

FLOWLINES TRANSVERSE TO KNOT AND LINK FIBRATIONS

ROBERT GHRIST AND EIKO KIN

Let K be a knot or link in S^3 which is fibred — the complement fibres over S^1 with fibres spanning surfaces. We focus on those fibred knots and links which have the following property: every vector field transverse to the fibres possesses closed flow lines of all possible knot and link types in S^3 . Our main result is that a large class of fibred knots and links has this property, including all fibred non-torus 2-bridge knots. In general, sufficient conditions include a pseudo-Anosov type monodromy map and a sufficiently high degree of symmetry.

1. Introduction

We consider fibrations of knot or links complements in S^3 from the point of view of transverse vector fields.

Periodic flowlines of a vector field on S^3 possess knotting and linking information which is intimately related to the dynamical properties of the flow. Examples abound of classes of systems for which simple dynamics implicate simple knotted orbits (those whose complement cannot possess a hyperbolic structure) and vice versa: see [21] [Morse-Smale flows], [10] [Smale flows], [7, 9] [integrable Hamiltonian flows], [4] [the Lorenz system], and [8] [flows tangent to plane fields]. In this paper, we demonstrate that complicated fibrations typically force complicated knot and link types in any transverse vector field — indeed, as complicated as can be imagined.

Consider a knot or link K in S^3 which is fibred; that is, there is a fibration $\pi : S^3 - K \rightarrow S^1$ with fibre a spanning surface Σ for K . Choose any vector field X transverse to the fibres of π (in particular, X must be nonvanishing). Birman and Williams originally asked the question, “Which knot types are forced to exist as periodic orbits of X ?” The question splits into cases based on Thurston’s classification theorem for surface maps applied to the monodromy $\Phi : \Sigma \rightarrow \Sigma$ of π . If the complement of K is geometrically “simple” (e.g., the unknot, torus knots, iterated torus knots), then only a finite set of knot types are forced to exist for all X (again, typically unknots, torus knots, and iterations). On the other hand, if the complement of K is “hyperbolic” (in the sense that the monodromy map is of pseudo-Anosov type), then there are always an infinite number of distinct knot types as periodic orbits in any vector field X transverse to π .

The paper [5] carefully constructed a **template** (a branched surface with semi-flow) in the complement of the figure eight knot which captures all knot and link types forced by a transverse vector field. It was there noted that, although many

knot types were present, others were seemingly impossible to locate. To the contrary, the paper [14] showed that this template is **universal** — every knot and link type can be found on this branched surface. It follows that any vector field transverse to a fibration of the figure eight knot complement must possess all knot and link types as orbits. In this paper, we explore to what extent this property holds for other fibred knots and links.

Definition 1.1. A fibred knot/link $K \subset S^3$ is said to be **universally fibred** if each vector field X transverse to the fibration possesses closed orbits of all knot and link types.

An obvious prerequisite for being universally fibred is that the monodromy be sufficiently complex: pseudo-Anosov type. For in the case of periodic type, the forced links may have only a finite number of knot types represented (by suspending the periodic monodromy).

Our results are phrased in the language of braids: see §2 for details and Fig. 1 for examples of braids. We summarize our results in a simplified form; see §5 for stronger results.

Main Theorem: Let b be a braid of the form

$$(1) \quad b = \sigma_1^{\epsilon_1} \sigma_2^{\epsilon_2} \cdots \sigma_N^{\epsilon_N},$$

where $\epsilon_i = +1$ or -1 for each i (see Fig. 1[right]) and not all the ϵ_i are the same. Then for every $m > 1$, the closure of b^m is a fibred knot/link in S^3 of pseudo-Anosov type. Furthermore:

- (a) The closure of b^m has the universal fibration property for all but finitely many m .
- (b) The closure of b^2 always has the universal fibration property.
- (c) Whenever b contains the subword $\sigma_{i-1}^{-1} \sigma_i \sigma_{i+1}^{-1} \sigma_{i+2}$ (or $\sigma_{i-2} \sigma_{i-1}^{-1} \sigma_i \sigma_{i+1}^{-1}$), then the closure of b^m is universally fibred for all $m > 1$.

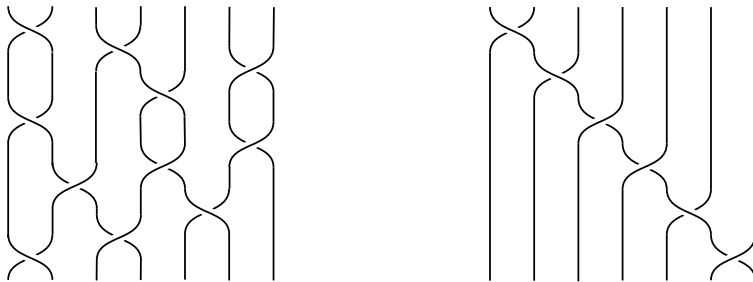


Figure 1. [left] an example of a braid on seven strands; [right] an example of a braid represented by Eqn. (1), $b = \sigma_1 \sigma_2 \sigma_3^{-1} \sigma_4^{-1} \sigma_5 \sigma_6^{-1}$

From result (b) above, we obtain a complete classification in the case of 2-bridge knots:

Corollary: Every fibred non-torus 2-bridge knot has the universal fibration property.

The proof of the Main Theorems utilizes a construction initiated in [5], based on work of [15] (and, ultimately, the work of Alexander). This involves taking a branched cover of S^3 over an unknot and lifting a branched surface constructed from a train track.

The outline of the paper is as follows. In §2, we review basic definitions and tools needed for the proofs. In §3, we introduce a family of pseudo-Anosov braid types and present their train tracks. We proceed with the general template constructions in §4, and identify universal subtemplates to prove the Main Theorem in §5. The final section, §6, gives a summary of to what extent we can classify the universally fibred knots and links. We propose a class of examples of pseudo-Anosov fibrations which we believe do not induce all knot and link types in the transverse flow.

2. Background

Several of the topics below require entire books to do the material justice: we limit ourselves to the minimal set of ideas necessary to follow the remaining sections.

2.1. Fibred knots and links. A knot/link K is said to be **fibred** if there is a fibration $\pi : S^3 - K \rightarrow S^1$ with fibre a spanning surface Σ for K . The complement of a neighborhood of K in S^3 is homeomorphic to the mapping torus of a homeomorphism $\Phi : \Sigma \rightarrow \Sigma$: i.e., $S^3 - N(K) \cong (\Sigma \times [0, 1]) / (x, 0) = (\Phi(x), 1)$. The spanning surface Σ is called the **fibre surface**, and the homeomorphism Φ which is well-defined up to isotopy is called the **monodromy**. The union of the closed orbits of the suspension flow by Φ on $S^3 - N(K)$ is called a **planetary link** of Φ .

It follows from the Thurston classification theorem for surface homeomorphisms [20] that the monodromy of a fibred knot/link is isotopic to Φ' , one of the following three types of maps:

- 1) **periodic:** $(\Phi')^n = \text{Id}$ for some n ;
- 2) **pseudo-Anosov:** Φ' possesses a pair of transverse (singular) foliations λ^u and λ^s along which Φ' is uniformly expanding and contracting respectively;
- 3) **reducible:** there exists a collection of disjoint simple closed curves $\mathcal{C} \subset \Sigma$ such that $\Phi'(\mathcal{C}) = \mathcal{C}$, and each connected component of $\Sigma - \mathcal{C}$ has negative Euler characteristic.

We say that a fibred knot/link K is of periodic, pseudo-Anosov, or reducible type respectively if its monodromy map is isotopic to a periodic, pseudo-Anosov, or reducible map.

We will be most interested exclusively in those fibred knots/links of pseudo-Anosov type (e.g., the figure-eight knot) since these alone may permit universal fibrations. We may reduce the problem to the case where the monodromy is the pseudo-Anosov representative thanks to a theorem of Asimov and Franks [1] which guarantees that any map isotopic to a pseudo-Anosov map (and hence any vector field transverse to the fibration) may not remove any of these periodic orbits — isotoping the monodromy may generate more, but not less. Hence, the set of planetary links of the pseudo-Anosov map is “minimal” with regards to changing

the monodromy map (or the vector field). Henceforth, by *the* planetary link of a knot/link is meant the planetary link of its pseudo-Anosov monodromy map.

2.2. Braids and branched covers. We use the language of braids throughout the remainder of the paper. Recall that **braids** are isotopy classes of disjointly embedded arcs monotonically connecting fixed endpoints (as in Fig. 1). Braids on n strands form a group B_n under concatenation, with standard generators σ_i denoting an elementary crossing of the i^{th} over the $(i+1)^{\text{st}}$ strand. Inverses correspond to reversing the crossing of the sign.¹ A **closed** or **geometric braid** is obtained by joining the two sets of endpoints around some fixed **braid axis**: algebraically, this corresponds to taking the conjugacy class of the braid in the braid group.

The classification of monodromies into periodic, pseudo-Anosov, or reducible type has its analogue for braids. Let β denote the closure of b , an n -braid with braid axis α . Since α is unknotted, its complement fibres over S^1 with fibre a disc A meeting β at n points. The monodromy map on A is fixed on the boundary and, by removing the intersection with β , becomes a map on an n -punctured disc. The Thurston Classification theorem applied to this monodromy map implies that one may classify a braid b as being of **periodic type**, **pseudo-Anosov type**, or **reducible type**. The pseudo-Anosov type braids will be of central importance in analyzing fibrations.

