QUASIFUCHSIAN STATE SURFACES

DAVID FUTER, EFSTRATIA KALFAGIANNI, AND JESSICA S. PURCELL

Abstract. This paper continues our study of essential state surfaces in link complements that satisfy a mild diagrammatic hypothesis (homogeneously adequate). For hyperbolic links, we show that the geometric type of these surfaces in the Thurston trichotomy is completely determined by a simple graph–theoretic criterion in terms of a certain spine of the surfaces. For links with $A$– or $B$–adequate diagrams, the geometric type of the surface is also completely determined by a coefficient of the colored Jones polynomial of the link.

1. Introduction

A major goal in modern knot theory is to relate the geometry of a knot complement to basic topological invariants that are easy to read from a diagram of the knot. In a recent monograph [13], we find connections between geometric invariants of a knot or link complement, combinatorial properties of its diagram, and stable coefficients of its colored Jones polynomials. The bridge among these different invariants consists of state surfaces associated to Kauffman states of a link diagram [17]. These surfaces lie in the link complement and are naturally constructed from a diagram, while certain graphs that form a spine for these surfaces aid in the computation of Jones polynomials [7].

In this paper, we continue the study of these state surfaces, with the goal of obtaining additional geometric information on a link complement, and relating it back to diagrammatical and quantum invariants of the link. In particular, we establish combinatorial criteria that characterize the geometric types of state surfaces in the Thurston trichotomy. This trichotomy, proved by Thurston [26] and Bonahon [2], asserts that every essential surface in a hyperbolic 3-manifold fits into exactly one of three types: semi-fiber, quasifuchsian, or accidental. (See Definition 1.2 below for details.) We show that under a mild diagrammatic hypothesis, certain state surfaces will never be accidental, and a simple graph–theoretic property determines whether the state surface is a semi-fiber or quasifuchsian. For the class of $A$– or $B$–adequate diagrams, which arise in the study of knot polynomial invariants [19, 25], the geometric type of the surface is determined by the colored Jones polynomials of the knot. See Theorem 1.4 below.

The problem of determining the geometric types of essential surfaces in knot and link complements has been studied fairly well in the literature. For example, Menasco and Reid proved that no alternating link complement contains an
embedded quasifuchsian closed surface [21], which led to the result that there are no embedded totally geodesic surfaces in alternating link complements. More recently, Masters and Zhang found closed, immersed quasifuchsian surfaces in any hyperbolic link complement [20]. As for accidental surfaces, Finkelstein and Moriah established conditions for the existence of closed accidental surfaces in a wide range of link complements [10, 11]. This work was generalized by Wu [30].

Turning to surfaces with boundary, it is known that all three geometric types occur in hyperbolic link complements. For example, Tsutsumi constructed hyperbolic knots with accidental Seifert surfaces of arbitrarily high genus [27]. On the other hand, Fenley proved that minimal genus Seifert surfaces cannot be accidental [9]. An alternate proof of this was given by Cooper and Long [5]. Wise showed that checkerboard surfaces in alternating link complements are not virtual fibers [29], and Adams showed that they are always quasifuchsian [1]. Here we give an alternate proof of this fact, and provide broad families of non-accidental surfaces constructed from non-alternating diagrams.

The results of this paper have some direct consequences in hyperbolic geometry. First, they dovetail with recent work of Thistlethwaite and Tsvietkova, who gave an algorithm to construct the hyperbolic structure on a link complement directly from a diagram [24, 28]. Their algorithm works whenever a link diagram admits a non-accidental state surface, which is exactly what our results ensure for a very large class of diagrams. Second, the quasifuchsian surfaces that we construct fit into the machinery developed by Adams [1]. He showed that if a cusped hyperbolic manifold contains a properly embedded quasifuchsian surface with boundary, then there are restrictions on the cusp geometry of that manifold.

1.1. Definitions and main results. To describe our results precisely, we need some definitions. As we will be working with both orientable and non-orientable surfaces, we need to clarify the notion of an essential surface.

Definition 1.1. Let $M$ be an orientable 3–manifold and $S \subset M$ a properly embedded surface. We say that $S$ is essential in $M$ if the boundary of a regular neighborhood of $S$, denoted $\tilde{S}$, is incompressible and boundary–incompressible.

Note that if $S$ is orientable, then $\tilde{S}$ consists of two copies of $S$, and the definition is equivalent to the standard notion of “incompressible and boundary–incompressible” for orientable surfaces.

Definition 1.2. Let $M$ be a compact 3–manifold with boundary consisting of tori, and let $S$ be a properly embedded essential surface in $M$. An accidental parabolic on $S$ is a free homotopy class of a closed curve that is not boundary–parallel on $S$ but can be homotoped to the boundary of $M$. If $M$ is hyperbolic, then the embedding of $S$ into $M$ induces a faithful representation $\rho: \pi_1(S) \hookrightarrow \pi_1(M) \subset PSL(2, \mathbb{C})$. In this case, an accidental parabolic is a non–peripheral element of $\pi_1(S)$ that is, is mapped by $\rho$ to a parabolic in $\pi_1(M)$. A surface $S$ with accidental parabolics is called accidental.

If $M$ is hyperbolic, the surface $S$ is called quasifuchsian if the embedding $S \hookrightarrow M$ lifts to a topological plane in $\mathbb{H}^3$ whose limit set $\Lambda \subset \partial \mathbb{H}^3$ is a topological circle. Note that we permit $S$ to be non–orientable: in this case, the two disks bounded by the Jordan curve $\Lambda$ will be be interchanged by isometries corresponding to $\pi_1(S)$.
Finally, we say the surface \( S \) is a *semi-fiber* if it is a fiber in \( M \) or covered by a fiber in a two-fold cover of \( M \). If \( S \) is a semi-fiber but not a fiber, we call it a *strict* semi-fiber.

By the work of Thurston [26] and Bonahon [2] (see also Canary, Epstein and Green [3]), every properly embedded, essential surface \( S \) in a finite volume hyperbolic 3–manifold \( M \) falls into exactly one of the three types in Definition 1.2: \( S \) is either a semi-fiber, or accidental, or quasifuchsian.

We will apply the above definitions to surfaces constructed from \textit{Kauffman states} of link diagrams. For any crossing of a link diagram \( D(K) \), there are two associated diagrams, obtained by removing the crossing and reconnecting the diagram in one of two ways, called the \( A \–resolution \) and \( B \–resolution \) of the crossing, shown in Figure 1.

A choice of an \( A \–o r \( B \–resolution \) for each crossing of \( D \) is called a \textit{Kauffman state} [17]. The result of applying a Kauffman state \( \sigma \) to a link diagram \( D \) is a collection of circles \( s_\sigma \) disjointly embedded in the projection plane \( S^2 \subset S^3 \). These circles bound embedded disks whose interiors can be made disjoint by pushing them below the projection plane. Now, at each crossing of \( D \), we connect the pair of neighboring disks by a half–twisted band to construct a \textit{state surface} \( S_\sigma \subset S^3 \) whose boundary is \( K \).

State surfaces generalize the classical checkerboard knot surfaces, and they have recently appeared in the work of several authors, including Przytycki [23] and Ozawa [22]. They are the primary object of interest in this paper, for certain states. In order to describe these states, we need a few more definitions.

From the collection of state circles \( s_\sigma \), we obtain a trivalent graph \( H_\sigma \) by attaching edges, one for each crossing of the original diagram \( D(K) \), as shown by the dashed lines of Figure 1. As in [13], the edges of \( H_\sigma \) that come from crossings of the diagram are referred to as *segments*, and the other edges are portions of state circles. See Figure 2.

In the literature, a graph that is more common than the graph \( H_\sigma \) is the *state graph* \( G_\sigma \), which is formed from \( H_\sigma \) by collapsing components of \( s_\sigma \) to vertices. Remove redundant edges between vertices to obtain the *reduced state graph* \( G'_\sigma \).

**Definition 1.3.** Following Lickorish and Thistlethwaite [19] [25], a state \( \sigma \) of a diagram \( D \) is said to be *adequate* if every segment of \( H_\sigma \) has its endpoints on distinct state circles of \( s_\sigma \). In this case, the diagram \( D \) is called \( \sigma \–adequate \). When \( \sigma \) is the all–\( A \) state (all–\( B \) state), we call the diagram \( A \–adequate \) (\( B \–adequate \)).

