$ that both starts and ends at either a crossing or a cusp.

Definition 3.2. [24, Section 4] Let Λ be an oriented Legendrian link with front projection $D(\Lambda)$, and let X_Λ be a set in bijection with the cusped strands of $D(\Lambda)$. At each cusp, label the neighboring uncusped strands using the cusp relations in Figure 4. Then, at each crossing, impose the corresponding crossing relation between uncusped strands in Figure 4 on $\mathrm{FGLR}(X_\Lambda)$. The *GL-rack of* Λ, denoted by $\mathcal{G}(\Lambda)$, is defined to be the set of equivalence classes of elements of $\mathrm{FGLR}(X_\Lambda)$ modulo the equivalence relation generated by these relations. If L is a smooth link with link diagram $D(L)$, then we define the *fundamental quandle of* L, denoted by $\mathcal{Q}(L)$, in a similar way. However, we use the free quandle on X_Λ in place of $\mathrm{FGLR}(X_\Lambda)$, and we forgo any cusp relations.

While Karmakar et al. in [24] define X_Λ using uncusped strands, the cusp relations make these two definitions equivalent. For examples of how to compute $\mathcal{G}(\Lambda)$ given $D(\Lambda)$, see Subsection 3.2.

The assignment of $\mathcal{G}(\Lambda)$ to Λ (resp. $\mathcal{Q}(L)$ to L) is independent of the choice of front projection $D(\Lambda)$ (resp. link diagram $D(L)$), as captured in the following result of Karmakar et al.

Proposition 3.3. [24, Theorem 4.3] *If two oriented Legendrian front projections are related by a finite sequence of Legendrian Reidemeister moves, then their induced GL-racks are isomorphic. Hence, the GL-rack of a Legendrian link is invariant under Legendrian isotopy.*

This is a consequence of Proposition 2.2 and the fact that the GL-rack axioms capture the crossing and cusp relations induced by the Legendrian Reidemeister moves. In turn, Proposition 3.3 implies that the *GL-rack coloring number* of Λ with respect to a fixed GL-rack, as defined below, is invariant under Legendrian isotopy; see, e.g., [5, 24, 25].

Definition 3.4. Let R be a GL-rack. The *R-coloring number* of an oriented Legendrian link Λ, denoted by $\mathrm{Col}(\Lambda, R)$, is defined to be the cardinality of the hom-set $\mathrm{Hom}_{\mathsf{GLR}}(\mathcal{G}(\Lambda), R)$.

Kulkarni and Prathamesh in [29, Main Theorem 2], Kimura in [25, Theorem 4.1], and Karmakar et al. in [24, Theorem 4.6] each used R-coloring numbers to distinguish between infinitely many Legendrian unknots. Karmakar et al. also used R-coloring numbers to distinguish between infinitely many Legendrian trefoils in [24, Theorem 4.7], and Ceniceros et al. in [5, Example 16] used them to distinguish between connected sums of Legendrian trefoils. That said, there also exist distinct Legendrian knots having GL-racks; see [26, Subsection 4.2], so neither $\mathcal{G}(\Lambda)$ nor R-coloring numbers are complete Legendrian knot invariants. Nevertheless, we will use the latter in Subsection 3.2 to distinguish between unstabilized Legendrian representatives of knot types 6_2 and 8_{10}, which cannot be done using the graded ruling invariant or linearized contact homology.

Given Λ, note that imposing the equivalence relation $\mathtt{u}(x) \sim x \sim \mathtt{d}(x)$ for all $x \in X_\Lambda$ onto $\mathcal{G}(\Lambda)$ yields a quandle in the sense of Lemma 2.14. Geometrically, this amounts to "ignoring" all cusps in $D(\Lambda)$ and viewing $D(\Lambda)$ only as a diagram of the underlying smooth link L. This recovers $\mathcal{Q}(L)$ from $\mathcal{G}(\Lambda)$, yielding the following observation.

Lemma 3.5. [26, Remark 23] *Let Λ be an oriented Legendrian link, and let L be its underlying smooth link. After imposing an equivalence relation onto $\mathcal{G}(\Lambda)$ defined by $\mathtt{u}(x) \sim x \sim \mathtt{d}(x)$ for all $x \in X_\Lambda$, the resulting GL-rack is canonically isomorphic to $\mathcal{Q}(L)$ in the sense of Lemma 2.14.*

3.2. **Example calculations and applications.** In this section, we give several examples of how to compute the GL-rack of an oriented Legendrian knot. This allows us to give relatively brief algebraic proofs of conjectures in [8] and [3] about Legendrian 6_2 and 8_{10} knots, respectively.

Example 3.6. Let $q \geq 3$ be an odd integer, let L be a $(2, -q)$-torus knot, and let Λ be the Legendrian representative of L having maximal Thurston-Bennequin and rotation numbers. (By [17, Theorem 4.3], Λ is the unique such Legendrian representative up to Legendrian isotopy.) In this example, we compute $\mathcal{G}(\Lambda)$, $\mathcal{Q}(L)$, $\mathrm{Env}_{\mathsf{GLR}}(\mathcal{G}(\Lambda))$, and $\mathrm{Env}_{\mathsf{Qnd}}(\mathcal{Q}(L))$ using the front projection

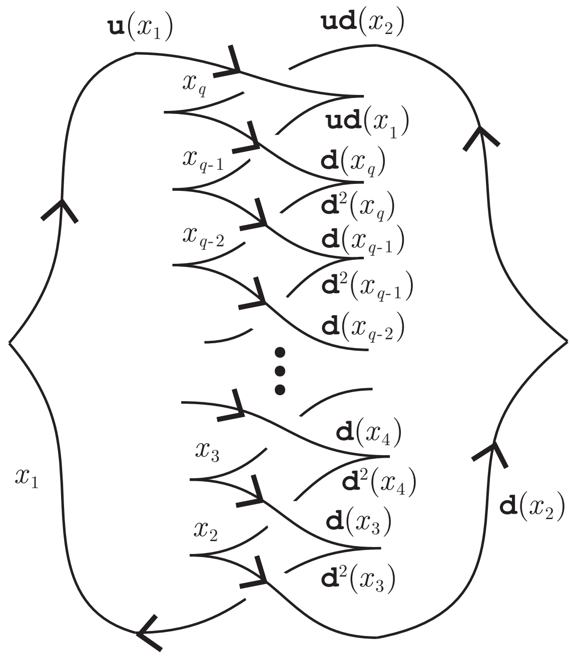

FIGURE 8. Front projection $D(\Lambda)$ and induced cusp relations of the Legendrian $(2,-q)$-torus knot Λ with maximal classical invariants.

$D(\Lambda)$ in Figure 8. Starting at any crossing (which, in Figure 8, we arbitrarily choose to be the bottommost crossing), traverse $D(\Lambda)$ along its depicted orientation. By recording the induced cusp and crossing relations using Figure 4, we compute that $\mathcal{G}(\Lambda)$ is the free GL-rack on the set $X_\Lambda = \{x_1, \dots, x_q\}$ modulo the crossing relations

$$s_{\mathtt{u}(x_1)}(x_q) = \mathtt{ud}(x_2),\ s_{\mathtt{d}(x_q)}(x_{q-1}) = \mathtt{ud}(x_1),\ \text{and } s_{\mathtt{d}(x_{i-1})}(x_{i-2}) = \mathtt{d}^2(x_i) \text{ for all } 3 \le i \le q.$$

Using GL-rack axiom (L3), we can simplify these crossing relations to

$$s_{x_1}(x_q) = \mathtt{ud}(x_2),\ s_{x_q}(x_{q-1}) = \mathtt{ud}(x_1),\ \text{and } s_{x_{i-1}}(x_{i-2}) = \mathtt{d}^2(x_i) \text{ for all } 3 \le i \le q.$$

Now that we have a presentation of $\mathcal{G}(\Lambda)$, let us compute $\mathcal{Q}(L)$. To do this, we could traverse $D(\Lambda)$ again while ignoring all cusps and only considering crossing relations. In view of Lemma 3.5, we could equivalently impose the relations $\mathtt{u}(x_i) = x_i = \mathtt{d}(x_i)$ for all $1 \le i \le q$ onto $\mathcal{G}(\Lambda)$. Either method shows that $\mathcal{Q}(L)$ is the free quandle on X_Λ modulo the crossing relations

$$s_{x_1}(x_q) = x_2,\ s_{x_q}(x_{q-1}) = x_1,\ \text{and } s_{x_{i-1}}(x_{i-2}) = x_i \text{ for all } 3 \le i \le q.$$

Indeed, if we invert each symmetry in the relations of $\mathcal{Q}(L)$, then we recover the fundamental quandle of the mirror image of L computed in [2, Remark 3], as predicted by [40, Section 1].

If $q = 3$, then L is a left-handed trefoil, and the crossing relations show that $\mathrm{Env}_{\mathsf{GLR}}(\mathcal{G}(\Lambda))$ and $\mathrm{Env}_{\mathsf{Qnd}}(\mathcal{Q}(L))$ are both isomorphic to the group

$$\begin{aligned}&\langle e_{x_1}, e_{x_2}, e_{x_3} \mid e_{s_{x_1}(x_3)} = e_{x_1}^{-1} e_{x_3} e_{x_1},\ e_{s_{x_2}(x_1)} = e_{x_2}^{-1} e_{x_1} e_{x_2},\ e_{s_{x_3}(x_2)} = e_{x_3}^{-1} e_{x_2} e_{x_3} \rangle \\ &= \langle e_{x_1}, e_{x_2}, e_{x_3} \mid e_{x_1} e_{x_2} = e_{x_3} e_{x_1},\ e_{x_2} e_{x_3} = e_{x_1} e_{x_2},\ e_{x_3} e_{x_1} = e_{x_2} e_{x_3} \rangle.\end{aligned}$$

Note that this is precisely the Wirtinger presentation of the knot group $\pi_1(\mathbb{R}^3 \setminus L) \cong \langle x, y \mid x^2 = y^3 \rangle$ of the trefoil; see [37, Subsection 4.2.5]. Subsection 3.3 will generalize this observation.