While fibrations of knot complements are difficult to visualize (the explanations of the trefoil, in [19, 10I], and the figure-eight knot, in [5] are not short!), the **branched covering** construction of Goldsmith [15] and Birman [3] provides a concrete mechanism for analysis. We use the method as presented in [5, pp. 26-30], keeping similar notation.

Lemma 2.1. [15, Lemma 1] *Let β be a single-component unknotted geometric braid with braid axis α and meridional disc A spanning α . Let $p : S^3 \rightarrow S^3$ be a branched covering space projection whose branch set is β . Then $\underline{\alpha} = p^{-1}(\alpha)$ is a non-trivial fibred knot/link in S^3 with fibre $\underline{A} = p^{-1}(A)$.*

A result of Birman [3] shows that every fibred knot may be obtained as $p^{-1}(\alpha)$ for some β and some (irregular) cover p . Moreover, the fibration of the complement of $\underline{\alpha}$ is itself a lift of the fibration of the complement of α .

For the remainder of this paper, we work with pairs of curves (α, β) which are **exchangeable**, i.e., there is an isotopy of S^3 which presents α as a geometric n -braid with braid axis β and vice versa [17]. Let a (resp. b) denote the braid in B_n whose closure is α , with β as its axis (resp. the braid whose closure is β with axis α). In this case, $\underline{\alpha}$ is the closure of a^m if p is m -fold.

2.3. Train tracks and templates. The problem of how to understand the complex dynamics associated to a pseudo-Anosov surface homeomorphism was resolved with the theory of **train tracks**. The central idea, going back to Williams [22], is to project the foliation down to a branched manifold. We call attention to [18, 2] for treatments of this theory from different perspectives.

Recall that a pseudo-Anosov surface map is characterized by the pair of transverse singular foliations, λ^s and λ^u , along which the map is uniformly contracting

¹There is a tradition of dynamicists and topologists using opposite sign conventions for braids: we employ the dynamicists' convention and apologize for the inevitable annoyance.

and expanding respectively. Roughly speaking, a **train track** for a pseudo-Anosov map is a branched 1-manifold obtained by cutting open the singular foliation λ^s in a certain manner and collapsing each leaf to a point: see [12] for examples relevant to this paper. The dynamics of the pseudo-Anosov homeomorphism is then easily represented by an induced self-immersion of the train track. We note that there are several presentations available for train tracks. For the remainder of this paper, we follow e.g., [2, 6] and represent the train track as a graph. The induced map is then easily represented as a map taking each edge of the graph to a sequence of edges. Two simple examples of train track graphs and associated graph maps are illustrated in Fig. 10.

The problem of how to capture all of the knot and link data of a dynamically complex 3-dimensional flow was successfully tackled by Birman and Williams in the early 1980s [4, 5] in the theory of templates (a.k.a. “knotholders”).

Definition 2.2. A **template** is an embedded branched 2-manifold with boundary, outfitted with an expansive semiflow. Templates have a natural decomposition into a finite number of **branchline charts** (Fig. 2[left]), each containing a number (> 1) of incoming and outgoing strips whose ends are joined respecting the direction of the semiflow.

The term “semiflow” means that the flow is well-defined in forward time, but not in backward time (at the branch lines in particular — there is a loss of uniqueness). By “expansive,” it is meant that the semiflow expands volume everywhere.

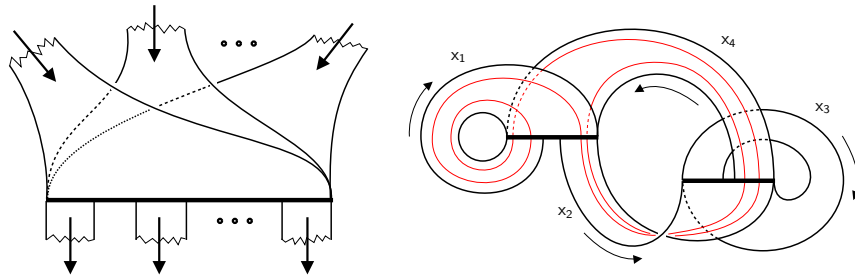


Figure 2. A branchline chart for a template [left]; an example of a template with an unknotted periodic orbit on it [right]. In the alphabet $\{x_1, x_2, x_3, x_4\}$, this knot corresponds to the word $(x_1^2(x_2x_4)^2) = (x_1x_1x_2x_4x_2x_4)$.

Every template carries an infinite link of periodic orbits of the semiflow. There is a well-defined symbolic language for describing these orbits. Upon labeling each strip of a template \mathcal{T} with a symbol x_i , it is clear that to each forward orbit of the semiflow on \mathcal{T} is associated a semi-infinite word in the alphabet $\{x_i\}$. Furthermore, from the expansivity of the semiflow, it can be shown that periodic flowlines on \mathcal{T} are in fact in bijective correspondence with (admissible) periodic words in this alphabet, up to cyclic permutations of the words (see [5] or [13, Lem. 2.4.1] for details).

The Template Theorem [5, Theorem 2.1] of Birman and Williams gives very general conditions under which the dynamics of a three-dimensional flow is accurately captured by a template: see [13] for a comprehensive treatment. For our purposes, we note that for a fibred knot/link K with pseudo-Anosov monodromy, there is a template $\mathcal{T} \subset S^3 - K$ whose knot and link types are in bijective correspondence with those of the flow except for a finite number of orbits on the boundary of the template. The template is a faithful representation of the fibration: not only are knot/link data preserved, but also the periods of these orbits with respect to the monodromy map are captured as the intersection number of the orbits with the branch set of the template.

The template is obtained by suspending the train track graph map for the monodromy, and cutting along the vertices of the graph as necessary. These cuts may produce “extra” orbits on the templates not in the original flow. To minimize confusion, we note that for the remainder of this paper, any such exceptional orbits which we “lose” are unknots, and are easily found elsewhere in the interior of the template.

Definition 2.3. A **universal template** in S^3 is one which possesses all knot and link types as closed orbits of the semiflow.

The paper [14] established that universal templates exist in abundance. From this work and [13] comes a practical criterion for determining when a given template is universal. One additional definition is needed. Given any closed orbit κ on a template $\mathcal{T} \subset S^3$, the **twist**, $\tau(\kappa)$, is defined to be the twist number of the normal bundle to \mathcal{T} along κ (which is either an annulus or Möbius band having κ as its core). For the remainder of this paper, we consider twists for unknotted curves only, avoiding any ambiguity in how to count twist: an unknot with zero twist is one whose normal bundle can be isotoped to be a plane annulus.

The following criterion is a very slight modification of [13, Cor. 3.2.17], with a near-identical proof. Since the method of proof relies heavily on terminology and techniques of [13], we suppress the details.

Theorem 2.4. *Let \mathcal{T} be a template in S^3 . Suppose that there exist three disjoint closed orbits on \mathcal{T} , κ , κ' , κ'' such that*

- 1) *they are separable unlinked unknots;*
- 2) *$\tau(\kappa) = 0$, $\tau(\kappa') > 0$, $\tau(\kappa'') < 0$; and*
- 3) *these three unknots intersect some branchline of \mathcal{T} as in Fig. 3[left] with the specified adjacencies and strip crossings.*

Then \mathcal{T} is a universal template.

The proofs of all the main theorems in this paper consist of constructing and simplifying templates for fibred knots and links, and then searching for the three unknots $\{\kappa, \kappa', \kappa''\}$ to which one may apply Theorem 2.4. Because these templates are quite complex, we introduce a “cartoon” notation (cf. [16]).

- 1) Strips in the template are collapsed along the direction transverse to the semiflow to become braided curves, except in a neighborhood of the branch lines;

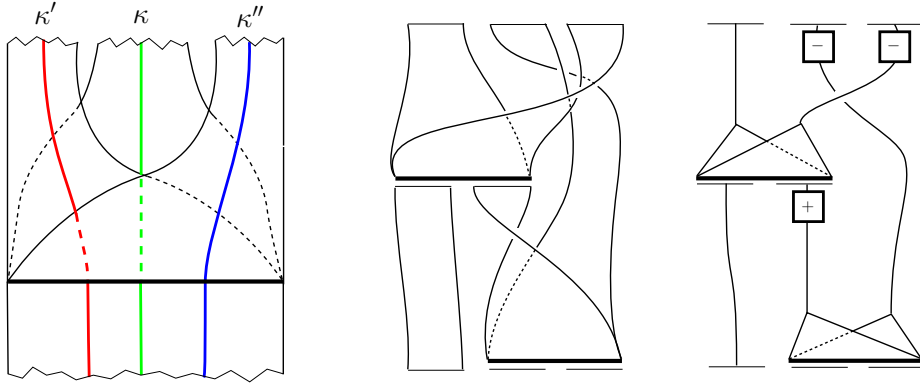


Figure 3. $\kappa', \kappa, \kappa''$ from left to right [left]; a template and its cartoon representation — top and bottom are identified [center, right].

- 2) Each half-twist of each strip is represented by a label + or - within a box, depending on the sign of the crossing;
- 3) Templates will often be “cut open” with the top and bottom to be identified.

For example, the template in Fig. 3[center] is expressed in cartoon form in Fig. 3[right].