In any state \( \sigma \), the circles of \( s_\sigma(D) \) divide the projection plane into components. Every crossing of \( D \) is associated to a segment of \( H_\sigma \), which belongs to one of
these components. Label each segment \( A \) or \( B \), in accordance with the choice of resolution at this crossing. We say that the state \( \sigma \) is homogeneous if all edges in a complementary region of \( s_\sigma \) have the same \( A \) or \( B \) label. In this case, we say that \( D \) is \( \sigma \)–homogeneous. An example is shown in Figure 2. If a link \( K \) admits a diagram that is both \( \sigma \)–homogeneous and \( \sigma \)–adequate, for the same state \( \sigma \), we call \( K \) homogeneously adequate.

Ozawa showed that the state surface \( S_\sigma \) of an adequate, homogeneous state \( \sigma \) is essential in the link complement \([22]\). A different proof of this fact follows from machinery developed by the authors \([13]\). The state surfaces \( S_A \) and \( S_B \) corresponding to the all–\( A \) and all–\( B \) states, respectively, also play a significant role in quantum topology. In \([13]\), we show that coefficients of the colored Jones polynomials detect topological information about these surfaces. For instance, if \( K \) is an \( A \)–adequate link, then \( S_A \) is a fiber in the link complement precisely when a particular coefficient vanishes (and similarly for \( S_B \)).

In this paper, we show that for hyperbolic link complements, the colored Jones polynomial completely determines the geometric type of \( S_A \) in the Thurston trichotomy of Definition \([1, 2]\). To state our result, let

\[
J^K_n(t) = \alpha_n t^{m_n} + \beta_n t^{m_n-1} + \ldots + \beta'_n t^{r_n+1} + \alpha'_n t^{r_n}
\]

denote the \( n \)-th colored Jones polynomial of a link \( K \), where \( m_n \) and \( r_n \) denote the highest and the lowest degree. Recall that \( J^K_2(t) \) is the usual Jones polynomial. Suppose that \( K \) is a link admitting an \( A \)–adequate diagram \( D \). Consider the all–\( A \) state graph \( G_A \) and the reduced graph \( G'_A \). By \([8]\) Theorem 3.1], for all \( n > 1 \), we have \( |\alpha'_n| = 1 \) and \( |\beta'_n| = 1 - \chi(G'_A) \). Thus we may define the stable coefficient

\[
(1) \quad \beta'_K := |\beta'_n| = 1 - \chi(G'_A).
\]

Similarly, if \( D \) is \( B \)–adequate, then \( |\alpha_n| = 1 \) and \( |\beta_n| = 1 - \chi(G'_B) \), hence there is a stable coefficient \( \beta_K := |\beta_n| = 1 - \chi(G'_B) = 1 - \chi(G'_B) \).

Finally, recall that a link diagram \( D \) is called prime if any simple closed curve that meets the diagram transversely in two points bounds a region of the projection plane without any crossings. A prime knot or link admits a prime diagram.

One of our results is the following theorem.
Theorem 1.4. Let $D(K)$ be a prime, $A$–adequate diagram of a hyperbolic link $K$. Then the stable coefficient $\beta'_K$ determines the geometric type of the all–$A$ surface $S_A$, as follows:

- If $\beta'_K = 0$, then $S_A$ is a fiber in $S^3 \setminus K$.
- If $\beta'_K \neq 0$, then $S_A$ is quasifuchsian.

Similarly, if $D(K)$ is a prime $B$–adequate diagram of a hyperbolic link $K$, then the stable coefficient $\beta_K$ determines the geometric type of $S_B$. This surface will be a fiber if $\beta_K = 0$, and quasifuchsian otherwise.

Remark 1.5. The class of $A$– or $B$–adequate links includes all alternating links, positive and negative closed braids, closed 3–braids, Montesinos links, Conway sums of alternating tangles, and planar cables of all the above. It also includes all but a handful of prime knots up to 12 crossings. See [13, Section 1.3] for more discussion and references. The class of homogeneously adequate links includes all of the above and also contains the homogeneous links studied by Cromwell [6].

We note that the class of homogeneously adequate links is strictly larger than that of $A$– and $B$–adequate links: For example, consider the knot $K = 12n0873$ of Knotinfo [4]. Its Jones polynomial $J_K(t) = 3t^{-4} - 7t^{-3} + 11t^{-2} - 14t^{-1} + 15 - 14t + 11t^2 - 7t^3 + 3t^4$ is not monic, hence $K$ is neither $A$– nor $B$–adequate. On the other hand, according to [4], $K$ is written as the closure of the homogeneous braid $b = \sigma_1 \sigma_2 \sigma_3^{-1} \sigma_4^{-1} \sigma_2 \sigma_3^{-1} \sigma_1 \sigma_2 \sigma_3^{-1} \sigma_2 \sigma_4^{-1} \sigma_3^{-1}$, where $\sigma_i$ denotes the $i$–th standard generator of the 5–string braid group. It is not hard to see that the Seifert state of the closed braid diagram is homogeneous and adequate.

At this writing, it is not known whether every hyperbolic link admits a homogeneously adequate diagram. See [22] and [13, Chapter 10] for related discussion and questions.

The main new result of this paper is the following theorem.

Theorem 1.6. Let $D(K)$ be a prime link diagram with an adequate, homogeneous state $\sigma$. Then the state surface $S_\sigma$ is essential and admits no accidental parabolics. Furthermore, $S_\sigma$ is a semi-fiber whenever it is a fiber, which occurs if and only if $G'_\sigma$ is a tree.

Theorem 1.4 follows immediately from Theorem 1.6: simply restrict to $A$–adequate diagrams, and note that equation (1) above implies $\beta'_K = 0$ precisely when $G'_A$ is a tree.

The result that checkerboard surfaces in hyperbolic alternating link complements are quasifuchsian (compare Adams [1]) also follows immediately from Theorem 1.6. This is because checkerboard surfaces correspond to the all–$A$ and all–$B$ states of alternating link diagrams, which are always homogeneous and adequate, and the corresponding graphs $G'_A$ and $G'_B$ will be trees only when the reduced alternating diagram of the link depicts a $(2,q)$ torus link, which is not hyperbolic.

The main novel content of Theorem 1.6 is that $S_\sigma$ is never accidental. Indeed, in [13, Theorem 5.21], we showed that $S_\sigma$ is a fiber precisely when the reduced state graph $G'_\sigma$ is a tree and that it is never a strict semi-fiber. Thus, by Thurston and Bonahon [2], for a hyperbolic link $K$ the surface $S_\sigma$ is quasifuchsian precisely when $G'_\sigma$ is not a tree.
1.2. **Organization.** In Section 2, we discuss accidental parabolic elements in the fundamental group of a state surface. We observe that the existence of such elements gives rise to an essential embedded annulus in the complement of the state surface, and then exclude such annuli in the case where $K$ is a knot (see Theorem 2.6). This, in particular, implies the main results for knots.

Proving Theorem 1.6 in the more general case of links is harder and involves knowing more details about the complement of the state surface. In Section 3, we describe the structure of an ideal decomposition of the state surface complement, which was first constructed in [13]. In Section 4, we study normal annuli in this polyhedral decomposition, and prove that such an annulus can never realize an accidental parabolic. We expect that some of the combinatorial results established in Section 4 will also prove useful for studying more general essential surfaces in the complements of homogeneously adequate links.

2. **Embedded annuli and knots**

In this section, we prove that if an essential state surface $S_\sigma$ has an accidental parabolic, that is, if a non-peripheral curve in $S_\sigma$ is homotopic to the boundary, then such a homotopy can be realized by an embedded annulus. This will quickly lead to a proof of Theorem 1.6 in the special case where $K$ is a knot.

**Definition 2.1.** Let $M$ be a compact orientable 3–manifold with $\partial M$ consisting of tori, and $S \subset M$ a properly embedded essential surface. We use the notation $M \setminus \! \! \setminus S$ to denote the path–metric closure of $M \setminus S$. Up to homeomorphism, $M \setminus \! \! \setminus S$ is the same as the complement of a regular neighborhood of $S$.

