2-SYSTEMS OF ARCS ON SPHERES WITH PRESCRIBED ENDPOINTS

SAMI DOUBA

Abstract. Let $S$ be an $n$-punctured sphere, with $n \geq 3$. We prove that $\binom{n}{3}$ is the maximum size of a family of pairwise non-homotopic simple arcs on $S$ joining a fixed pair of distinct punctures of $S$ and pairwise intersecting at most twice. On the way, we show that a square annular diagram $A$ has a corner on each of its boundary paths if $A$ contains at least one square and the dual curves of $A$ are simple arcs joining the boundary paths of $A$ and pairwise intersecting at most once.

1. Introduction

A $k$-system $\mathcal{A}$ of arcs on a punctured surface $S$ is a collection of essential simple arcs on $S$ such that no two arcs of $\mathcal{A}$ are homotopic or intersect more than $k$ times. We begin with the following observation.

Remark 1.1. If $k = 0$, $S$ is an $n$-punctured sphere with $n \geq 3$, and the arcs of $\mathcal{A}$ all join a fixed pair of distinct punctures $p, q$ of $S$, then $|\mathcal{A}| \leq n - 2$. To see this, fix a complete hyperbolic metric on $S$ of area $2\pi(n - 2)$ and realize the arcs of $\mathcal{A}$ as geodesics on $S$. Cutting $S$ along $\mathcal{A}$, we obtain a collection of hyperbolic punctured strips. Since the boundary of each strip consists of two arcs of $\mathcal{A}$, and since each arc of $\mathcal{A}$ appears twice as a boundary component of some strip, we count precisely $|\mathcal{A}|$ strips. The bound on $|\mathcal{A}|$ now follows from the fact that each of these strips has area at least $2\pi$. Moreover, this bound is tight since we can easily devise a 0-system on $S$ whose complement consists entirely of once-punctured strips (see Figure 1). An area argument also shows that the maximum size of $\mathcal{A}$ is $2n - 5$ if we assume instead that $p = q$.

Problems involving bounding the size of a $k$-system of arcs, of which Remark 1.1 serves as a trivial example, originated in similar problems for curves. Juvan, Malnič, and Mohar introduced the term “$k$-system” and showed that the maximum size $N(k, \Sigma)$ of a $k$-system of essential simple closed curves on a fixed compact surface $\Sigma$ is finite [JMM96]. Independently, Farb and Leininger inquired about $N(k, g) := N(k, \Sigma)$ for $\Sigma$ closed and oriented of genus $g$ and $k = 1$. In response, Malestein, Rivin, and Theran provided an upper bound exponential in $g$, and showed that $N(1, 2) = 12$ [MRT14]. Also for $k = 1$, Przytycki produced an upper bound on the order of $g^3$ [Prz15, Theorem 1.4]; since then, tighter bounds on $N(1, g)$ have been found by Aougab, Biringer, and Gaster [ABG17], and more recently, Greene [Gre18a]. Moreover, Przytycki provided an upper bound on $N(k, g)$ for arbitrary $k$.

2010 Mathematics Subject Classification. Primary: 57M50, 57M20; Secondary: 05D99.

The author was supported in part by the grant #346300 for IMPAN from the Simons Foundation and the matching 2015-2019 Polish MNiSW fund.
that grows like $g^{k^2+k+1}$ [Prz15, Cor. 1.6]. This bound was subsequently improved by Greene to one that grows like $g^{k+1}\log g$ [Gre18b].

In [Prz15], so as to prove the aforementioned results about $k$-systems of curves, Przytycki first proved stronger results about $k$-systems of arcs – for example, that the maximum size of a $k$-system of arcs on a punctured surface $S$ of Euler characteristic $\chi<0$ (where distinct arcs are not required to have the same endpoints) grows like $|\chi|^{k+1}$. In the same article, Przytycki proved the following:

**Theorem 1.2.** [Prz15, Theorem 1.7] Let $p, q$ be punctures of an $n$-punctured sphere $S$, where $n \geq 3$. The maximum size of a 1-system $A$ of arcs on $S$ joining $p$ and $q$ is $(n-1)/2$.