2.4. Templates for planetary links. The branched cover construction allows one to construct a template for the planetary link of certain fibred knots/links. Recall the notation that β , the closure of b , is an unknotted geometric braid with braid axis α ; p is an m -fold branched cover over β ; and $\underline{\alpha} = p^{-1}(\alpha)$ is the lift of the braid axis, which, in the case of exchangeable braids is the closure of the braid a^m .

We summarize the procedure of [5, pp. 26-30] in the case of an exchangeable braid. If b is a braid of pseudo-Anosov type, then $\underline{\alpha}$ is fibred and also of pseudo-Anosov type, since the monodromy map for $\underline{\alpha}$ projects under p to the monodromy map of α represented by the pseudo-Anosov braid type b .

The following procedure yields a template for the fibration of the closure of a^m :

- 1) Construct a train track graph for b along with its induced map;
- 2) Suspend the train track graph map and cut as necessary to obtain a template \mathcal{T} in the solid torus $S^3 - \alpha$;
- 3) Peel off a copy of the unknot β from the boundary of \mathcal{T} and find a spanning disc D for this unknot;
- 4) Cut \mathcal{T} along D and glue m copies of this cut template together end-to-end cyclically to obtain \mathcal{U}^m , the template for the fibration of the complement of $\underline{\alpha}$.

This procedure was carried out carefully in [5, pp. 28-30] for the figure-eight knot, which is the closure of the braid $(\sigma_1\sigma_2^{-1})^2$. Note that in this case $a = b = \sigma_1\sigma_2^{-1}$ is the simplest pseudo-Anosov braid type. The train track graph for this braid is an interval, and the graph map is represented in Fig. 10[left]. We reproduce this example in cartoon notation in Fig. 4 in preparation for the proof of Main Theorem (c). Familiarity with this example will reveal patterns in the general case.

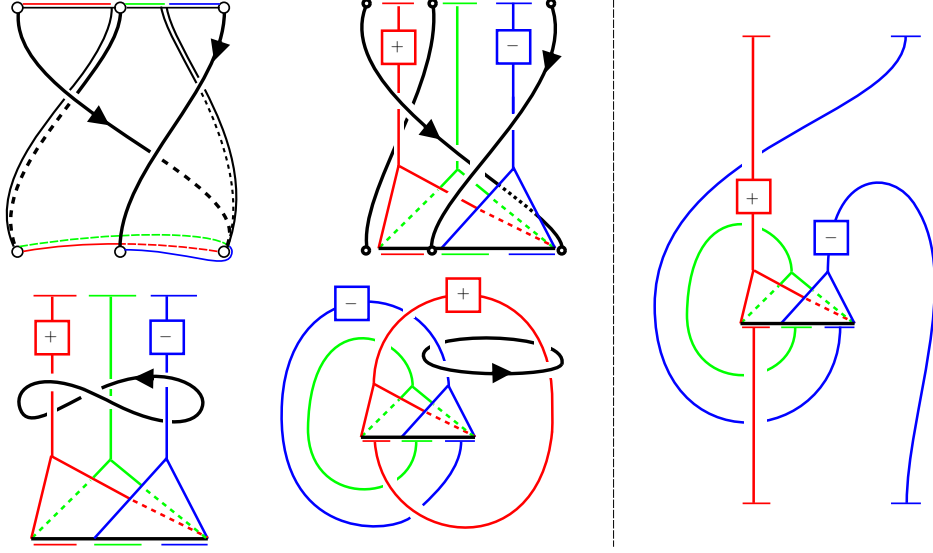


Figure 4. The branched cover construction for the figure-eight knot complement. The suspension of the train track for the braid $b = \sigma_1 \sigma_2^{-1}$ is a template [upper left]. By peeling off a copy of β and cutting along its spanning disc [lower left], one has a fundamental domain for the template of the m -fold cover [right].

3. Families of fibred knots and links

We focus on the following families of braids along which to perform the branched cover construction.

Definition 3.1. Given integers $n_1, n_2, \dots, n_k \geq 1$ (with $k > 1$), denote by $b := b_{(n_1, \dots, n_k)}$ the braid on $(1 + \sum_{r=1}^k n_r)$ strands given by the braid word

$$(2) \quad \underbrace{\sigma_1 \sigma_2 \cdots \sigma_{n_1}}_{n_1} \underbrace{\sigma_{n_1+1}^{-1} \cdots \sigma_{n_1+n_2}^{-1}}_{n_2} \cdots \underbrace{\sigma_{1+\sum_{r=1}^{k-1} n_r}^{(-1)^{(k+1)}} \cdots \sigma_{\sum_{r=1}^k n_r}^{(-1)^{(k+1)}}}_{n_k}.$$

Thus, b is equivalent to the form given in (1). For example, the braid in Fig. 1 is $b_{(2,2,1,1)}$. Clearly, one can also use the mirror image of these braids, and all the theorems we prove hold here as well.

Lemma 3.2. *The closure of $b_{(n_1, \dots, n_k)}$ is self-exchangeable. Specifically, given β the closure of $b_{(n_1, \dots, n_k)}$ with braid axis α , there exists an isotopy of S^3 taking α to the closure of $b_{(n_1, \dots, n_k)}$ with braid axis β .*

Proof: We induct on the length of the braid word b . Assume as an induction hypothesis that the N -strand closed braid β exchanges with α as in Fig. 5[left]: specifically, that there is an isotopy which is fixed on a solid ball as indicated. Now, for a braid of the form $b\sigma_N$ (in Fig. 5[right]) or $b\sigma_N^{-1}$, fit the final strand within

a larger fixed solid ball and perform the isotopy given by induction. Fig. 6 shows that this final strand of β may be exchanged relative to a yet smaller fixed ball. Note that in the diagram, the set of crossings in the braid word b is flipped and rotated, but is kept together rigidly. \square

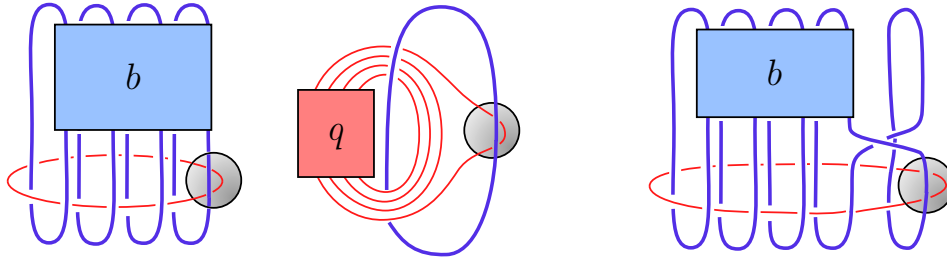


Figure 5. The induction hypothesis: the closure of the braid b can be exchanged with its axis rel a fixed ball [left]; the setup for the induction step [right].

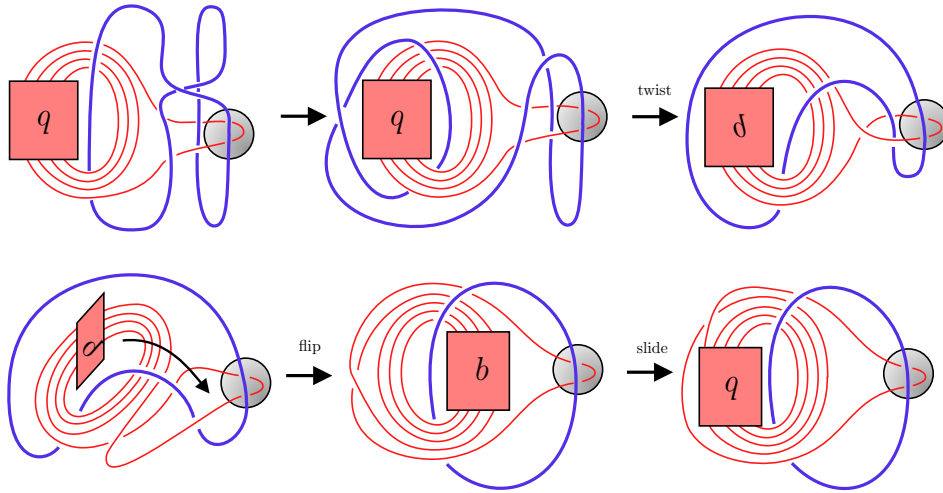


Figure 6. The induction step: the closure of $b\sigma_N$ can be exchanged with its axis rel a fixed ball.

Lemma 3.3. *The braid $b = b_{(n_1, \dots, n_k)}$ is of pseudo-Anosov type.*

A proof of this can be explicitly given by one of the [several] algorithms available.²

We note, however, that the braid b is precisely that considered by Gabai and Kazez [12], who show the pseudo-Anosov braid type.

²We have used the Bestvina-Handel algorithm [2] for this family: though straightforward, the algorithm is lengthy and of little consequence for the remainder of this article.

By Lemma 3.3, we have the following;

Corollary 3.4. *For each integer $m > 1$, the closure of $(b_{(n_1, \dots, n_k)})^m$ is a fibred knot/link of pseudo-Anosov type.*

The braid $b_{(n_1, \dots, n_k)}$ induces a very simple map on the closed disc consisting of a collection of k rotations which alternate direction, and the associated train track is very straightforward to compute. Let $G = G_{(n_1, \dots, n_k)}$ be a chain of k radial “stars” S_1, \dots, S_k , each star having valence $(n_i + 1)$ vertex if $n_i > 1$ (Fig. 7). The radial stars alternate their up-down orientation, and small loops (corresponding to the periodic orbit) are attached at the ends of the radial oriented edges as in Fig. 7. The set of non-loop edges in S_i equals $\{e_i^0\}$ if $n_i = 1$ (resp. $\{e_i^0, \dots, e_i^{n_i}\}$ if $n_i > 1$). For example, see Fig. 8.