The **parabolic locus** $P$ is the portion of $\partial M$ that remains in $\partial (M \setminus \! \! \setminus S)$. If every torus of $\partial M$ is cut along $S$, then the parabolic locus $P$ will consist of annuli. Otherwise, it will consist of annuli and tori. The remaining, non-parabolic boundary $\partial (M \setminus \! \! \setminus S) \setminus \partial M$ can be identified with $\tilde{S}$, the boundary of a regular neighborhood of $S$. In the special case where $M = S^3 \setminus K$ is a link complement and $S = S_\sigma$ is a state surface, we use the notation $M_\sigma$ to refer to $M \setminus \! \! \setminus S_\sigma = (S^3 \setminus K) \setminus S_\sigma = S^3 \setminus S_\sigma$.

The following lemma recounts a standard argument. It should be compared, for example, to [5, Lemma 2.1].

**Lemma 2.2.** Let $M$ be a compact orientable 3–manifold with $\partial M$ consisting of tori. Let $S \subset M$ be a properly embedded essential surface. If $S$ has an accidental parabolic, then there is an embedded essential annulus $A \subset M \setminus \! \! \setminus S$ with one boundary component on $\tilde{S}$ and the other on the parabolic locus $P = \partial M \setminus \partial S$. Furthermore, if $\partial S$ meets every component of $\partial M$, the component $\partial A \subset P$ is parallel to a component of $\partial \tilde{S}$.

**Proof.** If $S$ admits an accidental parabolic, then there exists a non-peripheral closed curve $\gamma$ on $\tilde{S}$ which is freely homotopic into $\partial M$ through $M$. The free homotopy defines a map of an annulus $A_1$ into $M$, with one boundary component on $\gamma$ and the other on $\partial M$. Put $A_1$ into a general position with respect to $S$. Because $S$ may be non-orientable, we will work with the boundary of a regular neighborhood of $S$, denoted $\tilde{S}$. We may move the component of $\partial A_1$ on $\tilde{S}$ in a bi-collar of $S$ to be disjoint from $\tilde{S}$. Now, any closed curve of intersection of $A_1$ and $\tilde{S}$ that bounds a disk in $A_1$ can be pushed off $\tilde{S}$ by the fact that $\tilde{S}$ is incompressible (because $S$ is essential; see Definition 1.1). Likewise, we can push off any arcs of intersection of
A₁ and \( \tilde{S} \) which have both endpoints on \( \partial M \), because \( \tilde{S} \) is boundary incompressible. Because we have moved the other boundary component of \( A_1 \) off \( \tilde{S} \), there can be no arcs of intersection of \( A_1 \) and \( \tilde{S} \). There may be closed curves of intersection that are essential on \( A_1 \).

Apply a homotopy to minimize the number of closed curves of intersection. Then there is a sub-annulus \( A_2 \subseteq A_1 \) that is outermost, i.e. has one boundary component on \( \partial M \) and one on \( \tilde{S} \). Note that \( A_2 \) might equal \( A_1 \). By construction, the interior of \( A_2 \) is mapped to the interior of \( M \setminus \tilde{S} \). We may assume that the mapping of \( A_2 \) into \( M \setminus \tilde{S} \) is non-degenerate, i.e. cannot be homotoped into the boundary of \( (M \setminus \tilde{S}) \), for otherwise the map of \( A_1 \) into \( M \) can be simplified by homotopy. Now, the annulus theorem of Jaco [16, Theorem VIII.13] implies there exists an essential embedding of an annulus \( A \) into \( M \setminus \tilde{S} \), with one end in \( \tilde{S} \) and the other end on the parabolic locus \( P \).

Now \( M \setminus \tilde{S} \) is the disjoint union of an \( I \)-bundle over \( S \) and a manifold homeomorphic to \( M \setminus S \), with the non-parabolic portions of \( M \setminus \tilde{S} \) homeomorphic to the non-parabolic portions of \( M \setminus S \). The \( I \)-bundle over \( S \) cannot contain any accidental parabolic annuli, for such an annulus would realize a homotopy between a peripheral and a non-peripheral curve in \( S \). Thus \( A \) must lie in the component of \( M \setminus \tilde{S} \) which is homeomorphic to \( M \setminus S \). □

In [13], we constructed a polyhedral decomposition of \( M_\sigma \). In the next section, we will outline several of its pertinent features, while referring to [13,14] for details. To handle the case where \( K \) is a knot, we mainly need the following result.

**Theorem 2.3** (Theorem 3.23 of [13]). Let \( D(K) \) be a connected diagram with an adequate, homogeneous state \( \sigma \). There is a decomposition of \( M_\sigma \) into 4-valent, checkerboard colored ideal polyhedra. The ideal vertices lie on the parabolic locus \( P \), the white faces are glued to other polyhedra, and the shaded faces lie in \( \tilde{S}_\sigma \), the non-parabolic part of \( \partial M_\sigma \).

Normal surface theory ensures that the intersections of the annulus \( A \) of Lemma 2.2 with the polyhedral decomposition of \( M_\sigma \) can be taken to have a number of nice properties.

**Definition 2.4.** We say a surface is in normal form if it satisfies the following conditions:

(i) Each component of its intersection with the polyhedra is a disk.

(ii) Each disk intersects a boundary edge of a polyhedron at most once.

(iii) The boundary of such a disk cannot enter and leave an ideal vertex through the same face of the polyhedron.

(iv) The surface intersects any face of the polyhedra in arcs.

(v) No such arc can have endpoints in the same ideal vertex of a polyhedron, or in a vertex and an adjacent edge.

**Lemma 2.5.** Let \( D(K) \) be a link diagram with an adequate, homogeneous state \( \sigma \). Suppose the state surface \( S_\sigma \) has an accidental parabolic. Then the embedded annulus \( A \) of Lemma 2.2 can be moved by isotopy into normal form with respect to the polyhedral decomposition of \( S^3 \setminus S_\sigma \). The intersections of \( A \) with white faces of the polyhedra are all lines running from one boundary component of \( A \) to the other.
Proof. Note that $M_\sigma = S^3 \setminus S_\sigma$ is topologically a handlebody, hence irreducible. By Haken [15] we may isotope $A$ into normal form. Consider the intersections of $A$ with white faces. A component of intersection cannot be a simple closed curve, by item (iv) of the definition of normal form. If a component of intersection is an arc with both endpoints on $N(K)$, we can remove this intersection by [13, Lemma 3.20]: every white face of the polyhedral decomposition is boundary incompressible in $M \setminus S_\sigma$. Similarly, suppose an arc of intersection has both endpoints on $S_\sigma$. Then we may pass to an outermost such arc and obtain a normal bigon, that is, a normal disk with two sides. This contradicts [13, Proposition 3.24]: the polyhedral decomposition of $M \setminus S_\sigma$ contains no normal bigons. □

We are now ready to prove that an adequate, homogeneous state surface for a knot admits no accidental parabolics.

Theorem 2.6. Let $D(K)$ be a knot diagram with an adequate, homogeneous state $\sigma$. Then the state surface $S_\sigma$ cannot be accidental.

Proof. Suppose not: suppose $S_\sigma$ is accidental. Then Lemma 2.2 implies there is an embedded annulus $A$ in $M_\sigma$ with one boundary component on $S_\sigma$ and the other on the parabolic locus $N(K)$. Consider the intersections of $A$ with a fixed white face $W$. Because the boundary component of $A$ on $N(K)$ runs parallel to $S_\sigma$, the annulus $A$ must intersect each ideal vertex of $W$. Moreover, by Lemma 2.5, any component of intersection $A \cap W$ runs from the component of $A$ on $N(K)$ to the component on $\widehat{S}_\sigma$. Hence on $W$, this intersection is an arc from an ideal vertex of $W$ to one of the sides of $W$ (shaded faces are on $\widehat{S}_\sigma$).

Because $A$ is normal, item (v) of Definition 2.4 implies that such an arc cannot run from an ideal vertex to an adjacent edge. But now we have a contradiction: there is no way to embed a collection of arcs in $W$ such that each arc meets one ideal vertex and one side of $W$ without having an arc that runs from an ideal vertex to an adjacent edge. □

3. Details of the ideal polyhedra

The proof of Theorem 2.6 for links requires knowing more information about the polyhedral decomposition of [13]. In this section, we review some of the relevant features, referring to [13, Chapters 2–4] for more details.