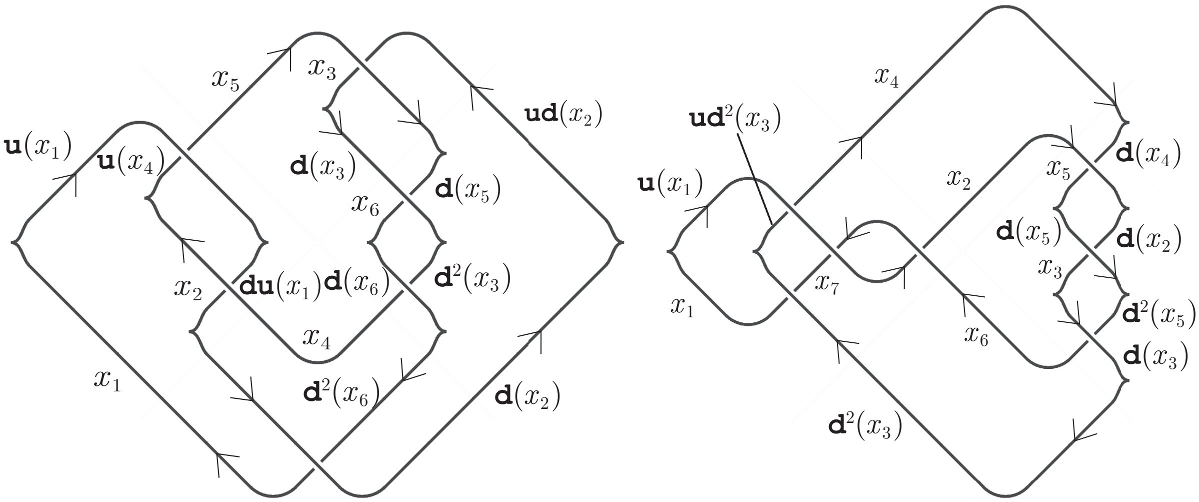

FIGURE 9. Front projections of the two Legendrian representatives of the topological knot 6_2 with $(\mathrm{tb}, \mathrm{rot}) = (-7, 2)$ given in [8]. Created using [27]; cf. [28].

Example 3.7. Let Λ_1 and Λ_2 be the oriented Legendrian knots on the left and right of Figure 9, respectively. In this example, we compute $\mathcal{G}(\Lambda_1)$ and $\mathcal{G}(\Lambda_2)$ in preparation for a proof that Λ_1 and Λ_2 are not Legendrian isotopic. We note from [8] that Λ_1 and Λ_2 are both Legendrian representatives of the topological knot 6_2 that satisfy $(\mathrm{tb}, \mathrm{rot}) = (-7, 2)$.

Let us begin with Λ_1. Traverse $D(\Lambda_1)$ using its given orientation while labeling all uncusped strands as in Figure 4. By writing down the induced crossing relations as in Figure 4, we find that $\mathcal{G}(\Lambda_1)$ is the free GL-rack on the set $X_{\Lambda_1} = \{x_1, \dots, x_6\}$ modulo the following crossing relations:

$$\mathcal{G}(\Lambda_1) \begin{cases} s_{\mathtt{u}(x_1)}(\mathtt{u}(x_4)) = x_5 \iff s_{x_1}(\mathtt{u}(x_4)) = x_5, \\ s_{x_4}(\mathtt{du}(x_1)) = x_2, \\ s_{\mathtt{d}(x_2)}(x_1) = \mathtt{d}^2(x_6) \iff s_{x_2}(x_1) = \mathtt{d}^2(x_6), \\ s_{x_5}(x_3) = \mathtt{ud}(x_2), \\ s_{\mathtt{d}(x_3)}(x_6) = \mathtt{d}(x_5) \iff s_{x_3}(x_6) = \mathtt{d}(x_5), \\ s_{\mathtt{d}(x_6)}(x_4) = \mathtt{d}^2(x_3) \iff s_{x_6}(x_4) = \mathtt{d}^2(x_3). \end{cases} \tag{1}$$

Note that we have simplified the first, third, fifth, and sixth relations using GL-rack axiom (L3).

Similarly, we compute $\mathcal{G}(\Lambda_2)$ to be the free GL-rack on the set $X_{\Lambda_2} = \{x_1, \dots, x_7\}$ modulo the following crossing relations:

$$\mathcal{G}(\Lambda_2) \begin{cases} s_{x_1}(\mathtt{ud}^2(x_3)) = x_4, & s_{x_5}(x_3) = \mathtt{d}(x_2), \\ s_{x_1}(x_6) = x_7, & s_{x_3}(x_6) = \mathtt{d}^2(x_5), \\ s_{x_6}(x_2) = \mathtt{u}(x_1), & s_{x_3}(x_7) = x_1, \\ s_{x_2}(x_5) = \mathtt{d}(x_4). \end{cases} \tag{2}$$

We can use these calculations to prove a conjecture of Chongchitmate and Ng in [8] that Λ_1 and Λ_2 in the previous example are not Legendrian isotopic. In 2021, Dynnikov and Prasolov [10, Proposition 2.3] proved this conjecture using impressive topological and combinatorial machinery. At the time of writing, theirs is the only proof of which we are aware. Indeed, Λ_1 and Λ_2 share the same classical invariants and cannot be distinguished using the graded ruling invariant or linearized contact homology; see [8]. However, R-coloring numbers offer a simpler algebraic alternative. In the following, we denote the symmetric group on n letters by S_n.

Theorem 3.8. *The two oriented Legendrian knots in Figure 9 are not Legendrian isotopic; in fact, they are distinguishable using coloring numbers with respect to a permutation GL-rack of order 3.*

Proof. As before, let Λ_1 and Λ_2 be the oriented Legendrian knots on the left and right of Figure 9, respectively. Let $Y := \{1,2,3\}$. In cycle notation, let $\sigma \in S_3$ be the permutation (123). In the notation of Example 2.9, let $R := (Y, \sigma, \sigma^{-1}, \mathrm{id}_Y)_p$, so that R is the 11th GL-rack in Table 3. We will show that $\mathrm{Col}(\Lambda_2, R) > \mathrm{Col}(\Lambda_1, R)$. To that end, let A denote the underlying set of $\mathcal{G}(\Lambda_2)$ as presented in Example 3.7, and define $\varphi_1, \varphi_2, \varphi_3 : A \to Y$ by the following:

$$\varphi_1(x_i) := \begin{cases} 1 & \text{if } i \in \{1,3,4\}, \\ 2 & \text{if } i \in \{2,6\}, \\ 3 & \text{if } i \in \{5,7\}. \end{cases} \quad \varphi_2(x_i) := \begin{cases} 2 & \text{if } i \in \{1,3,4\}, \\ 3 & \text{if } i \in \{2,6\}, \\ 1 & \text{if } i \in \{5,7\}. \end{cases} \quad \varphi_3(x_i) := \begin{cases} 3 & \text{if } i \in \{1,3,4\}, \\ 1 & \text{if } i \in \{2,6\}, \\ 2 & \text{if } i \in \{5,7\}. \end{cases}$$

Using the relations in (2), it is straightforward to verify that φ_1, φ_2, and φ_3 define GL-rack homomorphisms from $\mathcal{G}(\Lambda_2)$ to R. Hence, $\mathrm{Col}(\Lambda_2, R) \geq 3$. (In fact, using a similar method as in the remainder of this proof, one can show that this bound is actually an equality.)

On the other hand, we claim that $\mathrm{Hom}_{\mathsf{GLR}}(\mathcal{G}(\Lambda_1), R) = \emptyset$. Let B denote the underlying set of $\mathcal{G}(\Lambda_1)$ as presented in Example 3.7, and suppose to the contrary that some map $\varphi : B \to Y$ defines a GL-rack homomorphism from $\mathcal{G}(\Lambda_1)$ to R with $\varphi(x_i) = y_i$. Since φ is a GL-rack homomorphism, the relations in (1) must hold when we replace each x_i with y_i, each s_{x_i} with σ, each $\mathtt{u}$ with σ^{-1}, and each $\mathtt{d}$ with id_Y. These substitutions yield the following system of equations in R:

$$R \begin{cases} (\sigma \circ \sigma^{-1})(y_4) = y_5 \iff y_4 = y_5, \\ (\sigma \circ \sigma^{-1})(y_1) = y_2 \iff y_1 = y_2, \\ \sigma(y_1) = y_6, \\ \sigma(y_3) = \sigma^{-1}(y_2) \iff y_3 = \sigma(y_2), \\ \sigma(y_6) = y_5, \\ \sigma(y_4) = y_3. \end{cases} \tag{3}$$

Here, we have used the fact that $\sigma^3 = \mathrm{id}_Y$ to rewrite the fourth equality. We now deduce that

$$\sigma(y_2) = y_3 = \sigma(y_4) = \sigma(y_5) = \sigma^2(y_6) = \sigma^3(y_1) = y_1 = y_2.$$

However, σ has no fixed points in Y, so the system of equations in (3) has no solutions in R. Hence, φ cannot exist. □

Incidentally, Theorem 3.8 gives a positive answer to a question posed by Kimura in [25, Section 4], as we state below; cf. [25, Theorem 4.3].

Corollary 3.9. *If R is a nonquandle GL-rack, then it is not true in general that R-coloring numbers cannot distinguish between nonequivalent Legendrian knots having the same underlying smooth knot type and classical invariants.*

Similarly, R-coloring numbers distinguish between the Legendrian representatives of the topological knot 8_{10} with $(\mathrm{tb}, \mathrm{rot}) = (-8, 3)$ in Figure 10. This proves a conjecture of Bhattacharyya et al. in [3]. At the time of writing, we are unaware of any other proofs of this conjecture.

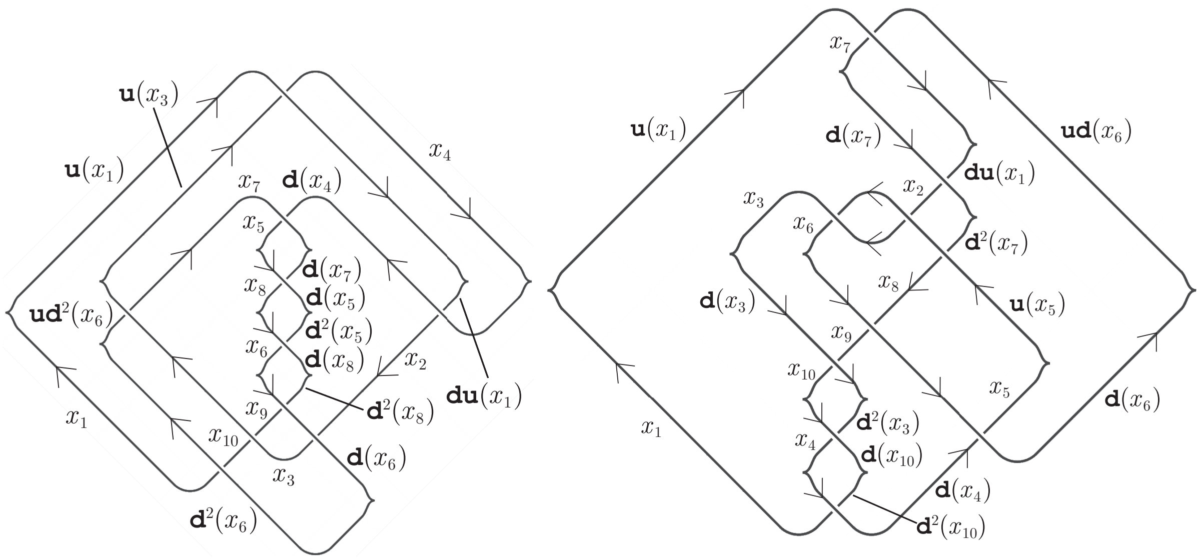

FIGURE 10. Front projections of the two Legendrian representatives of the topological knot 8_{10} with $(\mathrm{tb}, \mathrm{rot}) = (-8, 3)$ given in [3]. Created using [27]; cf. [28].