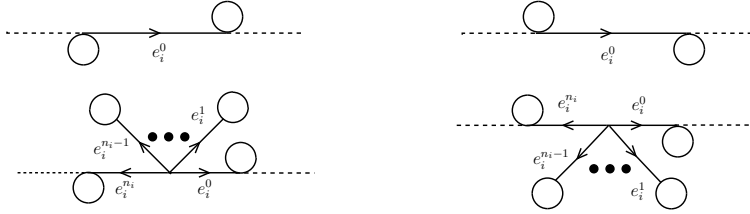


Figure 7. i odd, $n_i = 1$ [upper left]; i even, $n_i = 1$ [upper right]; i odd, $n_i > 1$ [lower left]; i even, $n_i > 1$ [lower right].

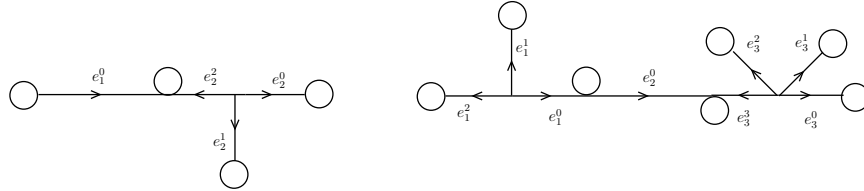


Figure 8. $G_{(1,2)}$ [left]; $G_{(2,1,3)}$ [right].

Lemma 3.5. *An efficient³ graph map $g = g_{(n_1, \dots, n_k)} : G \rightarrow G$ for the train track graph of $b_{(n_1, \dots, n_k)}$ is given as $g_k \circ \dots \circ g_1$, where g_i rotates the i -th star S_i in the clockwise (resp. counterclockwise) direction if i is even (resp. odd), see Fig. 9.*

The algebraic presentation of the train track map is simple to derive knowing that it is composed of rotations. For simplicity, we ignore all loop-edges in the train track. Given an oriented edge E , we denote the same edge oriented in the opposite direction by \overline{E} . The following lemma is used to derive a normal form of the template $\mathcal{T}_{(p,q)}$ in Section 4.1.

³For the definition of the **efficient graph maps**, see [2, pp. 114]. In general, the efficient graph map is not unique for the braid b .

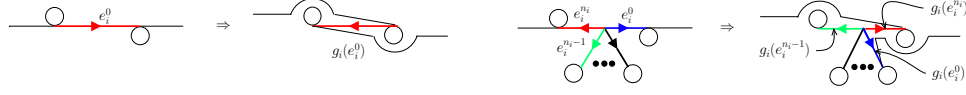


Figure 9. i even, $n_i = 1$ [left]; i even, $n_i > 1$ [right].

Lemma 3.6. *The images of the edges under $g = g_{(p,q)}$ are as follows; For $p = q = 1$,*

$$\begin{aligned} g(e_1) &= \overline{e_2^0} \overline{e_1^0}, \\ g(e_2) &= e_1^0 e_2^0 \overline{e_2^0}. \end{aligned}$$

For $p, q > 1$,

$$\begin{aligned} g(e_1^p) &= e_1^0 \overline{e_2^q} e_2^0, \\ g(e_2^q) &= e_2^0 \overline{e_2^q} e_2^q \overline{e_1^0} e_1^0, \\ g(e_1^i) &= e_1^{i+1} \quad (i = 0, \dots, p-1), \\ g(e_2^i) &= e_2^{i+1} \quad (i = 0, \dots, q-1), \end{aligned}$$

see Fig. 10.

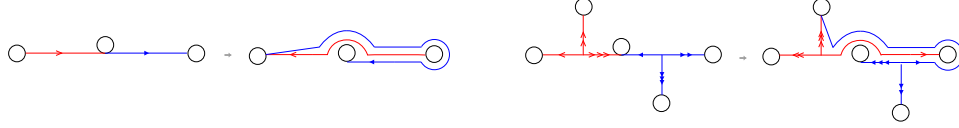


Figure 10. $g_{(1,1)}$ [left]; $g_{(2,2)}$ [right].

4. Subtemplates in branched covers

The various cases of the Main Theorem all possess the same strategy of proof. Given the braid $b = b_{(n_1, \dots, n_k)}$, we suspend the train track $G = G_{(n_1, \dots, n_k)}$ by the train track map $g = g_{(n_1, \dots, n_k)}$ to obtain a template $\mathcal{T}_{(n_1, \dots, n_k)}$. We then use the branched covering method to obtain a template $\mathcal{U}_{(n_1, \dots, n_k)}^m$ which captures the monodromy of the closure of the braid b^m . Since, in general, $\mathcal{U}_{(n_1, \dots, n_k)}^m$ is much too complex to visualize, we focus on a particular subtemplate which we may show to be universal. In this section, we prove the technical results for restricting attention to appropriately simple subtemplates.

4.1. A normal form. We now derive the branched surface $\mathcal{T}_{(p,q)}$ obtained from $G_{(p,q)}$ by suspending $g_{(p,q)}$ from the previous section. In what follows, we assume $p, q > 1$. (Other cases are much simpler and left to readers.) Let q_ℓ and q_r be the valence $(p+1)$ vertex and $(q+1)$ vertex of S_1 and S_2 respectively. These suspend to give the knots k_ℓ and k_r . Notice that the set of loop-edges in $S_1 \cup S_2$ is a periodic orbit, say $A_{(p,q)}$, corresponding to the closure of $b_{(p,q)}$.

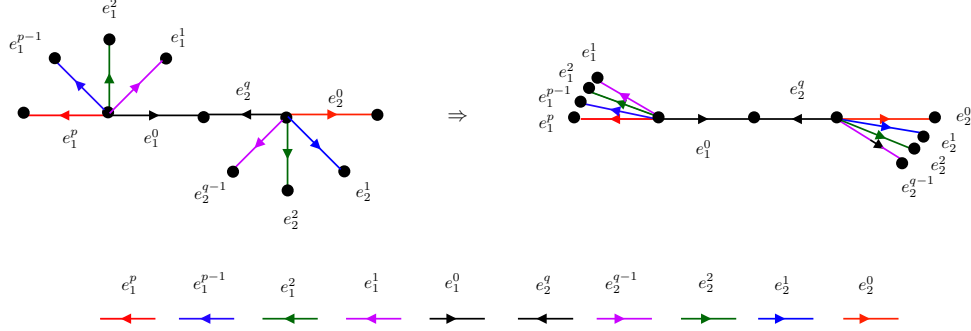


Figure 11. Flattening a pair of stars into strips.

To visualize $\mathcal{T}_{(p,q)}$ as a template, we need to “cut open” q_ℓ , q_r and $A_{(p,q)}$, and flatten out the strips in some canonical way. This is illustrated in Fig. 11.

Recall that $g(e_1^p) = e_1^0 e_2^q e_2^0$. We split the edge e_1^p into E and E' so that $g(E) = e_1^0 e_2^q$ and $g(E') = e_2^0$. Split the edge e_2^q into F, F' and F'' so that $g(F) = e_2^0$, $g(F') = e_2^0$ and $g(F'') = e_2^q e_1^0 e_1^1$. For the template $\mathcal{T}_{(p,q)}$, we can use the symbols $x_{i=0..p+1}$, and $y, z_{j=0..q+1}$ for the first and second stars respectively. The edge e_1^0 goes to x_0 , and the edge e_2^0 goes to z_0 , etc., and e_1^p is split into x_p and x_{p+1} corresponding to E and E' , and e_2^q split into z_q, z_{q+1}, y corresponding to F, F' and F'' . We denote the left end point and right end point of the branch segment of the strip x by $p_\ell(x)$ and $p_r(x)$ respectively. Since the initial vertex of $e_1^0, e_1^1, \dots, e_1^p$ is the same vertex q_ℓ , we must abstractly identify (1) $p_r(x_1), p_r(x_2), \dots, p_r(x_p)$ and $p_\ell(x_0)$. In the same manner, we need to identify (2) $p_r(x_0)$ and $p_\ell(y)$, (3) $p_r(y)$ and $p_\ell(z_{q+1})$, (4) $p_r(z_{q+1})$ and $p_\ell(z_q)$, (5) $p_\ell(z_0), p_\ell(z_1), \dots, p_\ell(z_{q-1})$ and $p_r(z_q)$, and (6) $p_\ell(x_p)$ and $p_r(x_{p+1})$.

Upon suspension of the train track maps, the symbols x_i , y , and z_i will correspond to portions of the branch lines, or, equivalently, to the exiting strips.

For the remainder of the paper, we conveniently leave these boundary curves as distinct. When constructing subtemplates of this branched surface, we are careful never to use these edges within the subtemplates. In this way, we do not need to worry about the changes to the periodic orbits set we have made.

The normal form of $\mathcal{T}_{(p,q)}$ appears in cartoon form as in Fig. 12.