A non-prime arc is an arc with both endpoints on the same state circle of $H_\sigma$, and interior disjoint from $H_\sigma$, which separates the subgraph of $H_\sigma$ on one side of the state circle into two graphs, each of which contain segments. Such a subgraph is called a non-prime half–disk. A collection of non-prime arcs is called maximal if, once we cut along all such arcs and all state circles, the graph decomposes into subgraphs, each of which contains a segment, and no larger collection of non-prime arcs has the same property.

Let $\{\alpha_1, \ldots, \alpha_n\}$ denote a maximal collection of non-prime arcs. We define a polyhedral region to be a non-trivial region of the complement of the state circles and the $\alpha_i$. The manifold $M_\sigma = S^3 \setminus S_\sigma$ decomposes into one upper polyhedron and several lower polyhedra. Each lower polyhedron corresponds to precisely one of these polyhedral regions. Furthermore, the state circles and segments that meet this polyhedral region naturally define a subgraph of $H_\sigma$ and a prime, alternating sub-diagram of $D(K)$. The 1–skeleton of the lower polyhedron is exactly the same as
the 4–valent projection graph of the prime, alternating link diagram corresponding
to this subgraph of $H_\sigma$.

Our maximal collection of non-prime arcs ensures that the polyhedral regions
correspond to prime sub-diagrams of $D(K)$ and to lower polyhedra without normal
bigons. Meanwhile, the vertices, edges, and faces of the upper polyhedron have the
following description:

(1) Each white face corresponds to a (non-trivial, i.e. non-innermost disk) com-
plementary region of $H_\sigma \cup (\bigcup_{i=1}^{n} \alpha_i)$.

(2) Each shaded face lies on $\tilde{S}_\sigma$ and is the neighborhood of a tree that we call
a spine. The spine is directed, in that each edge has a natural orientation.
Innermost disks are sources. Arrows are attached corresponding to tenta-
cles, which run from a state circle adjacent to a segment (the head) and
then turn left (all–A case) or right (all–B case) and have their tail along
a state circle, as well as non-prime switches, where four arrows meet at a
non-prime arc. See [13, Figure 3.7] for an illustration of these terms.

When an arc is running through the directed spine in the direction of
the arrows, we say it is running downstream.

(3) Each vertex of the upper polyhedron corresponds to a strand of $D(K)$
between consecutive under-crossings. In the graph $H_\sigma$, this strand follows
a zig-zag, that is, an alternating sequence of portions of state circles and
segments (possibly zero segments). See Figure 4, right, for a zig-zag with
one segment.

(4) Each edge of the upper polyhedron starts at the head of a tentacle of a
shaded face. As a result, ideal edges can be given an orientation, which
matches the orientation of the directed spine in that tentacle.

White faces of the lower polyhedra are glued to white faces of the upper poly-
hedron. We may transfer combinatorial information about the upper polyhedron
into the lower ones via a map called the clockwise map.

Definition 3.1. Let $W$ be a white face of the upper polyhedron, with $n$ sides. If
$W$ belongs to an all–A polyhedral region, the clockwise map $\phi$ on $W$ is defined by
composing the gluing map of the white face with a $2\pi/n$ clockwise rotation. See
Figure 3. If $W$ belongs to an all–B polyhedral region, the map $\phi$ is defined by
composing the gluing map with a $2\pi/n$ counter-clockwise rotation. We sometimes
call it the counter-clockwise map.

As illustrated in Figure 3 the clockwise or counter-clockwise map $\phi$ is orientation–
preserving. This is because the “viewer” is in the upper polyhedron: we see the
boundary of the upper polyhedron from the inside and each lower polyhedron from
the outside. With this convention, the gluing map preserves orientations, hence $\phi$
does also.

In the special case where $D(K)$ is prime and alternating, there is exactly one
lower polyhedron, and the 1–skeleta of both the upper and lower polyhedra coincide
with the 4–valent graph of the diagram. In this case, both the clockwise and
counter-clockwise maps can be seen as the “identity map” on regions of the diagram
[13]. In the non-alternating setting, more details about the clockwise map can be
found in [13, Sections 4.2 and 4.5].

The following lemma describes the effect of the clockwise and counter-clockwise
maps on normal squares, that is, normal disks with four sides. Here we allow a
portion of the quadrilateral that runs over $N(K)$ (i.e. a neighborhood of an ideal vertex of the polyhedral decomposition) to count as a side.

**Lemma 3.2.** Let $U$ be a polyhedral region of the projection plane, let $W_1, \ldots, W_k$ be the white faces in $U$, and let $P'$ be the lower polyhedron associated to $U$. Then the clockwise (counter-clockwise) map $\phi: W_1 \cup \cdots \cup W_k \to P'$ has the following properties:

1. If $x$ and $y$ are points on the boundary of white faces in $U$ that belong to the same shaded face of the upper polyhedron, then $\phi(x)$ and $\phi(y)$ belong to the same shaded face of $P'$.
2. Let $S$ be a normal square in the upper polyhedron with two sides on shaded faces (that is, on $\tilde{S}_\sigma$) and two sides on white faces $V$ and $W$, with $V$ and $W$ both belonging to polyhedral region $U$. Let $\beta_v = S \cap V$ and $\beta_w = S \cap W$. Then the arcs $\phi(\beta_v)$ and $\phi(\beta_w)$ can be joined along shaded faces to give a normal square $S' \subset P'$, defined uniquely up to normal isotopy. Write $S' = \phi(S)$.
3. Let $S$ be a square in the upper polyhedron with one side on a shaded face, two sides on white faces $V$ and $W$, and the fourth side on $N(K)$, meeting the upper polyhedron in a single ideal vertex between $V$ and $W$. Suppose further that $V$ and $W$ both belong to the polyhedral region $U$. Then the arcs $\beta_v = S \cap V$ and $\beta_w = S \cap W$ meet at a single ideal vertex in the lower polyhedron, and their other endpoints can be joined along a shaded face to...
In $S^3 \setminus K$ Upper polyhedron

Figure 4. Two arcs in white faces in the same all–A polyhedral region, meeting the same ideal vertex, must be as shown. In an all–B region, the picture is mirror reversed.

give a normal square $S' \subset P'$, defined uniquely up to normal isotopy. Write $S' = \phi(S)$.

(4) If $S_1$ and $S_2$ are disjoint normal squares in the upper polyhedron, all of whose white faces belong to $U$, then $\phi(S_1)$ is disjoint from $\phi(S_2)$.

Proof. Items (1) and (2) are proved in [13, Lemma 4.8] in the case where $U$ is an all–A polyhedral region. The proof of the all–B case is identical, with “clockwise” replaced by “counter-clockwise”. We do need to prove items (3) and (4).

For (3), let $S$ be a normal square in the upper polyhedron as described: sides $\beta_w$ and $\beta_v$ are arcs in white faces $V$ and $W$ lying in $U$, meeting at a single ideal vertex in the upper polyhedron. The proof of (2) implies that the endpoints of $\phi(\beta_w)$ and $\phi(\beta_v)$ on shaded faces can be connected by an arc in a single shaded face. Thus we focus on the endpoints which lie on an ideal vertex.

Because the clockwise (or counter-clockwise) map takes vertices of white faces to vertices, each of the arcs $\phi(\beta_w)$ and $\phi(\beta_v)$ still has one end on an ideal vertex in $P'$. We need to verify that they have this end on the same ideal vertex of $P'$.

Assume, without loss of generality, that $U$ is an all–A polyhedral region and the map $\phi$ is clockwise. (The proof for the counter-clockwise map will be identical.)

Recall that an ideal vertex in the upper polyhedron corresponds to a zig-zag in the graph $H_\sigma$. Because $V$ and $W$ belong to the same polyhedral region, they are not separated by any state circles. As a result, the vertex between them must be a zig-zag with a single segment. This single segment corresponds to a single over-crossing of the diagram and a single segment of the graph $H_\sigma$, as in Figure 4. But now the clockwise map rotates the vertices of each white face clockwise, to lie in the center of the next segment of $H_\sigma$ in the clockwise direction. Now, the endpoints of $\beta_v$ and $\beta_w$ are rotated to the center of the same segment, namely the segment corresponding to the single over-crossing of the ideal vertex.