Example 3.10. Let Λ_1 and Λ_2 be the oriented Legendrian knots on the left and right of Figure 10, respectively. We compute that $\mathcal{G}(\Lambda_1)$ and $\mathcal{G}(\Lambda_2)$ are the free GL-racks on the set $\{x_1, \dots, x_{10}\}$ modulo the following crossing relations:

$$\mathcal{G}(\Lambda_1)\begin{cases} s_{x_1}(\mathtt{u}(x_3)) = x_4, & s_{x_4}(\mathtt{du}(x_1)) = x_2,\\ s_{x_7}(x_5) = \mathtt{d}(x_4), & s_{x_5}(x_8) = \mathtt{d}(x_7),\\ s_{x_8}(x_6) = \mathtt{d}^2(x_5), & s_{x_6}(x_9) = \mathtt{d}(x_6),\\ s_{x_6}(x_3) = x_2, & s_{x_6}(x_{10}) = x_1,\\ s_{x_3}(x_7) = \mathtt{ud}^2(x_6), & s_{x_3}(x_9) = x_{10}. \end{cases} \quad \mathcal{G}(\Lambda_2)\begin{cases} s_{x_1}(x_7) = \mathtt{ud}(x_6), & s_{x_7}(x_2) = \mathtt{du}(x_1),\\ s_{x_5}(x_2) = x_3, & s_{x_3}(\mathtt{u}(x_5)) = x_6,\\ s_{x_3}(x_{10}) = x_9, & s_{x_{10}}(x_4) = \mathtt{d}^2(x_3),\\ s_4(x_1) = \mathtt{d}^2(x_{10}), & s_{x_6}(\mathtt{d}(x_4)) = x_5,\\ s_{x_5}(\mathtt{d}^2(x_7)) = x_8, & s_{x_6}(x_9) = x_8. \end{cases}$$

Theorem 3.11. *The two oriented Legendrian knots in Figure 10 are not Legendrian isotopic; they are distinguishable using coloring numbers with respect to a permutation GL-rack of order 2.*

Proof. Once again, let Λ_1 and Λ_2 be the oriented Legendrian knots on the left and right of Figure 10, respectively. Let $Y := \{1, 2\}$. In cycle notation, let $\sigma \in S_2$ be the permutation (12). In the notation of Example 2.9, let $R := (Y, \sigma, \sigma, \mathrm{id}_Y)_p$, so that R is the fourth GL-rack in Table 2. We will show that $\mathrm{Col}(\Lambda_1, R) > \mathrm{Col}(\Lambda_2, R)$. To that end, let A denote the underlying set of $\mathcal{G}(\Lambda_1)$ as presented in Example 3.10, and define $\varphi_1, \varphi_2 : A \to Y$ by the following:

$$\varphi_1(x_i) := \begin{cases} 1 & \text{if } i \in \{1, 2, 5, 8, 9\},\\ 2 & \text{if } i \in \{3, 4, 6, 7, 10\}. \end{cases} \quad \varphi_2(x_i) := \begin{cases} 2 & \text{if } i \in \{1, 2, 5, 8, 9\},\\ 1 & \text{if } i \in \{3, 4, 6, 7, 10\}. \end{cases}$$

Using the relations of $\mathcal{G}(\Lambda_1)$ in Example 3.10, it is straightforward to verify that φ_1 and φ_2 define GL-rack homomorphisms from $\mathcal{G}(\Lambda_1)$ to R. Hence, $\mathrm{Col}(\Lambda_1, R) \geq 2$ (which is actually an equality).

On the other hand, we claim that $\mathrm{Hom}_{\mathsf{GLR}}(\mathcal{G}(\Lambda_2), R) = \emptyset$. Let B denote the underlying set of $\mathcal{G}(\Lambda_2)$ as presented in Example 3.10, and suppose to the contrary that some map $\varphi : B \to Y$ defines a GL-rack homomorphism from $\mathcal{G}(\Lambda_2)$ to R with $\varphi(x_i) = y_i$. Just like before, the relations of $\mathcal{G}(\Lambda_2)$ in Example 3.10 yield the following system of equations in R:

$$R \begin{cases} \sigma(y_7) = \sigma(y_6), & \sigma(y_2) = \sigma(x_1), \\ \sigma(y_2) = y_3, & \sigma^2(y_5) = y_6, \\ \sigma(y_{10}) = y_9, & \sigma(y_4) = y_3, \\ \sigma(y_1) = y_{10}, & \sigma(y_4) = y_5, \\ \sigma(y_7) = y_8, & \sigma(y_9) = y_8. \end{cases}$$

Since $\sigma^2 = \mathrm{id}_Y$, we can also rewrite the equalities $\sigma(y_7) = \sigma(x_6)$, $\sigma^2(y_5) = y_6$, and $\sigma(y_{10}) = y_9$ as $y_7 = y_6$, $y_5 = y_6$, and $y_{10} = \sigma(y_9)$, respectively. Therefore, we have

$$y_7 = y_6 = y_5 = \sigma(y_4) = y_3 = \sigma(y_2) = \sigma(y_1) = y_{10} = \sigma(y_9) = y_8 = \sigma(y_7),$$

which is impossible since σ has no fixed points in Y. Hence, φ cannot exist. $\square$

We selected the constant GL-racks and coloring maps used to prove Theorems 3.8 and 3.11 using exhaustive computer searches in `GAP` [19]. See Subsection A.3 for details. To help complete the atlas of Legendrian knots, we encourage the reader to the download the program linked in Appendix A and tackle even more of the conjectures in [8] and [3] in this fashion.

3.3. **Isomorphism of $\mathrm{Env}_{\mathsf{GLR}}(\mathcal{G}(\Lambda))$ and $\pi_1(\mathbb{R}^3 \setminus L)$.** We now prove an empirical observation of Karmakar et al. in the original version of [23, Remark 8.2], which we state as Theorem 3.13. Although the authors have removed this remark from subsequent releases of the article, we are unaware of any other proofs at the time of writing. To allow for a short categorical proof, we begin with a more abstract lemma.

Lemma 3.12. *Let $R = (X, s, \mathtt{u}, \mathtt{d})$ be a GL-rack, and let $R' = (X/\sim, s^*, \mathrm{id}_{X/\sim}, \mathrm{id}_{X/\sim})$ be the GL-rack obtained by imposing an equivalence relation $\sim$ onto R defined by $\mathtt{u}(x) = x = \mathtt{d}(x)$ for all $x \in X$. Then $\mathrm{Env}_{\mathsf{GLR}}(R)$ and $\mathrm{Env}_{\mathsf{GLR}}(R')$ are isomorphic as groups. In particular, $\mathrm{Env}_{\mathsf{GLR}}(R)$ and $\mathrm{Env}_{\mathsf{Qnd}}(X/\sim, s^*)$ are isomorphic as groups.*

Proof. By definition, R' is the quotient object of the equivalence relation $\sim$ on R in GLR. In other words, R' is the colimit of the following diagram in GLR:

$$R \underset{\mathrm{id}_X}{\overset{\mathtt{u}}{\rightrightarrows}} R \underset{\mathrm{id}_X}{\overset{\mathtt{d}}{\rightrightarrows}} R$$

Recall that left adjoint functors preserve colimits. It follows from Proposition 2.17 that $\mathrm{Env}_{\mathsf{GLR}}(R')$ is the colimit of the following diagram in Grp:

$$\mathrm{Env}_{\mathsf{GLR}}(R) \underset{\mathrm{Env}_{\mathsf{GLR}}(\mathrm{id}_X)}{\overset{\mathrm{Env}_{\mathsf{GLR}}(\mathtt{u})}{\rightrightarrows}} \mathrm{Env}_{\mathsf{GLR}}(R) \underset{\mathrm{Env}_{\mathsf{GLR}}(\mathrm{id}_X)}{\overset{\mathrm{Env}_{\mathsf{GLR}}(\mathtt{d})}{\rightrightarrows}} \mathrm{Env}_{\mathsf{GLR}}(R)$$

By Proposition 2.17, the group homomorphism $\mathrm{Env}_{\mathsf{GLR}}(\mathtt{u})$ is defined by $e_x \mapsto e_{\mathtt{u}(x)}$ for all $x \in X$, but $e_x = e_{\mathtt{u}(x)}$ in $\mathrm{Env}_{\mathsf{GLR}}(R)$. Thus, $\mathrm{Env}_{\mathsf{GLR}}(\mathtt{u})$ is the identity map. Similarly, $\mathrm{Env}_{\mathsf{GLR}}(\mathtt{d})$ and $\mathrm{Env}_{\mathsf{GLR}}(\mathrm{id}_X)$ are the identity maps, so we have a group isomorphism

$$\mathrm{Env}_{\mathsf{GLR}}(R) \cong \mathrm{Env}_{\mathsf{GLR}}(R').$$

By Lemma 2.14, the right-hand side is isomorphic to $\mathrm{Env}_{\mathsf{Qnd}}(X/\sim, s^*)$, so we are done. $\square$

Theorem 3.13. *Let $\Lambda \subset \mathbb{R}^3$ be an oriented Legendrian link, and let L denote its underlying smooth link. Then there exists a group isomorphism*

$$\mathrm{Env}_{\mathsf{GLR}}(\mathcal{G}(\Lambda)) \cong \pi_1(\mathbb{R}^3 \setminus L).$$

Proof. In the setting of Lemma 3.12, take $R := \mathcal{G}(\Lambda)$. Then, in GLR, we have $R' \cong (\mathcal{Q}(L), \mathrm{id}_{X_L}, \mathrm{id}_{X_L})$ by Lemma 3.5. By Lemma 3.12, it suffices to show that $\mathrm{Env}_{\mathsf{Qnd}}(\mathcal{Q}(L)) \cong \pi_1(\mathbb{R}^3 \setminus L)$ in Grp. Indeed, Joyce showed this in [22, Section 15] using the Wirtinger presentation of $\pi_1(\mathbb{R}^3 \setminus L)$. $\square$

4. On medial GL-racks, hom-sets, and tensor products

In this section, we define medial GL-racks, propose a medial GL-rack-valued invariant of Legendrian links with questions for future research, and introduce tensor products of GL-racks that make the category of medial GL-racks symmetric monoidal closed. This generalizes Crans and Nelson's similar results for the category of medial quandles in [9]; we follow their approach closely.

4.1. **Hom-sets of medial GL-racks are also medial GL-racks.**

In this subsection, we define medial GL-racks, introduce a medial GL-rack structure on any hom-set from a GL-rack to a medial GL-rack, and propose a medial GL-rack-valued invariant of Legendrian links.