In order to construct $\mathcal{U}_{(p,q)}^m$, the template for the m -fold branched cover of $\mathcal{T}_{(p,q)}$, we must “peel off” a parallel copy of β and cut $\mathcal{T}_{(p,q)}$ by a spanning disc for this unknot: cf. the figure-eight knot case in Fig. 4. Thus, the fundamental domain of $\mathcal{U}_{(p,q)}^m$ depends on the linking properties of β with $\mathcal{T}_{(p,q)}$.

Lemma 4.1. *Let β be the closure of $b_{(p,q)}$ and β' a parallel copy. Then β' links $\mathcal{T}_{(p,q)}$ as in Fig. 13.*

Proof: Note that $g_{(n_1, n_2)}$ has three fixed points q_ℓ, q_c, q_r , where q_ℓ and q_r are as above and $q_c \in e_2^q$ (see Lemma 3.6). These suspend to give the three unknots k_ℓ, k_c , and k_r . It is clear from the image of the train track (see Figs. 10 and 14) that the fixed point q_c is “in back” of the image of all the other edges, and that consequently

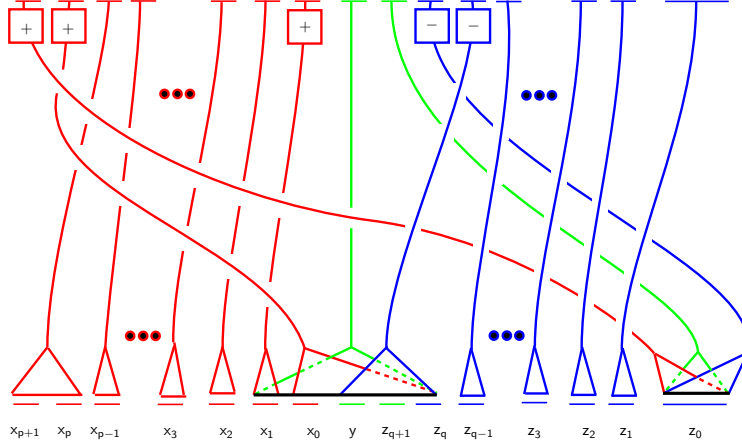


Figure 12. The normal form for the template $\mathcal{T}_{(p,q)}$.

the suspension of this fixed point, k_c , is an unknot which is of twist zero and separable from all other orbits on the template. Hence, $lk(k_c, \beta) = 0$. Since the train track map rotates each star about its central vertex with opposite orientations, it is easy to see that $lk(k_\ell, \beta) = +1$ and $lk(k_r, \beta) = -1$ (see Fig. 14[left]).

Since the strip y contains k_c and $lk(k_c, \beta) = 0$, y and β are linked as in Fig. 14. Because of the way we unfolded the star in Fig. 11, the way that z_{q+1} and β are linked is same as that of y and β .

Notice that the edges e_1^0, \dots, e_1^p were all “split off” of q_ℓ , and $lk(k_\ell, \beta) = +1$. Hence x_0, \dots, x_p, x_{p+1} and β are linked as in Fig. 14. Since the edges $e_2^0, \dots, e_2^{q-1}, F(\subset e_2^q)$ were also “split off” of q_r and $lk(k_r, \beta) = -1$, the strips z_0, \dots, z_{q-1}, z_q and β are linked as in Fig. 14. This completes the proof. \square

By Lemma 4.1, the fundamental domain of $\mathcal{U}_{(p,q)}^m$ is as in Fig. 15, where we have cut along a spanning disc of β . To form $\mathcal{U}_{(p,q)}^m$, take m copies of this fundamental domain joined cyclically end-to-end: see, e.g., Fig. 17.

4.2. Subtemplates. The (very complicated) normal form $\mathcal{U}_{(n_i, n_{i+1})}^m$ is tame compared to the full template $\mathcal{U}_{(n_1, \dots, n_k)}^m$. Fortunately, we do not need to consider the most general case.

Lemma 4.2. *Suppose i is odd [resp. even]. Then $\mathcal{T}_{(n_i, n_{i+1})}$ [resp. its mirror image] is a subtemplate of $\mathcal{T}_{(n_1, \dots, n_k)}$.*

Proof: We prove this result on the level of the train track (by subdividing and removing extraneous portions), and then suspend this to obtain the result for subtemplates. We only prove the case $n_i, n_{i+1} > 1$, for other cases are similar. Let $G = G_{(n_1, \dots, n_k)}$ and $g = g_{(n_1, \dots, n_k)}$. For the proof of the lemma, it is enough to show that there exist subdivisions $I_2 I_1 = e_i^{n_i}$, $J_3 J_2 J_1 = e_{i+1}^{n_{i+1}}$ of G that satisfy the following:

Remove I_2 and J_2 from S_i and S_{i+1} respectively. Then $(S_i \cup S_{i+1})'$ denotes the graph obtained from $(S_i \cup S_{i+1})$ by identifying the right

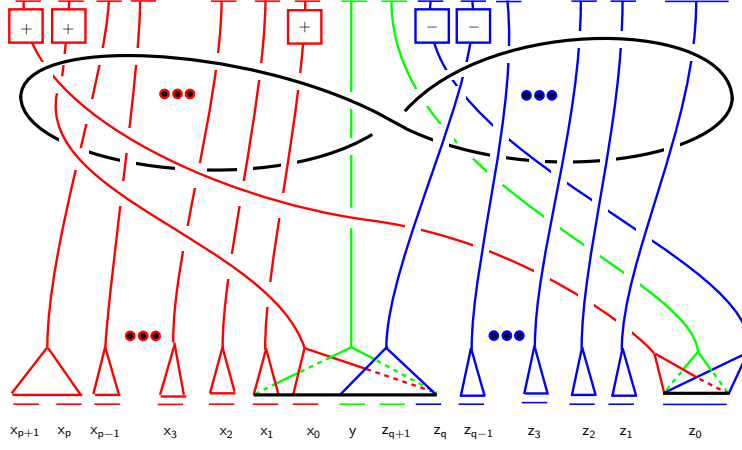


Figure 13. A parallel copy of the closed braid β links certain strips of $\mathcal{T}_{(p,q)}$.

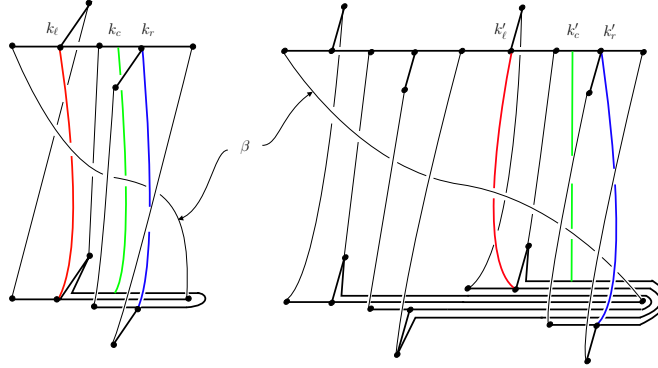


Figure 14. $p = q = 2$ [left]; $k = 4$ and $n_1 = n_2 = n_3 = n_4 = 2$ [right].

end point of J_3 and the left end point of J_1 . Then $g((S_i \cup S_{i+1})') = g_{i+1}(g_i(S_i \cup S_{i+1}))$, see Fig. 16.

We demonstrate the case $i = 1$, the proof for other cases being similar. Denote by c_i the following edges of the train track: $c_i = e_i^0$ if $n_i = 1$ and $c_i = \overline{e_i^{n_i}} e_i^0$ if $n_i > 1$. By induction on k , one demonstrates that $g(e_1^{n_1}) = e_1^0 c_2 \cdots c_k$, $g(e_2^{n_2}) = e_2^0 c_3 \cdots c_{k-1} c_k \overline{c_{k-1}} \cdots \overline{c_2} e_1^0$, and $g(e) = g_2(g_1(e))$ for $e \in S_1 \cup S_2 \setminus \{e_1^{n_1}, e_2^{n_2}\}$. Take subdivisions $I_2 J_1 = e_1^{n_1}$ and $J_3 J_2 J_1 = e_2^{n_2}$ such that $g(I_1) = e_1^0 c_2$, $g(J_3) = e_2^0$, and $g(J_1) = \overline{c_2} e_1^0$. Since $g(I_1) = g_2(g_1(e_1^{n_1}))$, $g(J_3)g(J_1) = g_2(g_1(e_2^{n_2}))$ and $g(e) = g_2(g_1(e))$ for $e \in S_1 \cup S_2 \setminus \{e_1^{n_1}, e_2^{n_2}\}$, we have $g((S_1 \cup S_2)') = g_2(g_1(S_1 \cup S_2))$. \square

Lemma 4.3. *Suppose i is odd [resp. even]. Then $\mathcal{U}_{(n_i, n_{i+1})}^m$ [resp. its mirror image] is a subtemplate of $\mathcal{U}_{(n_1, \dots, n_k)}^m$.*