Finally, for item (4), as $\phi$ is a homeomorphism on white faces, sides of $\phi(S_1)$ and $\phi(S_2)$ on white faces are disjoint. If both $\phi(S_1)$ and $\phi(S_2)$ pass through the interior of a shaded face $F$, then the argument of [13, Lemma 4.8] shows they are disjoint. If $\phi(S_1)$ passes through the interior of a shaded face $F$ and $\phi(S_2)$ passes through a vertex, then they will be disjoint in $F$. Finally, if $\phi(S_1)$ and $\phi(S_2)$ both pass through ideal vertices of $F$, if they pass through distinct vertices then their images will be disjoint. If they pass through (a neighborhood of) the same vertex in the upper polyhedron, since the squares are disjoint, in the adjacent white faces the arcs of $S_1$ must lie on the same side of the arc of $S_2$. This will be preserved by
the clockwise map acting on both faces, and so the images can be connected at the vertex in a manner that keeps them both disjoint. □

4. The case of links

The goal of this section is to prove Theorem 4.1 which generalizes Theorem 2.6 to links with multiple components. We note that, unlike Theorem 2.6, this result needs the hypothesis of prime diagrams.

Theorem 4.1. Let $D(K)$ be a prime, $\sigma$–adequate, $\sigma$–homogeneous link diagram. Then the state surface $S_\sigma$ has no accidental parabolics.

Suppose, to the contrary, that the state surface $S_\sigma$ is accidental. Then Lemma 2.2 implies there is an embedded annulus $A \subset M_\sigma$ with one boundary component on $\tilde{S}_\sigma$ and the other on the parabolic locus $N(K)$. After placing $A$ in normal form (as in Lemma 2.5), we obtain a number of normal squares in individual polyhedra. Following the annulus, these squares $A_1, \ldots, A_n$ alternate by lying in the upper polyhedron, then a lower polyhedron, then the upper polyhedron again, and so on. Each $A_i$ has two sides on white faces, one on a shaded face, and one on $N(K)$. Finally, each $A_i$ is glued to $A_{i+1}$ along a white face of the decomposition. Throughout this section, we adopt the convention that odd-numbered squares are in the upper polyhedron.

The proof of Theorem 4.1 is broken up into a number of lemmas, which analyze the intersection pattern of these squares and their clockwise images. In §4.1, we perform the first reductions in the proof and show Proposition 4.4: the annulus $A$ must be composed of at least 4 squares, and some white face met by $A$ has at least 4 sides. Then, in §4.2, we use the conclusion of Proposition 4.4 to restrict the possibilities for $D(K)$ further and further, until we show in §4.3 that $S_\sigma$ has no accidental parabolics.

4.1. First reductions in the proof. We begin with the following lemma.

Lemma 4.2. The annulus $A$ must contain at least 4 normal squares.

Proof. Since the squares $A_i$ alternate between the upper and lower polyhedra, the number of these squares must be even. Thus, suppose $A$ consists of only two squares: $A_1$ in the upper polyhedron and $A_2$ in a lower polyhedron. Since $A_1$ is glued to $A_2$ along both of its white faces, these white faces $V$ and $W$ must lie in the same polyhedral region $U$.

Recall that $A_1$ is glued to $A_2$ across $V$, and that the clockwise map $\phi$ differs from the gluing map by a $2\pi/n$ rotation. Thus in $V$, the arc of $A_1'$ differs from that of $A_2'$ by a single clockwise rotation. Similarly in $W$. The arcs of $A_1'$ and $A_2'$ in $V$ and $W$ must be as in Figure 5 left. The dashed lines in that figure indicate the clockwise motions of $A_2$. These must be the lines on the white faces $V$ and $W$ corresponding to $A_1'$. Note that the points where the dashed lines meet a vertex, labeled $x$ and $y$, must agree in the polyhedron. Putting these two points together, the diagram must be as in Figure 5 right.

But note in particular that there is a circle coming from the edges of the polyhedra which separates the two endpoints of the solid line representing $A_2$. (It also
Lemma 4.3. Let $A_1 \subset A$ be a normal square in the upper polyhedron. If both white faces met by $A_1$ are triangles, these triangles are in different polyhedral regions.

Proof. Suppose that $A_1$ lies in the upper polyhedron with both of its white faces in the same polyhedral region, and both of those white faces are triangles. Then we may map $A_1$ to the lower polyhedron of this polyhedral region via the clockwise (or counter-clockwise) map. Without loss of generality, we may assume that the map $\phi$ is clockwise in this region. Since $A_1$ is glued to $A_2$ and $A_n$, this lower polyhedron contains both $A_2$ and $A_n$.

The square $A_2$ in a lower polyhedron runs through one shaded face, one triangular white face, one other white face, and an ideal vertex. By Lemma 3.2 part (3), $A'_1 = \phi(A_1)$ is also a normal square that passes through an ideal vertex. Because $A_1$ is glued to $A_2$, we have one side of $A'_1$ and one side of $A_2$ in the same white triangle, and these sides differ by a single clockwise rotation. Thus $A'_1$ and $A_2$ must be as shown in Figure 6, left. Note that the shaded face met by $A_2$ and the shaded face met by $A'_1$ cannot agree: if they did, this single shaded face would meet the white face along two edges, contradicting [13, Proposition 3.24] (no normal bigons). Hence the arcs shown in that figure can connect to closed curves only if the triangular faces labeled $V_1$ and $V_2$ actually coincide.

Since $V_1 = V_2$, the configuration must be as in Figure 6, right. But now, recall that $A_1$ is glued to square $A_n$ along this white face $V_1 = V_2$. By Lemma 4.2, the squares $A_2$ and $A_n$ are distinct. Furthermore, since $A$ is embedded, $A_2$ and $A_n$ are disjoint. However, the side of $A_n$ on the face $V_1 = V_2$ differs from $A'_1$ by a single clockwise rotation. It is impossible for this arc to be disjoint from $A_2$, which is a contradiction.

We can now prove the main result of this section.

Proposition 4.4. The annulus $A$ consists of at least 4 squares. In addition, some white face met by $A$ has at least 4 sides.

Proof. The first claim in the proposition is proved in Lemma 4.2. To prove the second claim, let $A_1 \subset A$ be a normal square in the upper polyhedron. We will show that this particular normal square meets a white face with at least 4 sides.
First we rule out white faces that are bigons. In a bigon face, each edge is adjacent to each of the two vertices. Thus any arc from an ideal vertex to an edge would violate condition (v) of Definition 2.4, meaning \( A \) cannot be normal if it meets a bigon face. This contradiction implies every white face met by \( A \) has at least 3 sides.

If both white faces met by \( A \) are triangles, then Lemma 4.3 implies that these triangles are in different polyhedral regions. To study this situation, we need the following lemma.

**Lemma 4.5.** Suppose \( A \) is a normal square in the upper polyhedron, with one side on an ideal vertex, two sides on white faces \( V \) and \( W \), where \( V \) is triangular, and one side, labeled \( \gamma \), on a shaded face. Label the state circles around \( V \) so that \( \partial A \) runs from a vertex of \( V \) on the state circle \( C_1 \) to a tentacle whose tail is on the state circle \( C_2 \). Then either

1. \( W \) is inside the region \( R_1 \) on the opposite side of \( C_1 \) from \( V \) or
2. \( W \) is inside \( R_2 \) on the opposite side of \( C_2 \) from \( V \).

Furthermore, when we direct \( \gamma \) from \( V \) to \( W \), it runs across \( C_1 \) or \( C_2 \), respectively, running downstream. See Figure 7.

**Proof.** The square \( A \) has one side on the parabolic locus, which is a vertex of the upper polyhedron. Each vertex is a zig-zag. Because \( A \) meets a vertex on \( C_1 \), part of the zig-zag must lie on \( C_1 \).

If all of the zig-zag lies on \( C_1 \), that is, if the zig-zag consists of a single bit of state surface, then \( W \) lies in \( R_1 \) on the opposite side of \( C_1 \) from \( V \).

If the zig-zag contains one or more segments, then at least one segment of the zig-zag is attached to \( C_1 \), on one side or the other. If the segment is attached to \( C_1 \) on the side of the region \( R_1 \), then \( W \) must be inside \( R_1 \). (Otherwise, there would be a staircase from state circle \( C_1 \) back to \( C_1 \), contradicting the Escher Stairs Lemma [13, Lemma 3.4].) If the segment is attached to the side opposite \( R_1 \), then because it belongs to a single vertex, it must in fact be the segment labeled \( s \) in Figure 7 which connects \( C_1 \) to \( C_2 \) alongside face \( V \). In this case, the zig-zag includes a portion of \( C_2 \), and \( W \) will lie on one side or the other of \( C_2 \). By the assumption that \( V \) and \( W \) are in different polyhedral regions, \( W \) must lie inside the region \( R_2 \) on the opposite side of \( C_2 \) from \( V \).
Figure 7. Notation for Lemma 4.5. The conclusion of the lemma is that square $A_1$ must run through shaded face $F_2$ to a shaded face $W$ contained in region $R_1$ or region $R_2$.