Definition 4.1. A rack (X, s) is called *medial* or *abelian* if, for all $x, y, z \in X$, we have

$$s_{s_x(z)} \circ s_y = s_{s_x(y)} \circ s_z.$$

If in addition $(\mathtt{u}, \mathtt{d})$ defines a GL-structure on (X, s), then we call $(X, s, \mathtt{u}, \mathtt{d})$ a *medial* or *abelian* GL-rack. (Note that this definition is not synonymous with the condition that (X, s) is *commutative*, which states that $s_x(y) = s_y(x)$ for all $x, y \in X$.)

Since R-coloring numbers are not complete invariants of Legendrian links (see [25, Theorem 4.3]), it would be desirable to construct *enhancements* or *refinements* of R-coloring numbers that encode additional information about Legendrian front projections. To this end, we will show that if M is a medial GL-rack, then $\mathrm{Hom}_{\mathsf{GLR}}(\mathcal{G}(\Lambda), M)$ also enjoys a canonical medial GL-rack structure.

Lemma 4.2. *Let (X, s) be a rack, and let (Y, t) be a medial rack. Let $\widetilde{H} := \mathrm{Hom}_{\mathsf{Rack}}((X, s^X), (Y, s^Y))$, and define $\widetilde{s} : \widetilde{H} \to \mathrm{Sym}(\widetilde{H})$ by $g \mapsto s_g$, where $s_g(f) := [x \mapsto (s^Y_{g(x)} \circ f)(x)]$. Then, $\widetilde{R} := (\widetilde{H}, \widetilde{s})$ is a medial rack. If in addition (Y, s^Y) is a quandle, then so is $\widetilde{R}$.*

Proof. In [9, Theorem 3], Crans and Nelson proved that $\widetilde{R}$ is a medial quandle under the additional assumptions that (X, s^X) and (Y, s^Y) are quandles. However, their proof did not use the quandle axiom that $s^X_x(x) = x$ for all $x \in X$. Moreover, their proof that $\widetilde{R}$ satisfies the nonquandle rack axioms and mediality did not use the quandle axiom that $s^Y_y(y) = y$ for all $y \in Y$; the authors only used this axiom to show that $\widetilde{R}$ also satisfies it. $\square$

Theorem 4.3. *In the setting of Lemma 4.2, suppose in addition that $R_1 := (X, s^X, \mathtt{u}_1, \mathtt{d}_1)$ and $R_2 := (Y, s^Y, \mathtt{u}_2, \mathtt{d}_2)$ are GL-racks, so that R_2 is medial. Let $H := \mathrm{Hom}_{\mathsf{GLR}}(R_1, R_2) \subset \widetilde{H}$, let $s := \widetilde{s}|_H$, and let $R := (H, s)$. Define $\mathtt{u} : H \to H$ by $f \mapsto \mathtt{u}_2 \circ f$, and define $\mathtt{d} : H \to H$ by $f \mapsto \mathtt{d}_2 \circ f$. Then, $(R, \mathtt{u}, \mathtt{d})$ is a medial GL-rack. If R_2 is also a GL-quandle, then so is $(R, \mathtt{u}, \mathtt{d})$.*

Proof. In the notation of Lemma 4.2, $\widetilde{R}$ is a medial rack. To show that R is a medial rack, it suffices to show that R is a subrack of $\widetilde{R}$. To that end, fix $f, g \in H$. Then, we have $s_g(f) \in H$ because

$$\begin{aligned}
\mathtt{u}_2 \circ s_g(f) &= [x \mapsto (\mathtt{u}_2 \circ s^Y_{g(x)} \circ f)(x)] \\
&= [x \mapsto (s^Y_{(\mathtt{u}_2 \circ g)(x)} \circ \mathtt{u}_2 \circ f)(x)] && \text{by Proposition 2.12} \\
&= [x \mapsto (s^Y_{(g \circ \mathtt{u}_1)(x)} \circ f \circ \mathtt{u}_1)(x)] && \text{since } f, g \in H \\
&= s_g(f) \circ \mathtt{u}_1
\end{aligned}$$

and, similarly, $\mathtt{d}_2 \circ s_g(f) = s_g(f) \circ \mathtt{d}_1$. Thus, R is a subrack of $\widetilde{R}$, so R is medial. In particular, if R_2 is a GL-quandle, then Lemma 4.2 implies that R is a subquandle of $\widetilde{R}$.

It remains to show that $(\mathtt{u}, \mathtt{d})$ defines a GL-structure on R. Fix $f, g \in H$. Since f is a GL-rack homomorphism and $(\mathtt{u}_1, \mathtt{d}_1)$ satisfies GL-rack axiom (L1), we have

$$\begin{aligned}(\mathtt{ud} \circ s_f)(f) &= [x \mapsto (\mathtt{u}_2 \circ \mathtt{d}_2 \circ s^Y_{f(x)} \circ f)(x)] \\ &= [x \mapsto (\mathtt{u}_2 \circ \mathtt{d}_2 \circ f \circ s^X_x)(x)] \\ &= [x \mapsto f((\mathtt{u}_1 \circ \mathtt{d}_1 \circ s^X_x)(x))] \\ &= [x \mapsto f(x)] = f\end{aligned}$$

and, similarly, $(\mathtt{du} \circ s_f)(f) = f$. So, $(\mathtt{u}, \mathtt{d})$ satisfies axiom (L1). Since $(\mathtt{u}_2, \mathtt{d}_2)$ satisfies axiom (L2), we also have

$$(\mathtt{u} \circ s_g)(f) = [x \mapsto (\mathtt{u}_2 \circ s^Y_{g(x)} \circ f)(x)] = [x \mapsto (s^Y_{g(x)} \circ \mathtt{u}_2 \circ f)(x)] = s_g(\mathtt{u}_2 \circ f) = (s_g \circ \mathtt{u})(f)$$

and, similarly, $(\mathtt{d} \circ s_g)(f) = (s_g \circ \mathtt{d})(f)$. So, $(\mathtt{u}, \mathtt{d})$ satisfies axiom (L2). Finally, since $(\mathtt{u}_2, \mathtt{d}_2)$ satisfies axiom (L3), we have

$$s_{\mathtt{u}(g)}(f) = [x \mapsto (s^Y_{\mathtt{u}_2(g(x))} \circ f)(x)] = [x \mapsto (s^Y_{g(x)} \circ f)(x)] = s_g(f)$$

and, similarly, $s_{\mathtt{d}(g)}(f) = s_g(f)$. Hence, $(\mathtt{u}, \mathtt{d})$ satisfies axiom (L3), and the proof is complete. ☐

Proposition 3.3 and Theorem 4.3 imply that, for a fixed medial GL-rack M and for any oriented Legendrian link Λ, the isomorphism class of $\mathcal{H}(\Lambda, M) := \mathrm{Hom}_{\mathsf{GLR}}(\mathcal{G}(\Lambda), M)$ as a medial GL-rack is an invariant of Λ. In light of Lemmas 3.5 and 2.14, $\mathcal{H}(\Lambda, M)$ recovers the medial quandle-valued invariant $\mathrm{Hom}_{\mathsf{Qnd}}(\mathcal{Q}(L), Q)$ of smooth links from [9, Section 6], where Q is a medial quandle.

This medial GL-rack-valued invariant of Legendrian links raises intriguing questions for future research. For example, do there exist Legendrian links Λ_1 and Λ_2 and a medial GL-rack M such that $\mathrm{Col}(\Lambda_1, M) = \mathrm{Col}(\Lambda_2, M)$ but $\mathcal{H}(\Lambda_1, M) \not\cong \mathcal{H}(\Lambda_2, M)$ as medial GL-racks? In the spirit of Corollary 3.9, do there exist such Legendrian links that also share the same underlying smooth link type and classical invariants? Moreover, Elhamdadi et al. recently introduced proper enhancements of $\mathrm{Hom}_{\mathsf{Qnd}}(\mathcal{Q}(L), Q)$ by considering k-algebra homomorphisms between quandle rings and colorings of smooth links by idempotents of quandle rings in [14, Theorems 4.2 and 5.1]. Do similar proper enhancements of $\mathcal{H}(\Lambda, M)$ also exist?

4.2. **Tensor products of GL-racks.** Let $\mathsf{GLR}^{\mathrm{med}}$ be the full subcategory of GLR whose objects are medial. In this subsection, we define tensor products in GLR and $\mathsf{GLR}^{\mathrm{med}}$ that also induce symmetric monoidal structures. In the case of $\mathsf{GLR}^{\mathrm{med}}$, we show that this structure is compatible with the closed structure given by Theorem 4.3. (Note that GLR and $\mathsf{GLR}^{\mathrm{med}}$ also have Cartesian monoidal structures given by the categorical product, i.e., the Cartesian product $\times$.)

Definition 4.4. If $R_1 = (X, s^X, \mathtt{u}_1, \mathtt{d}_1)$ and $R_2 = (Y, s^Y, \mathtt{u}_2, \mathtt{d}_2)$ are GL-racks, then we define their *tensor product*, denoted by $R_1 \otimes R_2$, to be the free GL-rack $\mathrm{FGLR}(X \times Y)$ modulo the following relations for all $x, x_1, x_2 \in X$ and $y, y_1, y_2 \in Y$:

(1) $s_{(x,y_2)}(x, y_1) = (x, s^Y_{y_2}(y_1))$.
(2) $s_{(x_2,y)}(x_1, y) = (s^X_{x_2}(x_1), y)$.
(3) $\mathtt{u}(x, y) = (\mathtt{u}_1(x), y) = (x, \mathtt{u}_2(y))$.
(4) $\mathtt{d}(x, y) = (\mathtt{d}_1(x), y) = (x, \mathtt{d}_2(y))$.

We also define the *medial tensor product* of R_1 and R_2, denoted by $R_1 \otimes_{\mathrm{med}} R_2$, to be $R_1 \otimes R_2$ modulo the following relations for all $x_1, y_1, z_1, a \in X$ and $x_2, y_2, z_2, b \in Y$:

$$(s_{s_{(x_1,x_2)}(z_1,z_2)} \circ s_{(y_1,y_2)})(a,b) = (s_{s_{(x_1,x_2)}(y_1,y_2)} \circ s_{(z_1,z_2)})(a,b).$$

Note that if R_1 or R_2 is a GL-quandle, then so is $R_1 \otimes R_2$. By Lemma 2.14, Definition 4.4 recovers tensor products of medial quandles as defined by Crans and Nelson in [9, Subsection 8.1]. The next two results show that medial tensor products of medial GL-racks also satisfy a universal property and internal hom-tensor adjunction similar to those of tensor products of A-modules.

Theorem 4.5. *The category* $\mathsf{GLR}^{\mathrm{med}}$ *is symmetric monoidal closed with respect to the closed structure* $\mathrm{Hom}_{\mathsf{GLR}^{\mathrm{med}}}(-,-)$ *from Theorem 4.3 and the medial tensor product* $\otimes_{\mathrm{med}}$.