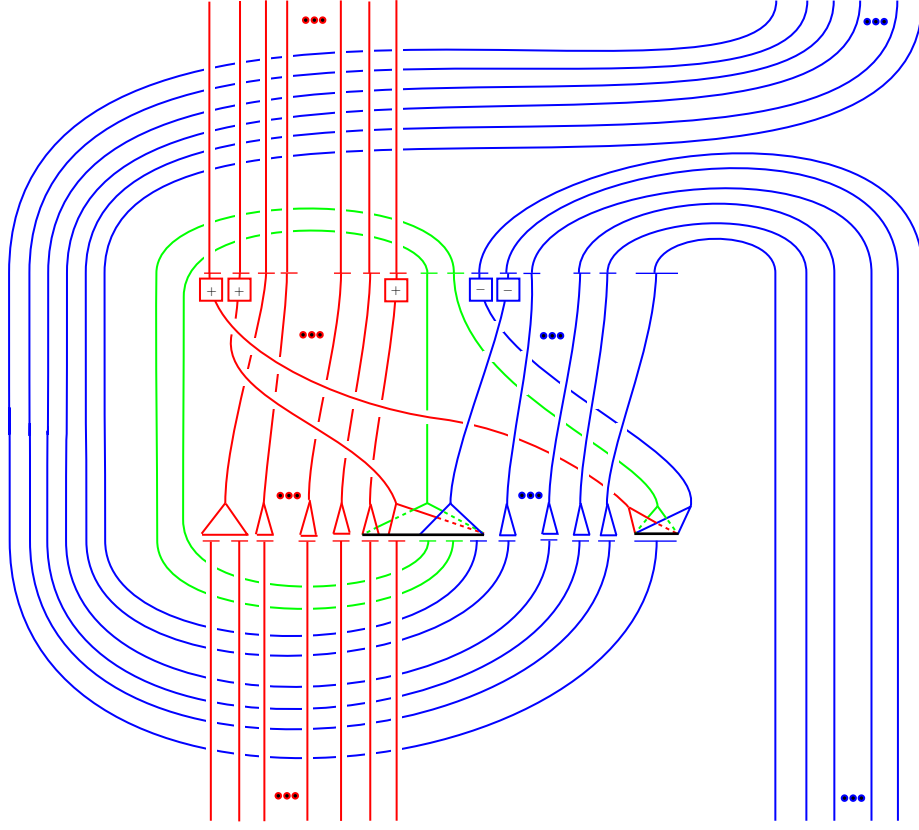


Figure 15. The fundamental domain of $U_{(p,q)}^m$, cf. Fig. 4.

Proof: We consider the case of i odd and $n_i, n_{i+1} > 1$; the other cases share identical proofs. The key step in this lemma is to determine the linking properties of β with the subtemplate obtained from Lemma 4.2.

Note that $g_{(n_1, \dots, n_k)}$ has three corresponding fixed points q'_ℓ, q'_c, q'_r , where q'_ℓ and q'_r are (n_i+1) vertex and $(n_{i+1}+1)$ vertex of S_i and S_{i+1} respectively, and $q'_c \in e_{i+1}^{n_{i+1}}$. Denote by k'_ℓ, k'_c, k'_r the three unknots given by suspending these points. Let β and β' be the closures of $b_{(n_1, n_2)}$ and $b_{(n_1, \dots, n_k)}$ respectively. As in the proof of Lemma 4.1, one shows that $\ell k(k'_\ell, \beta') = \ell k(k_\ell, \beta) = +1$, $\ell k(k'_c, \beta') = \ell k(k_c, \beta) = 0$, and $\ell k(k'_r, \beta') = \ell k(k_r, \beta) = -1$, see Fig. 14(b). This together with Lemma 4.2 implies Lemma 4.3. \square

5. The Main Theorems

We now have assembled all the ingredients to prove the Main Theorems.

5.1. Main Theorem (c). We begin with the easiest and least general of the three Main Theorems. A proof can be obtained implicitly by a combination of Lemma 4.3

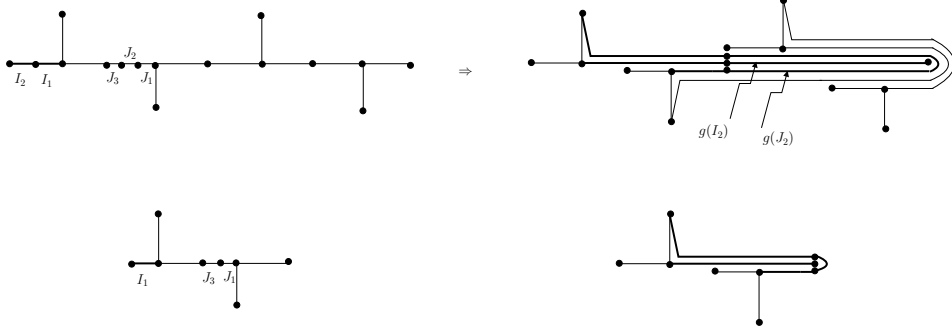


Figure 16. $g = g_{(2,2,1)}$ [top]; $(S_1 \cup S_2)'$ [lower left]; $g((S_1 \cup S_2)')$, which equals $g_2(g_1(S_1 \cup S_2))$ [lower right].

with a geometric argument from [14, pp. 444-5]. However, to set a pattern for the proofs of Main Theorems (a) and (b), we give a different proof of (c).

Theorem 5.1. *Let $b = b_{(n_1, \dots, n_k)}$ where $n_j = n_{j+1} = 1$ for some j . Then the closure of b^m is a knot/link in S^3 with the universal fibration property for every $m \geq 2$.*

Proof: From Lemma 4.3, we may restrict attention to the subtemplate $\mathcal{U}_{(1,1)}^m$ within $\mathcal{U}_{(n_1, \dots, n_k)}^m$. The template $\mathcal{T}_{(1,1)}$ is given in cartoon form in Fig. 4, along with a representation of the fundamental domain of $\mathcal{U}_{(1,1)}^m$. Our strategy is to identify three unknots on $\mathcal{U}_{(1,1)}^m$ — κ , κ' , and κ'' — to which we can apply Theorem 2.4.

Specifically, using the symbolic representation of the orbits as periodic words, let $\kappa = (y)$, $\kappa' = (x^m)$, and $\kappa'' = (z^m)$. Recall that (x^m) means to follow the periodic orbit which traverses the x -strip m times. While there is an ambiguity in the symbolic representation (in terms of which fundamental domain the symbol is on), the only choice is for (y) , and by cyclic symmetry, the result is independent of the choice.

It is trivial to see from Fig. 17[left] that (1) these three curves are separable unknots; and (2) κ has zero twist, κ' has positive twist, and κ'' has negative twist. The only other ingredient needed to invoke Theorem 2.4 is that the three orbits meet at a branchline as in Fig. 3. This is not the case, since the strip z does not fully cover the branchline. To remedy this, we replace (x^m) with (yx^m) . This orbit is still a separable unknot (using [13, Prop. 3.1.19]) whose (already positive) twist has increased by two and which now passes through the triple branchline in precisely the manner of Fig. 3. Hence, by Theorem 2.4, $\mathcal{U}_{(1,1)}^m$ is universal. \square

5.2. Main Theorem (b). The following theorem will allow us to completely classify the fibrations of 2-bridge knot complements in the next section.

Theorem 5.2. *The closure of $(b_{(n_1, \dots, n_k)})^2$ has the universal fibration property.*

Proof: To prove Theorem 5.2, it suffices to show that $\mathcal{U}_{(p,q)}^2$ is universal for all p and q . We assume $p, q > 1$, the other cases being both simpler and similar to Main

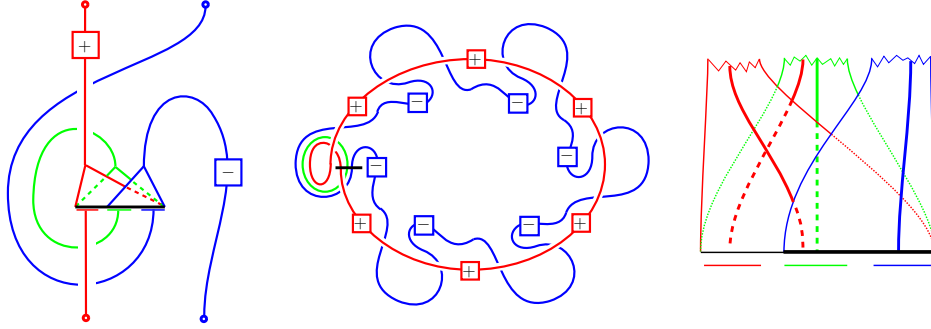


Figure 17. A cartoon representation of the fundamental domain of $\mathcal{U}_{(1,1)}^m$ [left]; the unknots κ , κ' , and κ'' in the case $m = 6$ [center]; all three orbits pass through the same branch line [right].

Theorem (c). The strategy, as in the previous theorem, is to find three well-chosen unknots $\kappa, \kappa', \kappa''$ on $\mathcal{U}_{(p,q)}^2$.

As before, choose $\kappa := (y)^\infty$ the untwisted unknot separable from all other orbits on the template. For p odd (resp. even), define

$$\kappa' := (yx_0x_1x_2 \cdots x_{p-1}x_p) \quad (\text{resp. } \kappa' := (yx_1x_2 \cdots x_{p-1}x_p)),$$

see Fig. 18. For q odd (resp. even), define

$$\kappa'' := (yz_qz_0z_1 \cdots z_{q-1}) \quad (\text{resp. } \kappa'' := (yz_{q+1}z_0z_1 \cdots z_{q-1})),$$

see Fig. 19. Note that there is an ambiguity as to which fundamental domain the orbit segment y of κ' and κ'' passes through. We specify as follows: take κ' and κ'' such that the orbit segment y passes through the fundamental domain where κ lies. The figures imply that these are separable unlinked unknots with $\tau(\kappa) = 0$, $\tau(\kappa') > 0$, and $\tau(\kappa'') < 0$. These unknots κ, κ' and κ'' pass through the triple branchline as in Fig. 20. Hence, by Theorem 2.4, $\mathcal{U}_{(p,q)}^2$ is universal. \square

5.3. Main Theorem (a). For part (a) of the Main Theorem — that the universal fibration property holds for m sufficiently large — we give a more precise formulation.