Now we argue that $\gamma$ runs downstream across $C_1$ or $C_2$ when directed away from $V$ towards $W$. As in Figure 7, the shaded face containing $\gamma$ is called $F_2$. For ease of exposition, we also refer to $F_2$ as the blue face. Thus $\gamma$ starts next to white face $V$ by entering a blue tentacle adjacent to $C_2$.

First suppose $W$ is in $R_2$. If $\gamma$ crosses $C_2$ immediately from the tail of the blue tentacle, then it must do so running downstream, since only heads of tentacles (rather than no non-prime switches or innermost disks) can attach to tails of tentacles on the opposite side of a state circle. So suppose $\gamma$ runs upstream into the head of the blue tentacle, crossing state circle $C_3$. Since $C_3$ does not separate $V$ and $W$, in fact $\gamma$ must cross it twice, and the Utility Lemma [13, Lemma 3.11] implies that $\gamma$ crosses it first running upstream, then downstream. Between the second time $\gamma$ crosses $C_3$ and the first time it crosses $C_2$, $\gamma$ must exit out of every non-prime half–disk it enters, otherwise such a disk would separate $C_2$ and $C_3$. But no half–disk can separate $C_2$ and $C_3$, because they are connected by a segment. Thus the Downstream Lemma [13, Lemma 3.10] implies $\gamma$ crosses $C_2$ running downstream.

Finally, suppose $W$ is in $R_1$. The arc $\gamma$ begins in a blue tentacle with head on $C_3$ and tail on $C_2$. If $\gamma$ crosses $C_2$ first, it will be running downstream. But $C_2$ does not separate $V$ and $W$ in this case, so $\gamma$ must cross it twice. This contradicts the Utility Lemma. Thus $\gamma$ crosses $C_3$ first, running upstream. Again it crosses $C_3$ twice, and by the Utility Lemma, the second crossing of $C_3$ occurs running downstream. Then, as in the previous paragraph, the Downstream Lemma implies that $\gamma$ crosses $C_1$ running downstream. $\square$

Now we finish the proof of Proposition 4.4.

Let the notation be as in Lemma 4.5. In addition, as in Figure 7, let $F_i$ be the shaded face that has a tentacle lying on state circle $C_i$. Thus $\gamma$ runs through shaded face $F_2$.

To finish the proof, we pull a side of $A_1$ off the parabolic locus, i.e. off the ideal vertex, and into shaded face $F_1$ or $F_3$. This creates a normal square with two white sides and two shaded sides.

If $W$ is in $R_1$, pull $A_1$ off the ideal vertex and into the tentacle of $F_1$, to obtain an arc $\sigma \subset F_1$. This arc $\sigma$ must run downstream across $C_1$, by the Utility Lemma.
If $W$ is in $R_2$, pull $A_1$ off the ideal vertex and into the tentacle of $F_3$, obtaining an arc $\sigma \subset F_3$. Again the arc $\sigma$ must run downstream across $C_2$.

In either case, we have arcs $\gamma$ and $\sigma$ which run downstream from the same state circle (either $C_1$ if $W \subset R_1$, or $C_2$ if $W \subset R_2$). They terminate in the same white face, namely $W$. This contradicts the Parallel Stairs Lemma [13, Lemma 3.14]. □

4.2. Annuli and squares. In the next sequence of lemmas, we use Proposition 4.4 to set up the proof that the state surface $S_\sigma$ has no accidental parabolics. The overall theme of the proof is that each successive lemma places stiffer and stiffer restrictions on the annulus $A$, the polyhedral decomposition, and the diagram $D(K)$. In the end, we will reach a contradiction.

So far, we have an essential annulus $A \subset M_\sigma$, composed of normal squares $A_1, \ldots, A_n$. Each of these squares has two sides on white faces, one on a shaded face, and the final side on an ideal vertex.

In the arguments below, it is actually easier to view the pieces of $A$ as squares with two sides on shaded faces and two sides on white faces. This is accomplished as follows. Recall that the parabolic locus $\partial N(K) \setminus S_\sigma$ consists of annuli. One of the boundary circles of $A$ is embedded on one of these parabolic annuli. We may isotope $A$ slightly through $M_\sigma$, to move the boundary circle of $A$ from the parabolic locus and onto $\tilde{S}_\sigma$.

In the polyhedral decomposition, the pushed-off copy of $A$ will be cut into a collection of normal squares with two sides on white faces and two sides on shaded faces, such that one side on a shaded face cuts off a single ideal vertex. We denote these squares by $S_1, \ldots, S_n$. Note each $S_i$ is obtained by pulling $A_i$ off an ideal vertex and into an adjacent shaded face.

In fact, there are two different directions in which we may pull $A$ off the parabolic locus. We make the choice as follows.

**Convention 4.6.** Let $V$ be a white face with four or more vertices, which meets the annulus $A$. (The existence of such a white face is guaranteed by Proposition 4.4.) We arrange the labeling of normal squares $A_i$ so that square $A_1$ in the upper polyhedron is glued along $V$ to square $A_2$ in some lower polyhedron.

The normal square $A_1$ meets a vertex of $V$, which means that one component of $V \setminus A_1$ has two or more vertices. We pull $A$ off the parabolic locus in the direction of this (larger) component of $V \setminus A_1$. Thus, if $S_1$ is the normal square corresponding to $A_1$, the arc $S_1 \cap V$ has at least two vertices on each side.

**Lemma 4.7.** The annulus $A$ intersects only two white faces, $V$ and $W$, which belong to the same polyhedral region. Furthermore, every normal square $S_i$ intersects $V$ and $W$ in a way that cuts off at least two vertices on each side.

**Proof.** Let $V$ be the white face of Convention 4.6 and let $A_1$ and $S_1$ be the corresponding normal squares. Let $W$ be the other white face met by $S_1$. Since $S_1$ does not cut off an ideal vertex in $V$, and is glued to square $S_2$ across $V$, Proposition 4.13 implies that $V$ and $W$ are in the same polyhedral region $U$. □

1In the monograph [13], Proposition 4.13 and Lemma 4.10 are stated for $A$–adequate diagrams. As [13] Section 4.5 explains, these results and the other structural results about the polyhedra also apply to $\sigma$–adequate, $\sigma$–homogeneous diagrams.
Now, Lemma 3.2 part (2) says that we may map $S_1$ into the lower polyhedron corresponding to $U$ and obtain a normal square $S'_1 = \phi(S_1)$. Note that the arc $S'_1 \cap V$ will differ from $S_2 \cap V$ by a single rotation, by the definition of the clockwise (or counter-clockwise) map. Since $S'_1$ cuts off more than a single vertex in $V$, [13, Lemma 4.10] implies that $S'_1$ intersects $S_2$ non-trivially, in both of its white faces. But this means that $S_2$ meets both $V$ and $W$ in arcs that cut off more than a single vertex on each side.

The square $S_2$ is glued along $W$ to a square $S_3$ in the upper polyhedron. The arc $S_3 \cap W$ cuts off more than a single vertex on each side, because it is glued to $S_2$. Thus, as above, [13, Proposition 4.13] implies that both white faces of $S_3$ are in the same polyhedral region $U$, and [13, Lemma 4.10] implies that $S'_3 = \phi(S_3)$ intersects $S_2$ non-trivially, in both of its white faces. In other words, $S_3$ meets the same white faces $V$ and $W$ in arcs that cut off more than a single vertex on each side. Continue in this fashion to obtain the same conclusion for every $S_i$.

Let $S_i$ be an even-numbered square in a lower polyhedron. Lemma 4.7 tells us that $S_i$ is glued to $S_{i-1}$ across $V$ and to $S_{i+1}$ across $W$, where $V$ and $W$ are the same as $i$ varies.