Proof. The unit object in $\mathsf{GLR}^{\mathrm{med}}$ is the trivial GL-rack with one element. Using this fact, it is straightforward to verify that $\mathsf{GLR}^{\mathrm{med}}$ is monoidal and symmetric. On the other hand, $\mathsf{GLR}^{\mathrm{med}}$ is defined as an equational algebraic category, and $\otimes_{\mathrm{med}}$ is precisely the tensor product constructed in [30, Section 4]. Thus, the main theorem of Linton in [30] states that our claim is true if and only if, in the sense of universal algebra, $\mathsf{GLR}^{\mathrm{med}}$ is commutative as an algebraic theory; see [30, Section 6] and cf. [9, Subsection 8.1]. Indeed, for any medial GL-rack $(X, s, \mathtt{u}, \mathtt{d})$ and for all elements $x_{11}, x_{12}, x_{21}, x_{22} \in X$, we have the following equalities:

$$\begin{cases} (\mathtt{u} \circ s_{x_{12}})(x_{11}) = (s_{\mathtt{u}(x_{12})} \circ \mathtt{u})(x_{11}) & \text{by Proposition 2.12,} \\ (\mathtt{d} \circ s_{x_{12}})(x_{11}) = (s_{\mathtt{d}(x_{12})} \circ \mathtt{d})(x_{11}) & \text{by Proposition 2.12,} \\ (\mathtt{u} \circ \mathtt{d})(x_{11}) = (\mathtt{d} \circ \mathtt{u})(x_{11}) & \text{by Proposition 2.12,} \\ (s_{s_{x_{22}}(x_{21})} \circ s_{x_{12}})(x_{11}) = (s_{s_{x_{22}}(x_{12})} \circ s_{x_{21}})(x_{11}) & \text{since } (X,s) \text{ is medial.} \end{cases}$$

Together with the tautologies $\mathtt{u}^2(x_{11}) = \mathtt{u}^2(x_{11})$ and $\mathtt{d}^2(x_{11}) = \mathtt{d}^2(x_{11})$, these equalities show that $\mathsf{GLR}^{\mathrm{med}}$ forms a commutative algebraic theory. This completes the proof. ☐

Similarly, the tensor product $\otimes$ and medial tensor product $\otimes_{\mathrm{med}}$ both define symmetric monoidal structures on GLR. For future research, it would be interesting to investigate the relationships that any two GL-racks R_1 and R_2 have with $R_1 \otimes R_2$. For example, given an oriented Legendrian link Λ, how are $\mathrm{Col}(\Lambda, R_1)$ and $\mathrm{Col}(\Lambda, R_2)$ related to $\mathrm{Col}(\Lambda, R_1 \otimes R_2)$? In light of developing GL-rack (co)homology theories in [23, 24], how are the (co)homologies of R_1 and R_2 related to the (co)homology of $R_1 \otimes R_2$? It would also be interesting to study the relationships between $R_1 \otimes R_2$ and $R_1 \otimes_{\mathrm{med}} R_2$.

5. A sufficient condition for GL-rack isomorphisms

In [24, Section 5], Karmakar et al. constructed a homogeneous representation for any GL-rack R from the orbits of R under the action of $\mathrm{Aut}_{\mathsf{GLR}}(R)$. In this section, we adapt this construction into a category GrpTup with an essentially surjective functor $\mathcal{F} : \mathsf{GrpTup} \twoheadrightarrow \mathsf{GLR}$. This functor induces a group-theoretic sufficient condition for any two GL-racks or quandles to be isomorphic.

5.1. Construction of GrpTup.

In this subsection, we introduce a category GrpTup with a functorial relationship to GLR.

To define the objects in GrpTup, we adapt the work of Karmakar et al. in [24, Proposition 5.1]. Given a group G with a subgroup H, let G/H denote the set of left cosets of H in G. Let $N_G(H)$ denote the normalizer of H in G. Given $g \in G$, let $C_G(g)$ denote the centralizer of g in G. Now, let the objects in GrpTup be all sextuples $(I, \bigsqcup_{i \in I} G/H_i, Z_I, Q_I, R_I, \tau)$ satisfying the following:

(1) I is an indexing set, G is a group, and $Z_I = \{z_i^G \mid i \in I\}$, $Q_I = \{q_i^G \mid i \in I\}$, and $R_I = \{r_i^G \mid i \in I\}$ are multisets indexed by I whose elements lie in G.
(2) $\{H_i \mid i \in I\}$ is a family of subgroups of G such that $H_i \leq C_G(z_i^G)$ for all $i \in I$.
(3) $\tau : I \to I$ is a bijection such that the following hold for all $i \in I$:
 (a) $q_i^G \in N_G(H_{\tau(i)})$.
 (b) $r_i^G \in N_G(H_{\tau^{-1}(i)})$.
 (c) $z_i^G q_i^G r_{\tau(i)}^G$, $z_i^G r_i^G q_{\tau^{-1}(i)}^G \in H_i$.
 (d) $z_i^G q_i^G (z_{\tau(i)}^G)^{-1} = q_i^G$.
 (e) $z_i^G r_i^G (z_{\tau^{-1}(i)}^G)^{-1} = r_i^G$.

For the sake of brevity, we will denote such an object as $\widetilde{G}$ when there is no room for confusion. For an opposing object in GrpTup, we will write $\widetilde{K} := (J, \bigsqcup_{j \in J} K/L_j, Z_J, Q_J, R_J, \pi)$.

Now, we define the morphisms in GrpTup. Given any two objects $\widetilde{G}, \widetilde{K}$ in GrpTup, let $\mathrm{Hom}_{\mathsf{GrpTup}}(\widetilde{G}, \widetilde{K})$ be the set of all triples $\varphi := (\varphi_1, \varphi_2, \varphi_3)$ satisfying the following:
(1) $\varphi_1 : G \to K$ is a group homomorphism.
(2) $\varphi_2 : \bigsqcup_{i \in I} G/H_i \to \bigsqcup_{j \in J} K/L_j$ and $\varphi_3 : I \to J$ are morphisms in Set.
(3) $\pi \circ \varphi_3 = \varphi_3 \circ \tau$.
(4) For all $i \in I$ and $g \in G$, we have $\varphi_1(z_i^G) = z_{\varphi_3(i)}^K$, $\varphi_1(q_i^G) = q_{\varphi_3(i)}^K$, $\varphi_1(r_i^G) = r_{\varphi_3(i)}^K$, and $\varphi_2(gH_i) = \varphi_1(g) L_{\varphi_3(i)}$.

Define the composition of morphisms in GrpTup by $\psi \circ \varphi := (\psi_1 \circ \varphi_1, \psi_2 \circ \varphi_2, \psi_3 \circ \varphi_3)$. Also, define the identity morphism $\mathrm{id}^{\widetilde{G}} : \widetilde{G} \xrightarrow{\sim} \widetilde{G}$ by letting $\mathrm{id}_1^{\widetilde{G}}$, $\mathrm{id}_2^{\widetilde{G}}$, and $\mathrm{id}_3^{\widetilde{G}}$ as defined above be identity maps. Associativity and unit laws are immediate. Hence, GrpTup is a category.

5.2. **Construction of $\mathcal{F} : \mathsf{GrpTup} \to \mathsf{GLR}$.** We now construct an essentially surjective functor $\mathcal{F} : \mathsf{GrpTup} \to \mathsf{GLR}$ and deduce a sufficient condition for any two GL-racks to be isomorphic.

By [24, Proposition 5.1], given any object $\widetilde{G}$ in GrpTup, the set $X := \bigsqcup_{i \in I} G/H_i$ admits a GL-rack structure in which $s^X : X \to \mathrm{Sym}(X)$ and $\mathtt{u}_G, \mathtt{d}_G : X \to X$ are defined by

$$s^X(yH_j) := s^X_{yH_j} := [xH_i \mapsto y z_j^G y^{-1} x H_i],\ \mathtt{u}_G(xH_i) := x q_i^G H_{\tau(i)},\ \text{and } \mathtt{d}_G(xH_i) := x r_i^G H_{\tau^{-1}(i)}.$$

So, we can define a functor $\mathcal{F} : \mathsf{GrpTup} \to \mathsf{GLR}$ by sending any object $\widetilde{G}$ in GrpTup to the GL-rack $(X, s^X, \mathtt{u}_G, \mathtt{d}_G)$ and sending any morphism $\varphi \in \mathrm{Hom}_{\mathsf{GrpTup}}(\widetilde{G}, \widetilde{K})$ to φ_2.

Theorem 5.1. *$\mathcal{F}$ is an essentially surjective functor.*

Proof. Essential surjectivity is precisely the statement of [24, Theorem 5.2]. Certainly, $\mathcal{F}$ preserves identity morphisms and composition of morphisms. To complete the proof of functoriality, it remains to show that if $\varphi \in \mathrm{Hom}_{\mathsf{GrpTup}}(\widetilde{G}, \widetilde{K})$, then $\mathcal{F}\varphi : \mathcal{F}(\widetilde{G}) \to \mathcal{F}(\widetilde{K})$ is a GL-rack homomorphism. Write $\mathcal{F}(\widetilde{G}) = (X, s^X, \mathtt{u}_G, \mathtt{d}_G)$ and $\mathcal{F}(\widetilde{K}) = (Y, s^Y, \mathtt{u}_K, \mathtt{d}_K)$, and fix $gH_a \in X$. Since φ_1 is a group homomorphism, we have

$$\begin{aligned}
\mathcal{F}\varphi \circ s^X_{gH_a} &= [xH_i \mapsto \varphi_2(g z_a^G g^{-1} x H_i)] \\
&= [xH_i \mapsto \varphi_1(g z_a^G g^{-1} x) L_{\varphi_3(i)}] \\
&= [xH_i \mapsto \varphi_1(g) \varphi_1(z_a^G) \varphi_1(g^{-1}) \varphi_1(x) L_{\varphi_3(i)}] \\
&= [xH_i \mapsto \varphi_1(g) z^K_{\varphi_3(a)} \varphi_1(g)^{-1} \varphi_2(xH_i)] \\
&= s^Y_{\varphi_1(g) L_{\varphi_3(a)}} \circ \varphi_2 = s^Y_{\varphi_2(gH_a)} \circ \varphi_2 = s^Y_{\mathcal{F}\varphi(gH_a)} \circ \mathcal{F}\varphi,
\end{aligned}$$

so $\mathcal{F}\varphi$ is a rack homomorphism. Moreover, we have

$$\begin{aligned}\mathcal{F}\varphi \circ \mathtt{u}_G &= [xH_i \mapsto \varphi_2(xq_i^G H_{\tau(i)})]\\ &= [xH_i \mapsto \varphi_1(x)\varphi_1(q_i^G)L_{\varphi_3(\tau(i))}]\\ &= [xH_i \mapsto \varphi_1(x)q^K_{\varphi_3(i)}L_{\pi(\varphi_3(i))}]\\ &= [yL_j \mapsto yq_j^K L_{\pi(j)}] \circ [xH_i \mapsto \varphi_1(x)L_{\varphi_3(i)}]\\ &= \mathtt{u}_K \circ [xH_i \mapsto \varphi_2(xH_i)] = \mathtt{u}_K \circ \mathcal{F}\varphi\end{aligned}$$

and, similarly, $\mathcal{F}\varphi \circ \mathtt{d}_G = \mathtt{d}_K \circ \mathcal{F}\varphi$. Hence, $\mathcal{F}\varphi$ is a GL-rack homomorphism. □

This result gives us a group-theoretic way to show that two GL-racks R_1 and R_2 are isomorphic. In the proof of [24, Theorem 5.2], Karmakar et al. describe a procedure to construct objects $\widetilde{G}$ and $\widetilde{K}$ in GrpTup such that $R_1 \cong \mathcal{F}(\widetilde{G})$ and $R_2 \cong \mathcal{F}(\widetilde{K})$ in GLR. Their construction uses the decomposition of the underlying sets of R_1 and R_2 into orbits under the actions of $\mathrm{Aut}_{\mathsf{GLR}}(R_1)$ and $\mathrm{Aut}_{\mathsf{GLR}}(R_2)$, respectively. Then, to show that $R_1 \cong R_2$ in GLR, it suffices to find a morphism $\varphi \in \mathrm{Hom}_{\mathsf{GrpTup}}(\widetilde{G}, \widetilde{K})$ such that φ_2 is bijective, since then $\mathcal{F}\varphi : \mathcal{F}(\widetilde{G}) \to \mathcal{F}(\widetilde{K})$ will also be bijective and, hence, an isomorphism of GL-racks.