Theorem 5.3. *Let $N := \min_i(\max\{n_i, n_{i+1}\})$. The closure of $(b_{(n_1, \dots, n_k)})^m$ has the universal fibration property for all $m \geq N(N - 1)$.*

Proof: By Lemma 4.3, it is enough to show that $\mathcal{U}_{(p,q)}^m$ is universal for each $m \geq N(N - 1)$, where $N = \max\{p, q\}$. As before, we assume p and q greater than 1.

Let $m = pt' + s' = qt'' + s''$ be Euclidean integer factorizations of m ; hence $0 \leq s' < p$ and $0 \leq s'' < q$. As $m \geq N(N - 1)$, it follows that $t' \geq s'$ and $t'' \geq s''$.

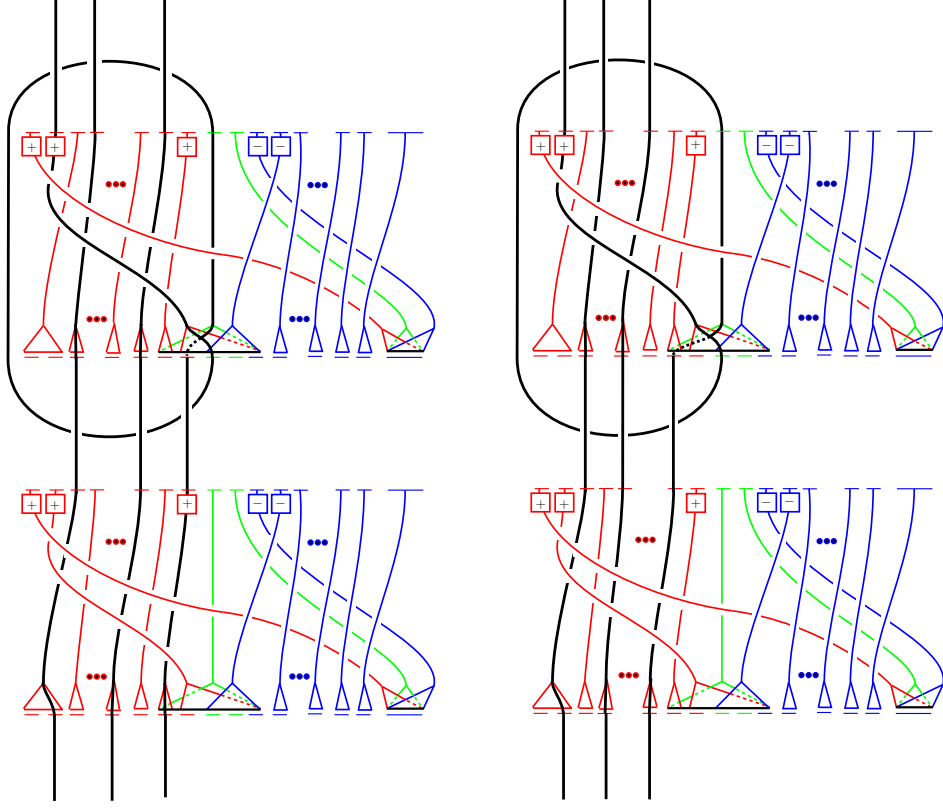


Figure 18. The orbit κ' in Main Theorem (b); p is odd [left]; even [right].

Consider the following three periodic orbits on $\mathcal{U}_{(p,q)}^m$:

$$(3) \quad \begin{aligned} \kappa &:= (y) \\ \kappa' &:= \left((y x_1 \cdots x_p)^{t'-s'} (x_0 x_1 \cdots x_p)^{s'} \right) \\ \kappa'' &:= \left((z_{q+1} z_0 z_1 \cdots z_{q-1})^{t''-s''} (z_q z_0 z_1 \cdots z_{q-1})^{s''} \right) \end{aligned} .$$

The orbit κ is, as before, an untwisted unknot which lies within one fundamental domain of $\mathcal{U}_{(p,q)}^m$. The orbit κ' passes through $p(t' - s') + (p + 1)s' = pt' + s' = m$ fundamental domains of $\mathcal{U}_{(p,q)}^m$. Except for the occasional excursions about the y orbit (which do not change the knot type), the orbit κ' can be thought of as a 1-strand braid about the braid axis of $\mathcal{U}_{(p,q)}^m$: it is therefore an unknot. All twisting in the x -strips is of a positive nature, so that κ' is an unknot with positive twist. A similar argument shows that κ'' passes through $q(t'' - s'') + (q + 1)s'' = m$ fundamental domains and is an unknot with negative twist separable from κ' .

These orbits are a triple of separable unknots which satisfy the conditions of Theorem 2.4, as illustrated in Fig. 21. Hence $\mathcal{U}_{(p,q)}^m$ is universal. \square

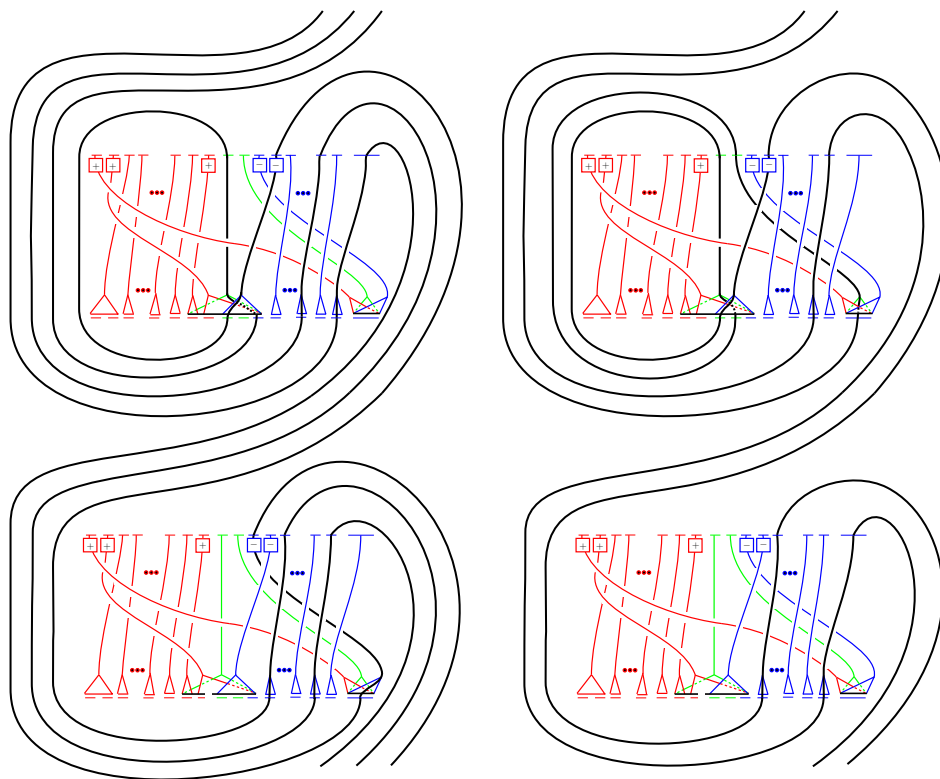


Figure 19. The orbit κ'' in Main Theorem (b): q is odd [left]; even [right].

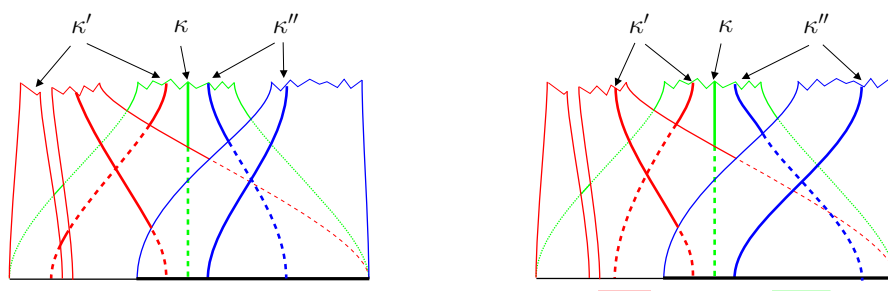


Figure 20. A closeup of the branch line in the proof of Main Theorem (b); p and q even [left]; p and q odd [right].

6. Concluding remarks

We have displayed a large family of fibred knots/links whose fibrations force all knot and link types in the complement. It remains an open question how large this family can be:

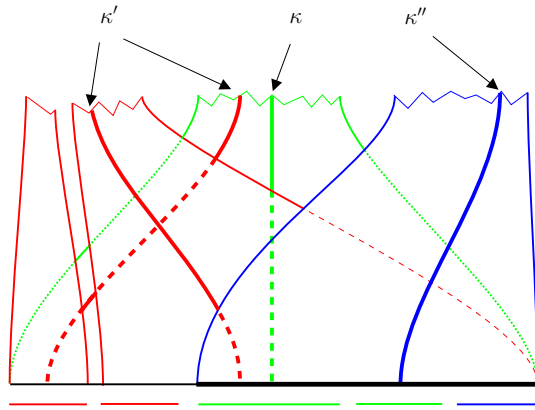


Figure 21. A closeup of the branch line in the proof of Main Theorem (a).