**Definition 4.8.** To continue studying the intersection patterns of normal squares in the lower polyhedron, we define

$$T_i = \begin{cases} \phi(S_i) & \text{if } i \text{ is odd}, \\ S_i & \text{if } i \text{ is even}. \end{cases}$$

Note that every $T_i$ lives in the lower polyhedron of the polyhedral region $U$.

For every square $T_i$, we label its four sides as follows. The sides of $T_i$ in white faces $V$ and $W$ are denoted $v_i$ and $w_i$, respectively. One shaded side of $S_i$ was created by pulling a side of $A_i$ off the parabolic locus; the corresponding side of $T_i$ is denoted $p_i$. (Note that by Lemma 3.2 part (3), if an odd-numbered square $S_i$ in the upper polyhedron has a shaded side that cuts off an ideal vertex, then so does $T_i = \phi(S_i)$.) We will orient the arcs $v_i$ and $w_i$ so that they point toward $p_i$, and orient $p_i$ from $v_i$ toward $w_i$. That is, $p_i$ is oriented from $V$ to $W$.

Similarly, an odd-numbered square $S_i$ in the upper polyhedron also contains an arc $q_i$ that was pulled off the parabolic locus. As before, we orient $q_i$ from $V$ to $W$.

**Lemma 4.9.** Let $i$ be even, so that $S_i = T_i$ is in a lower polyhedron, and suppose that we pulled $S_i$ off an ideal vertex that lies to the right of $p_i$. Then

1. $v_{i-1} = \phi(v_i)$ and $w_{i+1} = \phi(w_i)$, with orientations preserved.
2. $p_{i+1}$ cuts off an ideal vertex to its right.
3. In the upper polyhedron, $q_{i+1}$ also cuts off an ideal vertex to its right.

**Proof.** By construction, $v_i \subset S_i$ is glued to an arc of $S_{i-1} \cap V$, whose image under $\phi$ is $v_{i-1}$. Similarly for $w_i$ and $w_{i+1}$. Since $\phi$ is orientation-preserving, (1) follows.

Conclusion (2) follows immediately from Lemma 3.2 part (3) because $S_i$ was created by pulling $A_i$ off an ideal vertex in a direction that is consistent for all $i$. Similarly, conclusion (3) follows from Lemma 3.2 part (3) because $\phi$ is orientation-preserving.

**Lemma 4.10.** Each square $T_i$ encircles a bigon shaded face of the lower polyhedron.
Figure 8. Proof of Lemma 4.10: Squares $T_1$, $T_2$, and $T_3$ must meet a lower polyhedron as shown.

Proof. Assume without loss of generality that $V$ and $W$ are in an all-$A$ polyhedral region. We may also assume without loss of generality that $p_2$ was created by pulling $A_2$ off an ideal vertex so that the vertex lies to the right of $p_2$. (Otherwise, interchange the labels of faces $V$ and $W$, reversing the order of the indices and the orientation on every $p_i$.)

By Lemma 4.9, the arc $v_1$ is clockwise from $v_2$ in face $V$, and $w_3$ is clockwise from $w_2$ in face $W$. Moreover, $v_2$ intersects both $v_1$ and $v_3$, and similarly $w_2$ intersects both $w_1$ and $w_3$. But $T_1 = \phi(S_1)$ and $T_3 = \phi(S_3)$ are clockwise images of disjoint squares, hence are disjoint by Lemma 3.2 (4). Thus $T_1$, $T_2$, and $T_3$ must be as shown in Figure 8. In particular, $p_1$ and $T_3$ run parallel through the same shaded face. Dotted lines in the figure indicate that the boundary of the corresponding shaded face may meet additional vertices.

The arc $p_2$ cuts off an ideal vertex to its right, so by Lemma 4.9 the arcs $p_1$ and $p_3$ also cut off ideal vertices to their right. Thus the dotted line to the right of $p_1$ in Figure 8 must actually be solid. By primeness of the lower polyhedron, all other dotted lines must also be solid. Thus $T_2$ and $T_3$ each encircle a single bigon shaded face.

We may repeat the above argument with $T_{2k}$ taking the place of $T_2$, for any $k$; hence each $T_i$ encircles a bigon.

Lemma 4.11. The white faces $V$ and $W$ met by annulus $A$ are the only white faces of the polyhedral decomposition. As a consequence, $D(K)$ is the standard diagram of a $(2,n)$ torus link, and $S_\sigma$ is an annulus.

Proof. Recall that by Lemma 4.7, there is a polyhedral region $U$ containing white faces $V$ and $W$, such that every normal square $S_i$ passes through $V$ and $W$. These normal squares define squares $T_i$ in the lower polyhedron, as in Definition 4.8. By Lemma 4.10, every $T_i$ encircles a bigon shaded face of this lower polyhedron. The number of these bigons is $n$, the same as the number of normal squares in $A$.

This is enough to conclude that all the shaded faces of the lower polyhedron corresponding to $U$ are bigons, chained end to end. Thus $V$ and $W$ are the only white faces of this lower polyhedron. The 1–skeleton of this lower polyhedron coincides with the standard diagram of a $(2,n)$ torus link, as on the left of Figure 9.
Figure 9. Proof of Lemma 4.11. Left: $T_i$ encircles a bigon in the lower polyhedron. Center: The clockwise preimage $S_i = \phi^{-1}(T_i)$ in the upper polyhedron. Right: The ideal vertex cut off by $S_i$.

If the diagram $D(K)$ is prime and alternating, there is only one lower polyhedron whose 1–skeleton corresponds to $D(K)$. Thus $D(K)$ is the standard diagram of a $(2, n)$ torus link, where $n$ is even. The rest of the argument reduces us to this case.

In the general case, the upper polyhedron may be more complicated. However, one polyhedral region in the upper polyhedron looks like that of a $(2, n)$ torus link, as in the middle panel of Figure 9. A priori, there may be additional segments attached to the opposite sides of all state circles involved. This is indicated in that figure by the dashed lines along state circles.

For each square $T_i$ in the lower polyhedron, label three sides of $T_i$ by $v_i$, $w_i$, and $p_i$, as in Lemma 4.9. Focusing attention on $T_2 = S_2$, we may assume that arc $p_2$ in a shaded face was pulled off an ideal vertex to its right. (Otherwise, as in Lemma 4.10, switch the labels of $V$ and $W$.) Applying Lemma 4.9, part (2) inductively, we conclude that for each even index $j$, arc $p_j$ was pulled off an ideal vertex to its right.

Now, let $i$ be an odd index, so that $S_i$ is a square in the upper polyhedron. Since $T_i$ encircles an ideal bigon, as in Figure 9, the clockwise preimage $S_i = \phi^{-1}(T_i)$ must be as in the middle panel of Figure 9. By Lemma 4.9, the arc $q_i$ of $S_i$ that was pulled off the parabolic locus must cut off an ideal vertex to its right. This means that portions of state circles adjacent to $q_i$ to its right must actually be solid, to form a single zig-zag, with no segments to break it up. In other words, we have the third panel of Figure 9. The third panel of Figure 9 shows two dotted closed curves, each meeting the link diagram exactly twice. Using the hypothesis that the diagram is prime, each of these closed curves cannot enclose segments (which would correspond to crossings of the diagram).

We conclude that two consecutive state circles in $H_\sigma$ are innermost and contain no additional polyhedral regions. Repeating the same argument for the next odd-numbered square $S_{i+2}$ leads to the conclusion that the next two state circles in $H_\sigma$ are also innermost. Continuing in this way, we conclude that there is only one polyhedral region, which corresponds to the diagram of a $(2, n)$ torus link. □
4.3. Completing the proofs. We are now ready to prove Theorem 4.1 and Theorem 1.6.

Proof of Theorem 4.1 Suppose that \( S_\sigma \) has an accidental parabolic. Then Lemma 2.2 implies there is an embedded essential annulus \( A \subset S^3 \setminus S_\sigma \). By Lemma 4.7, \( A \) intersects only two white faces, \( V \) and \( W \). By Lemma 4.11, \( V \) and \( W \) are the only faces of the polyhedral decomposition, hence \( D(K) \) is the standard diagram of a \((2, n)\) torus link and \( S_\sigma \) is an annulus.