Finally, let $\mathsf{GrpTrip}$ be the full subcategory of GrpTup consisting of objects $\widetilde{G}$ for which $\tau = \mathrm{id}_I$, and Q_I and R_I are multisets only containing copies of 1_G. By Lemma 2.14 and [22, Theorem 7.2], $\mathcal{F}$ induces an essentially surjective functor $\mathsf{GrpTrip} \twoheadrightarrow \mathsf{Qnd}$. Hence, our above discussion specializes to a sufficient condition for any two quandles to be isomorphic.

References

[1] J. Adámek, J. Rosický, and E. M. Vitale, *Algebraic theories*, Cambridge Tracts in Mathematics, vol. 184, Cambridge University Press, Cambridge, 2011. A categorical introduction to general algebra, With a foreword by F. W. Lawvere. MR2757312

[2] Jagdeep Basi and Carmen Caprau, *Quandle coloring quivers of* $(p,2)$*-torus links*, J. Knot Theory Ramifications **31** (2022), no. 9, Paper No. 2250057, 14. MR4475496

[3] Nilangshu Bhattacharyya, Cyrus Cox, Justin Murray, Adithyan Pandikkadan, Shea Vela-Vick, and Angela Wu, *Legendrian knot atlas: List of* $(\mathrm{tb}, \mathrm{r})$ *for non-destabilizable Legendrian knots representing knot type* 8_{10}. `https://www.math.lsu.edu/~knotatlas/legendrian/8_10-knot.html`. Accessed: 2024-12-28.

[4] A. Cattabriga and E. Horvat, *Knot quandle decompositions*, Mediterr. J. Math. **17** (2020), no. 3, Paper No. 98, 22. MR4105750

[5] Jose Ceniceros, Mohamed Elhamdadi, and Sam Nelson, *Legendrian rack invariants of Legendrian knots*, Commun. Korean Math. Soc. **36** (2021), no. 3, 623–639. MR4292403

[6] Karina Cho and Sam Nelson, *Quandle cocycle quivers*, Topology Appl. **268** (2019), 106908, 10. MR4018585

[7] ———, *Quandle coloring quivers*, J. Knot Theory Ramifications **28** (2019), no. 1, 1950001, 12. MR3910948

[8] Wutichai Chongchitmate and Lenhard Ng, *An atlas of Legendrian knots*, Exp. Math. **22** (2013), no. 1, 26–37. MR3038780

[9] Alissa S. Crans and Sam Nelson, *Hom quandles*, J. Knot Theory Ramifications **23** (2014), no. 2, 1450010, 18. MR3197054

[10] Ivan Dynnikov and Maxim Prasolov, *Rectangular diagrams of surfaces: distinguishing Legendrian knots*, J. Topol. **14** (2021), no. 3, 701–860. MR4286839

[11] Mohamed Elhamdadi, *A survey of racks and quandles: some recent developments*, Algebra Colloq. **27** (2020), no. 3, 509–522. MR4141628

[12] Mohamed Elhamdadi, Jennifer Macquarrie, and Ricardo Restrepo, *Automorphism groups of quandles*, J. Algebra Appl. **11** (2012), no. 1, 1250008, 9. MR2900878

[13] Mohamed Elhamdadi and Sam Nelson, *Quandles—an introduction to the algebra of knots*, Student Mathematical Library, vol. 74, American Mathematical Society, Providence, RI, 2015. MR3379534

[14] Mohamed Elhamdadi, Brandon Nunez, and Mahender Singh, *Enhancements of link colorings via idempotents of quandle rings*, J. Pure Appl. Algebra **227** (2023), no. 10, Paper No. 107400, 16. MR4579329

[15] Mohamed Elhamdadi and Dipali Swain, *State sum invariants of knots from idempotents in quandle rings*, 2024. Preprint, arXiv:2402.14661 [math.GT].
[16] John B. Etnyre, *Legendrian and transversal knots*, Handbook of knot theory, 2005, pp. 105–185. MR2179261
[17] John B. Etnyre and Ko Honda, *Knots and contact geometry. I. Torus knots and the figure eight knot*, J. Symplectic Geom. **1** (2001), no. 1, 63–120. MR1959579
[18] John B. Etnyre and Lenhard L. Ng, *Legendrian contact homology in* $\mathbb{R}^3$, Surveys in differential geometry 2020. Surveys in 3-manifold topology and geometry, [2022] ©2022, pp. 103–161. MR4479751
[19] *GAP – Groups, Algorithms, and Programming, Version 4.14.0*, The GAP Group, 2024.
[20] Richard Henderson, Todd Macedo, and Sam Nelson, *Symbolic computation with finite quandles*, J. Symbolic Comput. **41** (2006), no. 7, 811–817. MR2232202
[21] Přemysl Jedlička, Agata Pilitowska, David Stanovský, and Anna Zamojska-Dzienio, *The structure of medial quandles*, J. Algebra **443** (2015), 300–334. MR3400403
[22] David Joyce, *A classifying invariant of knots, the knot quandle*, J. Pure Appl. Algebra **23** (1982), no. 1, 37–65. MR638121
[23] Biswadeep Karmakar, Deepanshi Saraf, and Mahender Singh, *Cohomology of generalised Legendrian racks and state-sum invariants of Legendrian links*, 2023. Preprint, arXiv:2301.06854v1 [math.GT].
[24] ———, *Generalised Legendrian racks of Legendrian links*, 2024. Preprint, arXiv:2301.06854 [math.GT].
[25] Naoki Kimura, *Bi-Legendrian rack colorings of Legendrian knots*, J. Knot Theory Ramifications **32** (2023), no. 4, Paper No. 2350029, 16. MR4586264
[26] ———, *Rack coloring invariants of Legendrian knots*, 2024. Thesis (Ph.D.)–Waseda University Graduate School of Fundamental Science and Engineering.
[27] Margaret Kipe, *`Legendrian-Knot-Mosaics`*, 2024. `https://github.com/margekk/Legendrian-Knot-Mosaics`. Accessed: 2024-12-28.
[28] Margaret Kipe, Samantha Pezzimenti, Leif Schaumann, Luc Ta, and Wing Hong Tony Wong, *Bounds on the mosaic number of Legendrian knots*, 2024. Preprint, arXiv:2410.08064 [math.GT].
[29] Dheeraj Kulkarni and T. V. H. Prathamesh, *On rack invariants of Legendrian knots*, 2017. Preprint, arXiv:1706.07626 [math.GT].
[30] F. E. J. Linton, *Autonomous equational categories*, J. Math. Mech. **15** (1966), 637–642. MR190205
[31] James McCarron, *Sequence A181770 in the On-line Encyclopedia of Integer Sequences*, 2010. `https://oeis.org/A181770`. Accessed: 2024-12-30.
[32] Sam Nelson, *What is … a quandle?*, Notices Amer. Math. Soc. **63** (2016), no. 4, 378–380. MR3444659
[33] Lenhard Lee Ng, *Invariants of Legendrian links*, ProQuest LLC, Ann Arbor, MI, 2001. Thesis (Ph.D.)–Massachusetts Institute of Technology. MR2717015
[34] Takefumi Nosaka, *Quandles and topological pairs*, SpringerBriefs in Mathematics, Springer, Singapore, 2017. Symmetry, knots, and cohomology. MR3729413
[35] Samantha Pezzimenti and Abhinav Pandey, *Geography of Legendrian knot mosaics*, J. Knot Theory Ramifications **31** (2022), no. 1, Paper No. 2250002, 22. MR4411812
[36] Joshua M. Sabloff, *What is . . . a Legendrian knot?*, Notices Amer. Math. Soc. **56** (2009), no. 10, 1282–1284. MR2572757
[37] John C. Stillwell, *Classical topology and combinatorial group theory*, Graduate Texts in Mathematics, vol. 72, Springer-Verlag, New York-Berlin, 1980. MR602149
[38] Jacek Świątkowski, *On the isotopy of Legendrian knots*, Ann. Global Anal. Geom. **10** (1992), no. 3, 195–207. MR1186009
[39] Yasuki Tada, *On categories of faithful quandles with surjective or injective quandle homomorphisms*, Hiroshima Math. J. **54** (2024), no. 1, 61–86. MR4728697
[40] Lorenzo Traldi, *Reorienting quandle orbits*, 2024. Preprint, arXiv:2411.11763 [math.GT].
[41] Petr Vojtěchovský and Seung Yeop Yang, *Racks and quandles of small orders*, 2018. `https://www.cs.du.edu/~petr/libraries_of_algebraic_structures.html`. Accessed: 2025-01-03.
[42] ———, *Enumeration of racks and quandles up to isomorphism*, Math. Comp. **88** (2019), no. 319, 2523–2540. MR3957904

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Appendix A. Exhaustive searches with GL-racks

In this section, we enumerate GL-racks, medial GL-racks, GL-quandles, and medial GL-quandles of orders $n \leq 7$ up to isomorphism and describe the algorithms we used to do so. An implementation of these algorithms in `GAP` [19] and the raw data we collected are available at the following GitHub repository: *(Link coming soon!)*

A.1. **Enumeration of small GL-racks.** In Table 1, we enumerate the number of GL-racks, medial GL-racks, GL-quandles, and medial GL-quandles of orders $n \leq 7$ up to isomorphism. For comparison, we also list the corresponding numbers for classical racks and quandles. We obtained the numbers $g(n)$ from Algorithm 2 and $g^m(n)$, $g_q(n)$, and $g_q^m(n)$ from Algorithm 3. Meanwhile, the numbers $r(n)$, $r^m(n)$, $r_q(n)$, and $r_q^m(n)$ were originally computed by McCarron in [31], Vojtěchovský and Yang in [42], Henderson et al. in [20], and Jedlička et al. in [21], respectively. It appears that each of $g(n)$, $g^m(n)$, $g_q(n)$, and $g_q^m(n)$ in Table 1 grows exponentially and at a much faster rate than its counterpart for classical racks.

n	0	1	2	3	4	5	6	7
$g(n)$	1	1	4	13	62	308	2132	17268
$g^m(n)$	1	1	4	13	61	298	2087	16941
$g_q(n)$	1	1	2	6	19	74	353	2080
$g_q^m(n)$	1	1	2	6	18	68	329	1965
$r(n)$	1	1	2	6	19	74	353	2080
$r^m(n)$	1	1	2	6	18	68	329	1965
$r_q(n)$	1	1	1	3	7	22	73	298
$r_q^m(n)$	1	1	1	3	6	18	58	251

Table 1. The number of GL-racks $g(n)$, medial GL-racks $g^m(n)$, GL-quandles $g_q(n)$, and medial GL-quandles $g_q^m(n)$ of order n up to isomorphism, compared against the corresponding number of racks $r(n)$, medial racks $r^m(n)$, quandles $r_q(n)$, and medial quandles $r_q^m(n)$.