Question 6.1. *Is every fibred knot/link of pseudo-Anosov type universally fibred ?*

We conclude this paper with a few remarks on this question.

6.1. 2-bridge knots. Recall that a **2-bridge knot** is one which can be isotoped so as to have precisely four critical points (two minima and two maxima) with respect to the standard height function in \mathbb{R}^3 . We can affirmatively answer Question 6.1 in this category.

Corollary 6.2. *Every fibred non-torus 2-bridge knot has the universal fibration property.*

Proof: The work of Gabai and Kazez [12] explicitly shows that the class of fibred 2-bridge knots is precisely that class of knots whose fibres are a chain of plumbed Hopf bands, and that the monodromy is of pseudo-Anosov type if and only if the Hopf bands are not all of the same sign, which is to say, if and only if it is not a torus knot. We claim that such a chain of plumbed Hopf bands has a closed braid form of $(b_{(n_1, \dots, n_k)})^2$. The proof is inductive on the number of Hopf bands and illustrated in Fig. 22. The key step is noting that the fibre for the closure of $(b_{(n_1, \dots, n_k)})^2$ is a stack of discs attached by a pairs of half-twisted bands: this is precisely a chain of plumbed Hopf bands. From Theorem 5.2, we have that this knot must be universally fibred. \square

6.2. Connected sums. We can enlarge the class of universally fibred knots considerably by taking connected sums.

Proposition 6.3. *The connected sums of any fibred knot/link with any universally fibred knot/link is universally fibred.*

Proof: In [11, Corollary 1.4.], it is shown that the Murasugi sum of fibre surfaces is “natural”. Specifically, if K_i is a fibred knot/link ($i = 1, 2$) with fibre surface Σ_i and monodromy Φ_i satisfying $\Phi_i|_{\partial\Sigma_i} = id$, then the Murasugi sum of Σ_1 and

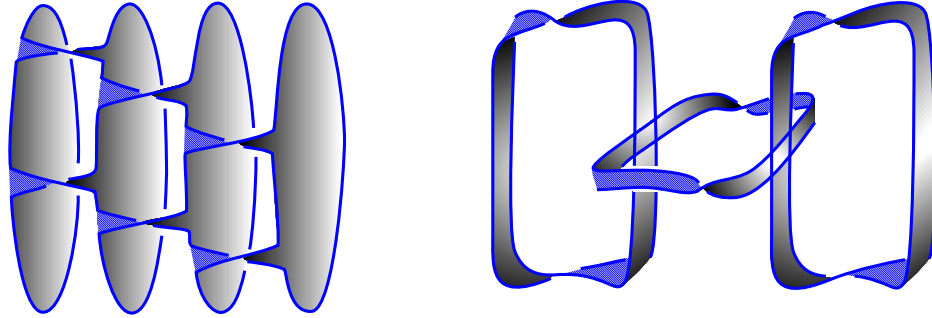


Figure 22. Plumbings of Hopf bands [right] can be arranged as a closed braid of the form $(b_{n_1, \dots, n_k})^2$ [left].

Σ_2 along a $2k$ -gon D common to Σ_1 and Σ_2 is fibre surface and has monodromy $\tilde{\Phi}_1 \circ \tilde{\Phi}_2$, where $\tilde{\Phi}_i$ is equal to Φ_i on Σ_i and the identity map elsewhere.

Even more importantly, the proof of this result uses vector fields transverse to the fibration to achieve the result. Thus, we actually have that a transverse vector field of the Murasugi sum decomposes naturally.

The simplest kind of Murasugi sum (where the attachment is along a 2-gon in the spanning surfaces) is precisely the connected sum. Choose the monodromy Φ_1 of the universally fibred knot to be the pseudo-Anosov representative, isotoped so as to be the identity map on the the boundary. Likewise, choose the monodromy Φ_2 to be the Thurston canonical form isotoped to be the identity on the boundary. The composition monodromy on the connected (in this case, Murasugi) sum is easily isotoped to have an invariant curve separating the universal pseudo-Anosov component from the Thurston form of Φ_2 . Thus, the theorem of Asimov and Franks implies that any transverse vector field must have at least this set of periodic orbits — all knots and links. \square

As a corollary of the proof, we see that in certain instances, more general Murasugi sums (e.g., plumbing) can preserve the universal fibration property as well. One would need to control (1) the dynamics on the attaching region, to preserve the pseudo-Anosov property of the monodromy, and (2) the location of the attaching region, so that it does not interfere with the universal subtemplate.

6.3. Too-twisted monodromies. We believe that there are pseudo-Anosov fibred knots or links whose monodromies are too “twisted” to admit a universal template in the suspension. Our proposed example stems from the fact that the proof of Main Theorem (c) requires a sufficiently high order branched cover.

Conjecture 6.4. *For p and q sufficiently large, the closure of $(b_{(p,q)})^3$ is not universally fibred.*

Our reason for conjecturing the non-universality stems from the difficulty in finding enough unknotted orbits on which to build a universal subtemplate.

References

- [1] D. Asimov and J. Franks, *Unremovable closed orbits*, in Geometric Dynamics, Ed. J. Palis, Lect. Notes in Math. 1007, Springer-Verlag, (1983) 22-29.
- [2] M. Bestivina and M. Handel, *Train-Tracks for surface homeomorphisms*, Topology 34 (1) (1994) 109-140.
- [3] J. Birman, *A representation theorem for fibered knots and their monodromy maps*, in Topology of Low-dimensional Manifolds, Lecture Notes in Math. 722, Springer-Verlag (1977) 1-8.
- [4] J. Birman and R. Williams *Knotted periodic orbits in dynamical systems – I: Lorenz’s equations*, Topology 22(1), (1983) 47-82.
- [5] J. Birman and R. Williams, *Knotted periodic orbits in dynamical systems – II: Knot holders for fibered knots*, Contemp. Math. 20, (1983) 1-60.
- [6] A. de Carvalho and T. Hall, *Braid forcing and star-shaped train tracks*, to appear in Topology. Preprint ArXiv math.DS/0204115, 2002.
- [7] J. Casasayas, J. Martinez Alfaro, and A. Nunes, *Knots and links in integrable Hamiltonian systems*, J. Knot Theory & Ramifications 7(2) (1998) 123-153.
- [8] J. Etnyre and R. Ghrist, *Gradient flows within plane fields*, Commun. Math. Helv. 74 (1999) 507-529.
- [9] A. Fomenko and T. Z. Nguyen, *Topological classification of integrable nondegenerate Hamiltonians on isoenergy three-dimensional spheres*, in Adv. Soviet Mathematics Vol. 6, A. Fomenko ed., pp. 267-296, AMS, 1991.
- [10] J. Franks, *Knots, links, and symbolic dynamics*, Ann. Math. 113 (1981) 529-552.
- [11] D. Gabai, *The Murasugi sum is a natural geometric operation. II*, Contemp. Math. 44, (1985) 93-100.
- [12] D. Gabai and W. Kazez *Pseudo-Anosov maps and surgery on fibred 2-braid knots*, Top. & Its Applications 37 (1990) 93-100.
- [13] R. Ghrist, P. Holmes and M. Sullivan, *Knots and Links in Three-Dimensional Flows*, Lect. Notes in Math. 1654, Springer-Verlag (1997).
- [14] R. Ghrist, *Branched two-manifolds supporting all links*, Topology 36 (2) (1997) 423-448.
- [15] D. Goldsmith, *Symmetric fibered links*, in Knots, Groups, and 3-Manifolds, Ann. of Math. Studies 84, Princeton Univ. Press, Princeton, (1975) 3-23.
- [16] P. Melvin and N. Tufflaro, *Templates and framed braids* Phys. Rev. A, 44(6) (1991) 3419-3422.
- [17] H. Morton and M. Rampichini, *Mutual braiding and the band presentation of braid groups*, in Knots in Hellas '98 Delphi, 335-346.
- [18] R. Penner and J. Harer, *Combinatorics of Train Tracks*, Ann. of Math. Studies 125, Princeton Univ. Press, Princeton (1992)
- [19] D. Rolfsen, *Knots and Links*, Publish or Perish Press, 1976.
- [20] W. Thurston, *On the geometry and dynamics of diffeomorphisms of surfaces*, Bull. Am. Math. Soc. 19 (2) (1988) 417-431.
- [21] M. Wada, *Closed orbits of nonsingular Morse-Smale flows on S^3* , J. Math. Soc. Japan 41(3) (1989), 405-413.
- [22] R. Williams, *One dimensional nonwandering sets*, Topology, 6 (1967), 473-487.

<http://www.math.uiuc.edu/~ghrist/>

DEPARTMENT OF MATHEMATICS, KYOTO UNIVERSITY, OIWAKE-CHO KITASHIRAKAWA SAKYO-KU
KYOTO-SHI, KYOTO 606-8502 JAPAN
E-mail address: kin@kusum.kyoto-u.ac.jp

RG supported by NSF Grants # DMS-0337713 and # INT-0089631.
EK supported in part by JSPS Research Fellowships for Young Scientists.