Note that $p$ and $q$ are not assumed to be distinct in the statement of Theorem 1.2. More recently, Bar-Natan showed that for $S, p, q$ as in Theorem 1.2, if $p = q$ then the maximum size of a 2-system of arcs on $S$ joining $p$ and $q$ is $(n/3)$ [BN17]. The main result of this article is that Bar-Natan’s maximum holds for $p, q$ distinct:

**Theorem 1.3.** Let $p, q$ be distinct punctures of an $n$-punctured sphere $S$, where $n \geq 3$. The maximum size of a 2-system $A$ of arcs on $S$ joining $p$ and $q$ is $(n/3)$.

**Organization.** In Section 3, we provide an example of a 2-system of size $(n/3)$ joining a fixed pair of distinct punctures of an $n$-punctured sphere for $n \geq 3$. The remaining sections are concerned with proving that $(n/3)$ is an upper bound on the size of such a 2-system $A$. This is proved by induction on $n$; we prove that the number of arcs of $A$ that become homotopic after forgetting a puncture of $S$ is not too large. This, in turn, is proved by induction, via the following lemma:

**Lemma 1.4.** Let $S$ be an $n$-punctured sphere, and let $p, q, r$ be distinct punctures of $S$. Let $P, Q$ be 1-systems of arcs starting at $r$ and ending at $p, q$, respectively, so that no arc of $P$ intersects an arc of $Q$. Suppose $R \subset P \times Q$ satisfies the following:

(i) there is at most one point of intersection between any two pairs of arcs in $R$;

(ii) the cyclic order around $r$ of any two intersecting pairs $(\alpha, \beta), (\alpha', \beta') \in R$ with $\alpha \neq \alpha', \beta \neq \beta'$ is alternating.

Then $|R| \leq (n-1)/2$.

Section 6 is devoted to the proof of Lemma 1.4. The inductive step again involves forgetting a puncture $s$ of $S$, but this time, we choose $s$ with care in order to control
the subsequent behavior of the arcs of $P$ and $Q$. More precisely, we require that $s$ be $p$-isolated (see Section 2 for definitions).

To guarantee that a puncture with this property exists, we take a detour into annular square diagrams. A $k$-system annular diagram $A$ is an annular diagram whose dual curves constitute a $k$-system of arcs joining the boundary paths of $A$. Such a diagram arises as the dual square complex to a $k$-system $A$ on a punctured sphere with distinct prescribed endpoints. In Section 5, we prove the following:

**Theorem 1.5.** Let $A$ be a 1-system annular diagram. Then either $A$ is a cycle, or $A$ has a corner on each of its boundary paths.

Roughly speaking, a corner corresponds to an isolated puncture. Note that Theorem 1.5 does not hold for $k = 2$; see Figure 4 (bottom left) for a counterexample, suggested by Przytycki.

**Acknowledgements.** I thank my supervisor Piotr Przytycki for his crucial guidance and remarkable patience throughout the course of this article’s preparation. I also thank Daniel Wise for providing helpful resources.

## 2. Definitions

### 2.1. Arc systems

A puncture is a topological end of a space $S$ obtained from a connected, oriented, compact surface $\Sigma$ by removing finitely many points $p_1, \ldots, p_n$ from $\Sigma$. Note that the punctures of $S$ are in bijection with $p_1, \ldots, p_n$, and that we allow punctures on the boundary of $\Sigma$. If $p_1, \ldots, p_n$ are taken from the interior of $\Sigma$, we call $S$ an $n$-punctured $\Sigma$.

An arc on $S$ is a proper map $\alpha : (0, 1) \to S$. A proper map induces a map between ends of topological spaces; in this sense, $\alpha$ “maps” each endpoint of $(0, 1)$ to a puncture $p$ of $S$. We call $p$ an end of $\alpha$. If $p, q$ are ends of $\alpha$, we say $\alpha$ starts at $p$ and ends at $q$, or that $\alpha$ joins $p$ and $q$. A segment of $\alpha$ is the restriction of $\alpha$ to some positive-length subinterval of $(0, 1)$.