For explicit representatives of each GL-rack isomorphism class counted in Table 1, see Appendix B for those of orders $2 \leq n \leq 4$ and the data linked above for those of orders $5 \leq n \leq 7$. The unique GL-racks of orders 0 and 1 up to isomorphism are the initial and terminal objects in GLR, respectively.

Interestingly, Table 1 states that $g_q(n) = r(n)$ and $g_q^m(n) = r^m(n)$ for all $n \leq 7$. This leads us to make the following conjecture.

Conjecture A.1. *For all $n \geq 0$, there is a one-to-one correspondence between isomorphism classes of racks of order n and isomorphism classes of GL-quandles of order n. This correspondence restricts to a one-to-one correspondence between isomorphism classes of medial racks of order n and isomorphism classes of medial GL-quandles of order n.*

A.2. **Classification of small GL-racks.** We now describe the exhaustive search algorithms in `GAP` [19] that we used to compute these isomorphism classes. We build upon the work of Vojtěchovský and Yang in [42], who compiled a library of representatives of all isomorphism classes of racks of orders $n \leq 11$ in [41]. In what follows, let $\mathcal{R}_n$ denote Vojtěchovský and Yang's list of racks of order n, and let S_n denote the symmetric group on n letters. We will also denote any GL-rack $(X, s, \mathtt{u}, \mathtt{d})$ as a list $[(X, s), \mathtt{u}, \mathtt{d}]$ containing three elements.

Algorithm 1: `isGLR(`$R,\mathtt{u},\mathtt{d}$`)` verifies whether $(\mathtt{u},\mathtt{d}) \in S_n \times S_n$ defines a GL-structure on a given finite rack R, given that $\mathtt{ud} = \mathtt{du}$.

Data: Rack $R = (X, s)$ with $X = \{1, \dots, n\}$ and bijections $\mathtt{u}, \mathtt{d} \in S_n$ such that $\mathtt{ud} = \mathtt{du}$
Result: Whether $[R, \mathtt{u}, \mathtt{d}]$ is a GL-rack
begin
  foreach x *in* X **do**
    if $(\mathtt{ud} \circ s_x)(x) \neq x$ **then** return false;
    if $\mathtt{u} \circ s_x \neq s_x \circ \mathtt{u}$ *or* $\mathtt{d} \circ s_x \neq s_x \circ \mathtt{d}$ **then** return false;
    if $s_x \neq s_{\mathtt{u}(x)}$ *or* $s_x \neq s_{\mathtt{d}(x)}$ **then** return false;
  return true;

Algorithm 1, called `isGLR(`$R,\mathtt{u},\mathtt{d}$`)`, tests whether two maps $\mathtt{u}, \mathtt{d} : X \to X$ define a GL-structure on a rack $R = (X, s)$ with $X = \{1, \dots, n\}$, given the necessary conditions that $\mathtt{u}, \mathtt{d} \in S_n$ and $\mathtt{ud} = \mathtt{du}$; see Proposition 2.12. The test is simply a verification of the three GL-rack axioms.

Algorithm 2: Classification of GL-racks of a given order $1 \leq n \leq 11$ up to isomorphism.

Data: List $\mathcal{R}_n$ of racks with underlying set $X = \{1, \dots, n\}$ from the library of Vojtěchovský and Yang in [41] with $1 \leq n \leq 11$
Result: List isoClasses of all isomorphism classes of GL-racks of order n with no repeats
begin
  isoClasses $\leftarrow \emptyset$;
  foreach *pair* $((X, s), \mathtt{u})$ *in* $\mathcal{R}_n \times S_n$ **do**
    foreach *bijection* $\mathtt{d}$ *in the centralizer* $C_{S_n}(\mathtt{u})$ **do**
      if `isGLR(`$(X,s),\mathtt{u},\mathtt{d}$`)` **then**
        seen $\leftarrow$ false;
        foreach *GL-rack* $[X, s', \mathtt{u}_2, \mathtt{d}_2]$ *in* isoClasses *such that* $s' = s$ **do**
          if $\mathtt{u}$ *and* $\mathtt{u}_2$ *or* $\mathtt{d}$ *and* $\mathtt{d}_2$ *are not conjugate in* S_n **then** continue;
          foreach *bijection* φ *in* S_n **do**
            if φ *defines a GL-rack homomorphism* $[(X, s), \mathtt{u}, \mathtt{d}] \to [(X, s'), \mathtt{u}_2, \mathtt{d}_2]$ **then**
              seen $\leftarrow$ true;
              break;
          if seen **then** break;
        if seen *is false* **then** Add(isoClasses, $[(X, s), \mathtt{u}, \mathtt{d}]$);

Algorithm 2 uses $\mathcal{R}_n$ to create a list with exactly one representative of each isomorphism class of GL-racks whose underlying set is $X = \{1, \dots, n\}$. For a complete classification, the algorithm runs `isGLR(`$(X,s),\mathtt{u},\mathtt{d}$`)` for each rack $(X, s) \in \mathcal{R}_n$ and each pair of bijections $\mathtt{u}, \mathtt{d} \in S_n$ such that $\mathtt{ud} = \mathtt{du}$; cf. Proposition 2.12. If `isGLR(`$(X,s),\mathtt{u},\mathtt{d}$`)` returns `true`, then to ensure there are no duplicates, the algorithm searches for a bijection $\varphi \in S_n$ that defines a GL-rack homomorphism (hence an isomorphism) from $[(X, s), \mathtt{u}, \mathtt{d}]$ to any previously encountered GL-rack $[(X, s'), \mathtt{u}_2, \mathtt{d}_2]$. This is true only if $\varphi \circ \mathtt{u} \circ \varphi^{-1} = \mathtt{u}_2$ and $\varphi \circ \mathtt{d} \circ \varphi^{-1} = \mathtt{d}_2$, so it suffices to consider only those GL-racks

$[(X,s'),\mathtt{u}_2,\mathtt{d}_2]$ such that $\mathtt{u}$ and $\mathtt{u}_2$ are conjugate and $\mathtt{d}$ and $\mathtt{d}_2$ are conjugate in S_n. On the other hand, any GL-rack isomorphism descends to an isomorphism of the underlying racks. Since the racks in $\mathcal{R}_n$ are pairwise nonisomorphic, it suffices to consider only those GL-racks $[(X,s'),\mathtt{u}_2,\mathtt{d}_2]$ such that $s=s'$. On our hardware, our implementation of Algorithm 2 in `GAP` took 11269047 milliseconds, or slightly over three hours, to classify GL-racks of order 7.

Algorithm 3: Classification of medial GL-racks, all GL-quandles, and medial GL-quandles of order n up to isomorphism, given a classification of GL-racks of order n.

```
Data: List isoClasses of isomorphism classes of GL-racks with underlying set
      X = {1, ..., n} returned by Algorithm 2
Result: Lists M_n, Q_n, and I_n of isomorphism classes of medial GL-racks, all
        GL-quandles, and medial GL-quandles with underlying set X, respectively
begin
    M_n, Q_n, I_n ← ∅;
    foreach GL-rack R = [(X, s), u, d] in isoClasses do
        if d = u^{-1} then
            isQuandle ← true;
            Add(Q_n, R);
        else
            isQuandle ← false;
        isMedial ← true;
        foreach ordered triple (x, y, z) in X^3 do
            if s_{s_x(z)} ∘ s_y ≠ s_{s_x(y)} ∘ s_z then
                isMedial ← false;
                break;
        if isMedial then
            Add(M_n, R);
            if isQuandle then Add(I_n, R);
```

Finally, Algorithm 3 tests whether or not each GL-rack $[(X,s),\mathtt{u},\mathtt{d}]$ in the output of Algorithm 2 is medial or a GL-quandle. By Proposition 2.13, the latter condition is equivalent to the condition that $\mathtt{d}=\mathtt{u}^{-1}$. The former test is a straightforward verification of Definition 4.1. On our hardware, our implementation of Algorithm 2 in `GAP` took about 2718094 milliseconds, or about 45 minutes, to classify medial GL-racks and all GL-quandles of order 7.

A.3. **Exhaustive searches for R-coloring numbers.** We now describe Algorithm 4, which computes all colorings of the GL-rack of an oriented Legendrian link Λ by all GL-racks in the list isoClasses computed by Algorithm 2. Before running the algorithm, the user must input a presentation of $\mathcal{G}(\Lambda)$ in terms of crossing relations between elements of $\mathrm{FGLR}(X_\Lambda)$ as in Subsection 3.2. Since a mapping $x_i\mapsto y_i$ defines a GL-rack homomorphism $\mathcal{G}(\Lambda)\mapsto[(Y,s),\mathtt{u},\mathtt{d}]$ if and only if the crossing relations in $\mathcal{G}(\Lambda)$ are satisfied in Y when making the appropriate substitutions (cf. Subsection 3.2), it suffices to search for all valid solutions in Y to the inputted crossing relations.

In particular, if $R:=[(Y,s),\mathtt{u},\mathtt{d}]$ is a GL-rack of order $n\leq 11$, then $\mathrm{Col}(\Lambda,R)$ is simply the number of lists in solutions produced by Algorithm 4 whose first three list elements are s, $\mathtt{u}$, and $\mathtt{d}$. To distinguish between two oriented Legendrian links Λ_1 and Λ_2, it suffices to run Algorithm

Algorithm 4: Computation of colorings of an oriented Legendrian link Λ by GL-racks of a given order computed in Algorithm 2.