Note that the only non-trivial simple closed curve in an annulus is boundary-parallel. Therefore, the component of \( \partial A \) that lies on \( \tilde{S}_\sigma \) is actually parallel to \( \partial \tilde{S}_\sigma \). This contradicts the assumption that \( A \) is an essential annulus realizing an accidental parabolic. \( \square \)

Proof of Theorem 1.6 By [13, Theorem 3.25], \( S_\sigma \) is essential in \( S^3 \setminus K \), and by Theorem 4.1 it has no accidental parabolics. By [13, Theorem 5.21] (or [12]) \( S_\sigma \) is a fiber in \( S^3 \setminus K \) if and only if \( G'_\sigma \) is a tree. Furthermore, by [13, Theorem 5.21], if \( S_\sigma \) lifts to a fiber in a double cover of \( S^3 \setminus K \), then \( M_\sigma \) is an \( I \)-bundle, hence \( G'_\sigma \) is a tree.

It follows that if \( K \) is hyperbolic, the surface \( S_\sigma \) is quasifuchsian if and only if the reduced state graph \( G'_\sigma \) is not a tree. \( \square \)

References

[1] Colin Adams, Noncompact Fuchsian and quasi-Fuchsian surfaces in hyperbolic 3-manifolds, Algebr. Geom. Topol. 7 (2007), 565–582, DOI 10.2140/agt.2007.7.565. MR2308957 (2008d:57021)
[2] Francis Bonahon, Bouts des variétés hyperboliques de dimension 3 (French), Ann. of Math. (2) 124 (1986), no. 1, 71–158, DOI 10.2307/1971388. MR847953 (88c:57013)
[3] R. D. Canary, D. B. A. Epstein, and P. Green, Notes on notes of Thurston, Analytical and geometric aspects of hyperbolic space (Coventry/Durham, 1984), London Math. Soc. Lecture Note Ser., vol. 111, Cambridge Univ. Press, Cambridge, 1987, pp. 3–92. MR90850 (89e:57008)
[4] Jae Choon Cha and Charles Livingston, Knotinfo: Table of knot invariants, http://www.indiana.edu/~knotinfo, 2011.
[5] D. Cooper and D. D. Long, Some surface subgroups survive surgery, Geom. Topol. 5 (2001), 347–367 (electronic), DOI 10.2140/gt.2001.5.347. MR1825666 (2002g:57031)
[6] P. R. Cromwell, Homogeneous links, J. London Math. Soc. (2) 39 (1989), no. 3, 535–552, DOI 10.1112/jlms/s2-39.3.535. MR1002465 (90f:57001)
[7] Oliver T. Dasbach, David Futer, Efstratia Kalfagianni, Xiao-Song Lin, and Neal W. Stoltzfus, The Jones polynomial and graphs on surfaces, J. Combin. Theory Ser. B 98 (2008), no. 2, 384–399, DOI 10.1016/j.jctb.2007.08.003. MR2389605 (2009d:57020)
[8] Oliver T. Dasbach and Xiao-Song Lin, On the head and the tail of the colored Jones polynomial, Compos. Math. 142 (2006), no. 5, 1332–1342, DOI 10.1112/S0010437X06002296. MR2246669 (2007g:57018)
[9] Sérgio R. Fenley, Quasi-Fuchsian Seifert surfaces, Math. Z. 228 (1998), no. 2, 221–227, DOI 10.1007/PL00004607. MR1630563 (99c:57037)
[10] Elizabeth Finkelstein and Yoav Moriah, Tubed incompressible surfaces in knot and link complements, Topology Appl. 96 (1999), no. 2, 153–170, DOI 10.1016/S0166-8641(98)00043-1. MR1702308 (2001b:57015)
[11] Elizabeth Finkelstein and Yoav Moriah, Closed incompressible surfaces in knot complements, Trans. Amer. Math. Soc. 352 (2000), no. 2, 655–677, DOI 10.1090/S0002-9947-99-02333-3. MR1487613 (2000c:57007)
[12] David Futer, Fiber detection for state surfaces, Algebr. Geom. Topol. 13 (2013), no. 5, 2799–2807, DOI 10.2140/agt.2013.13.2799. MR3116303
[13] David Futer, Efstratia Kalfagianni, and Jessica Purcell, Guts of surfaces and the colored Jones polynomial, Lecture Notes in Mathematics, vol. 2069, Springer, Heidelberg, 2013. MR3024609

[14] David Futer, Efstratia Kalfagianni, and Jessica Purcell, Jones polynomials, volume, and essential knot surfaces: a survey, Proceedings of Knots in Poland III, Banach Center Publications 100 (2014), Issue 1, 51–77.

[15] Wolfgang Haken, Theorie der Normalflächen (German), Acta Math. 105 (1961), 245–375. MR0141106 (25 #4519a)

[16] William Jaco, Lectures on three-manifold topology, CBMS Regional Conference Series in Mathematics, vol. 43, American Mathematical Society, Providence, R.I., 1980. MR565450

[17] Louis H. Kauffman, State models and the Jones polynomial, Topology 26 (1987), no. 3, 395–407, DOI 10.1016/0040-9383(87)90009-7. MR899057 (88f:57006)

[18] Marc Lackenby, The volume of hyperbolic alternating link complements, Proc. London Math. Soc. (3) 88 (2004), no. 1, 204–224, DOI 10.1112/S0024611503014291. With an appendix by Ian Agol and Dylan Thurston. MR2018964 (2004i:57008)

[19] W. B. R. Lickorish and M. B. Thistlethwaite, Some links with nontrivial polynomials and their crossing-numbers, Comment. Math. Helv. 63 (1988), no. 4, 527–539, DOI 10.1007/BF02566777. MR966948 (90a:57010)

[20] Joseph D. Masters and Xingru Zhang, Closed quasi-Fuchsian surfaces in hyperbolic knot complements, Geom. Topol. 12 (2008), no. 4, 2095–2171, DOI 10.2140/gt.2008.12.2095. MR2431017 (2009g:57029)

[21] William Menasco and Alan W. Reid, Totally geodesic surfaces in hyperbolic link complements, Topology ’90 (Columbus, OH, 1990), Ohio State Univ. Math. Res. Inst. Publ., vol. 1, de Gruyter, Berlin, 1992, pp. 215–226. MR1184413 (94g:57016)

[22] Makoto Ozawa, Essential state surfaces for knots and links, J. Aust. Math. Soc. 91 (2011), no. 3, 391–404, DOI 10.1017/S1446788712000055. MR2990614

[23] Józef H. Przytycki, From Goeritz matrices to quasi-alternating links, The mathematics of knots, Contrib. Math. Comput. Sci., vol. 1, Springer, Heidelberg, 2011, pp. 257–316. MR2777853 (2012e:57014)

[24] Morwen Thistlethwaite and Anastasiia Tsvietkova, An alternative approach to hyperbolic structures on link complements, Algebr. Geom. Topol. 14 (2014), no. 3, 1307–1337, DOI 10.2140/agt.2014.14.1307. MR3190595

[25] Morwen B. Thistlethwaite, On the Kauffman polynomial of an adequate link, Invent. Math. 93 (1988), no. 2, 285–296, DOI 10.1007/BF01394334. MR948102 (89g:57009)

[26] William P. Thurston, The geometry and topology of three-manifolds, Princeton Univ. Math. Dept. Notes, 1979.

[27] Yuri Tsukumis, Hyperbolic knots spanning accidental Seifert surfaces of arbitrarily high genus, Math. Z. 246 (2004), no. 1-2, 167–175, DOI 10.1007/s00209-003-0593-0. MR2031451 (2005b:57044)

[28] Anastasiia Tsvietkova, Hyperbolic structures from link diagrams, Ph.D. thesis, University of Tennessee, 2012. MR3121975

[29] Daniel T. Wise, Subgroup separability of the figure 8 knot group, Topology 45 (2006), no. 3, 421–463, DOI 10.1016/j.top.2005.06.004. MR2218750 (2007a:57010)

[30] Ying-Qing Wu, Incompressible surfaces in link complements, Proc. Amer. Math. Soc. 129 (2001), no. 11, 3417–3423 (electronic), DOI 10.1090/S0002-9939-01-05938-X. MR1845021 (2002g:57046)

Department of Mathematics, Temple University, Philadelphia, Pennsylvania 19122
E-mail address: dfuter@temple.edu

Department of Mathematics, Michigan State University, East Lansing, Michigan 48824
E-mail address: kalfagia@math.msu.edu

Department of Mathematics, Brigham Young University, Provo, Utah 84602
E-mail address: jpurcell@math.byu.edu