Data: List $\mathsf{isoClasses}$ of isomorphism classes of GL-racks with underlying set $Y = \{1, \ldots, n\}$ from Algorithm 2 and a presentation of $\mathcal{G}(\Lambda) = [(X, s^\Lambda), \mathtt{u}^\Lambda, \mathtt{d}^\Lambda)]$

Result: List $\mathsf{solutions}$ whose elements are lists $[s, \mathtt{u}, \mathtt{d}, \mathbf{y}]$ such that the mapping $x_i \mapsto y_i$ defines a GL-rack homomorphism $\mathcal{G}(\Lambda) \to [(Y, s), \mathtt{u}, \mathtt{d}]$

begin
- $m \leftarrow |X_\Lambda|$;
- $\mathsf{solutions} \leftarrow \emptyset$;
- **foreach** *GL-rack* $[(Y, s), \mathtt{u}, \mathtt{d}]$ *in* $\mathsf{isoClasses}$ **do**
  - **foreach** *ordered m-tuple* $\mathbf{y} \leftarrow (y_1, \ldots, y_m)$ *in* Y^m **do**
    - **if** *all crossing relations are satisfied after replacing each* $x_i \in X_\Lambda$, s^Λ, $\mathtt{u}^\Lambda$, *and* $\mathtt{d}^\Lambda$ *with* y_i, s, $\mathtt{u}$, *and* $\mathtt{d}$, *respectively* **then** Add($\mathsf{solutions}$, $[s, \mathtt{u}, \mathtt{d}, \mathbf{y}]$);

```
Finding all colorings of knot 1 by GL-rack 222 of 308…
Finding all colorings of knot 2 by GL-rack 222 of 308…
 [ […], (1,3,5,2,4), (1,3,5,2,4), 1, 2, 3, 5, 1, 4, 5]
 [ […], (1,3,5,2,4), (1,3,5,2,4), 2, 3, 4, 1, 2, 5, 1]
 [ […], (1,3,5,2,4), (1,3,5,2,4), 3, 4, 5, 2, 3, 1, 2]
 [ […], (1,3,5,2,4), (1,3,5,2,4), 4, 5, 1, 3, 4, 2, 3]
 [ […], (1,3,5,2,4), (1,3,5,2,4), 5, 1, 2, 4, 5, 3, 4]
```

FIGURE 11. Excerpt from the output of our `GAP` implementation of Algorithm 4. Here, knots 1 and 2 are the Legendrian knots in Figure 9; GL-rack 222 of 308 is the Legendrian rack defined in Example A.2.

4 twice, once inputting $\mathcal{G}(\Lambda_1)$ and again inputting $\mathcal{G}(\Lambda_2)$, and find a GL-rack R in $\mathsf{isoClasses}$ such that $\mathrm{Col}(\Lambda_1, R) \neq \mathrm{Col}(\Lambda_2, R)$. For example, running Algorithm 4 with $n = 3$ and $n = 2$ is how we determined which GL-racks and homomorphisms to use in our proofs of Theorems 3.8 and 3.11, respectively. Running the algorithm with $n = 5$ also gave us the following example.

Example A.2. In this example, we use Algorithm 4 to once again distinguish the Legendrian 6_2 knots Λ_1 and Λ_2 on the left and right of Figure 9, respectively. This time, we use the 222nd GL-rack of order 5 listed in the data linked above, which is a Legendrian rack as introduced by Ceniceros et al. in [5]. Let $Y := \{1, 2, 3, 4, 5\}$. In cycle notation, define $\sigma, f \in S_5$ by $\sigma := (12345)$ and $f := (13524)$. In the notation of Example 2.9, let $R := (Y, \sigma, f, f)_p$.

We input the relations of $\mathcal{G}(\Lambda_1)$ in (1) and then those of $\mathcal{G}(\Lambda_2)$ in (2) into our `GAP` implentation of Algorithm 4. After running the program with $n = 5$, the program outputs the text in Figure 11 upon reaching $\mathsf{isoClasses}[222] = R$. The output states that $\mathrm{Col}(\Lambda_1, R) = 0 \neq 5 = \mathrm{Col}(\Lambda_2, R)$, and the images of $(x_1, \ldots, x_7)$ in $\mathcal{G}(\Lambda_2)$ under each element of $\mathrm{Hom}_{\mathsf{GLR}}(\mathcal{G}(\Lambda), R)$ are given by the orbit of $(1, 2, 3, 5, 1, 4, 5) \in Y^7$ under the action of σ on Y^7.

Example A.2 yields the following analogue of Corollary 3.9 for Legendrian racks.

Proposition A.3. *There exist Legendrian knots sharing the same topological knot type and classical invariants and that can be distinguished using Legendrian rack coloring numbers.*

Appendix B. Tabulation of GL-racks of orders 2, 3, and 4

Tables 2, 3, and 4 tabulate all isomorphism classes of GL-racks having orders 2, 3, and 4, respectively, computed using Algorithm 2. Let X be the set $\{1, \dots, n\}$, where n is the order of the GL-rack, and let $\mathrm{id} : X \to X$ denote the identity map. In the tables, we write each bijection s_i, $\mathtt{u}$, and $\mathtt{d}$ as either id or a nonidentity element of S_n in cycle notation. The number of GL-racks of each order is given by the number of entries in the second column of each table. These entries denote all valid GL-structures $[\mathtt{u}, \mathtt{d}]$ up to isomorphism on the rack (X, s), where s is given by the corresponding entry in the first column. For example, the permutation GL-rack of order 3 with $s_1 = s_2 = s_3 = (123)$ and GL-structure $[\mathtt{u}, \mathtt{d}] = [(132), \mathrm{id}]$, which we used to prove Theorem 3.8, appears as the 11th entry in Table 3.

$[s_1, s_2]$	$[\mathtt{u}, \mathtt{d}]$	GL-quandle?	Medial?
$[\mathrm{id}, \mathrm{id}]$	$[\mathrm{id}, \mathrm{id}]$, $[(12), (12)]$	Yes	Yes
$[(12), (12)]$	$[\mathrm{id}, (12)]$, $[(12), \mathrm{id}]$	No	Yes

Table 2. The four isomorphism classes of GL-racks of order 2.

$[s_1, s_2, s_3]$	$[\mathtt{u}, \mathtt{d}]$	GL-quandle?	Medial?
$[\mathrm{id}, \mathrm{id}, \mathrm{id}]$	$[\mathrm{id}, \mathrm{id}]$, $[(23), (23)]$, $[(132), (123)]$	Yes	Yes
$[\mathrm{id}, (23), (23)]$	$[\mathrm{id}, (23)]$, $[(23), \mathrm{id}]$	No	Yes
$[(23), \mathrm{id}, \mathrm{id}]$	$[\mathrm{id}, \mathrm{id}]$, $[(23), (23)]$	Yes	Yes
$[(23), (23), (23)]$	$[\mathrm{id}, (23)]$, $[(23), \mathrm{id}]$	No	Yes
$[(123), (123), (123)]$	$[\mathrm{id}, (132)]$, $[(132), \mathrm{id}]$, $[(123), (123)]$	No	Yes
$[(23), (13), (12)]$	$[\mathrm{id}, \mathrm{id}]$	Yes	Yes

Table 3. The 13 isomorphism classes of GL-racks of order 3.

$[s_1, s_2, s_3, s_4]$	$[\mathtt{u}, \mathtt{d}]$	GL-quandle?	Medial?
$[\mathrm{id}, \mathrm{id}, \mathrm{id}, \mathrm{id}]$	$[\mathrm{id}, \mathrm{id}]$, $[(34), (34)]$, $[(243), (234)]$, $[(1432), (1234)]$, $[(14)(23), (14)(23)]$	Yes	Yes
$[\mathrm{id}, (13)(24), \mathrm{id}, (13)(24)]$	$[\mathrm{id}, (24)]$, $[(24), \mathrm{id}]$, $[(13), (13)(24)]$, $[(13)(24), (13)]$	No	Yes
$[(13)(24), (13)(24), (13)(24), (13)(24)]$	$[\mathrm{id}, (13)(24)]$, $[(24), (13)]$, $[(1432)(1432)]$, $[(14)(23), (12)(34)]$, $[(13)(24), \mathrm{id}]$	No	Yes
$[\mathrm{id}, \mathrm{id}, (34), (34)]$	$[\mathrm{id}, (34)]$, $[(34), \mathrm{id}]$, $[(12), (12)(24)$, $[(12)(34), (12)]$	No	Yes
$[\mathrm{id}, (34), \mathrm{id}, \mathrm{id}]$	$[\mathrm{id}, \mathrm{id}]$, $[(34), (34)]$	Yes	Yes
$[\mathrm{id}, (34), (34), (34)]$	$[\mathrm{id}, (34)]$, $[(34), \mathrm{id}]$	No	Yes
$[(34), (34), \mathrm{id}, \mathrm{id}]$	$[\mathrm{id}, \mathrm{id}]$, $[(34), (34)]$, $[(12), (12)]$, $[(12)(34), (12)(34)]$	Yes	Yes
$[(34), (34), (34), (34)]$	$[\mathrm{id}, (34)]$, $[(34), \mathrm{id}]$, $[(12), (12)(34)]$, $[(12)(34), (12)]$	No	Yes
$[\mathrm{id}, (234), (234), (234)]$	$[\mathrm{id}, (243)]$, $[(243), \mathrm{id}]$, $[(234), (234)]$	No	Yes
$[(234), \mathrm{id}, \mathrm{id}, \mathrm{id}]$	$[\mathrm{id}, \mathrm{id}]$, $[(243), (234)]$, $[(234), (243)]$	Yes	Yes

$[(234), (234), (234), (234)]$	$[\mathrm{id}, (243)]$, $[(243), \mathrm{id}]$, $[(234), (234)]$	No	Yes
$[(234), (243), (243), (243)]$	$[\mathrm{id}, (234)]$, $[(243), (243)]$, $[(234), \mathrm{id}]$	No	Yes
$[(34), (34), (12), (12)]$	$[\mathrm{id}, \mathrm{id}]$, $[(34), (34)]$, $[(12)(34), (12)(34)]$	Yes	Yes
$[(34), (34), (12)(34), (12)(34)]$	$[\mathrm{id}, (34)]$, $[(34), \mathrm{id}]$, $[(12), (12)(34)]$, $[(12)(34), (12)]$	No	Yes
$[(12), (12), (34), (34)]$	$[\mathrm{id}, (12)(34)]$, $[(34), (12)]$, $[(12)(34), \mathrm{id}]$	No	Yes
$[(12), (12), (12)(34), (12)(34)]$	$[\mathrm{id}, (12)(34)]$, $[(34), (12)]$, $[(12), (34)]$, $[(12)(34), \mathrm{id}]$	No	Yes
$[(1324), (1324), (1324), (1324)]$	$[\mathrm{id}, (1423)]$, $[(1423), \mathrm{id}]$, $[(12)(34), (1324)]$, $[(1324), (12)(34)]$	No	Yes
$[\mathrm{id}, (34), (24), (23)]$	$[\mathrm{id}, \mathrm{id}]$	Yes	No
$[(234), (143), (124), (132)]$	$[\mathrm{id}, \mathrm{id}]$	Yes	Yes

Table 4: The 62 isomorphism classes of GL-racks of order 4.