An arc $\alpha$ is simple if it is an embedding, in which case we identify $\alpha$ and its segments with their images in $S$. If $J$ is a subinterval of $(0, 1)$ with endpoints $t_1, t_2$ and $\alpha$ is a simple arc mapping $t_i$ to $x_i$ for $i = 1, 2$, we denote the segment $\alpha|_J$ by $(x_1, x_2)$. If $R \subset S$ is a subset and $p$ is an end of $\alpha$ corresponding to an endpoint $t_0 = 0, 1$ of $(0, 1)$, we say the $p$-end of $\alpha$ lies in $R$ if $\alpha^{-1}(R)$ is a neighbourhood of $t_0$ in $(0, 1)$.

A homotopy between arcs $\alpha_1$ and $\alpha_2$ is a proper map $(0, 1) \times [0, 1] \to S$ whose restrictions to $(0, 1) \times \{0\}$ and $(0, 1) \times \{1\}$ are $\alpha_1$ and $\alpha_2$, respectively. In particular, a homotopy preserves ends. If $r$ is a puncture of $S$, we say that two arcs on $S$ are $r$-homotopic if they are homotopic on the surface $\tilde{S}$ obtained from $S$ by forgetting $r$. Two arcs are in minimal position if the number of their intersection points cannot be decreased by a homotopy. Note that if a pair of arcs have a point of intersection that is not transversal, then they are not in minimal position. An arc $\alpha$ is essential if it cannot be homotoped into a puncture, in the sense that there is no proper map $(0, 1) \times [0, 1] \to S$ whose restriction to $(0, 1) \times \{0\}$ is $\alpha$. Unless otherwise stated, all arcs in the article are simple and essential, and all intersections between arcs are transversal. Note that an arc joining distinct punctures of a punctured surface is automatically essential.

Let $R$ be a closed disc with at most 2 punctures on its boundary and possibly with punctures in its interior. A region between arcs $\alpha_1, \alpha_2$ on $S$ is a properly
embedded $R \subset S$ such that $\partial R$ is a union of exactly two segments $\sigma_1, \sigma_2$, where $\sigma_i$ is a segment of $\alpha_i$ for $i = 1, 2$ (see Figure 2). We say that $\alpha_1, \alpha_2$ (or, more specifically, $\sigma_1, \sigma_2$) form or bound $R$. If $R$ has no punctures in its interior, we say $R$ is empty. If $R$ has exactly 0 (respectively, 1, 2) punctures on its boundary and $R \cap (\alpha_1 \cup \alpha_2) = \partial R$, we call $R$ a bigon (respectively, half-bigon, strip). We say $R$ is adjacent to a puncture $p$ of $S$ if $p$ lies on the boundary of $R$. If $p, s$ are distinct punctures of $S$ and $A$ is a collection of arcs on $S$ with $s$ contained in a half-bigon or strip $H$ adjacent to $p$ formed by a pair of arcs of $A$ such that $H$ is a component of $S - \bigcup A$, we say that $s$ is $p$-isolated by $A$.

We will make frequent use of the following lemma.

**Lemma 2.1** (The bigon criterion). [FM12, Proposition 1.7] Two intersecting arcs on a punctured surface are in minimal position if and only if they form no empty regions.

Since an empty region bounded by intersecting arcs must contain an empty bigon or half-bigon, we immediately obtain the following corollary.

**Corollary 2.2.** Two intersecting arcs on a punctured surface are in minimal position if and only if they form no empty bigons or half-bigons.

A $k$-system of arcs on a punctured surface $S$ is a collection $A$ of essential simple arcs on $S$ such that no two arcs of $A$ are homotopic or have more than $k$ points of intersection. We will mainly consider the case where $S$ is a sphere punctured at least thrice and $A$ is a 2-system of arcs joining a fixed pair of distinct punctures $p, q$ of $S$. Note that for any two arcs $\alpha_1, \alpha_2$ of such a collection $A$, a region bounded by $\alpha_1, \alpha_2$ that contains neither $p$ nor $q$ must be a bigon, a half-bigon, or a strip.

If a punctured surface $S$ has Euler characteristic $\chi < 0$, then $S$ admits a complete hyperbolic metric of area $2\pi|\chi|$. Under such a metric, the homotopy class of any arc contains a unique geodesic representative, and any two distinct geodesic arcs are in minimal position. Thus, for the purposes of determining the size of a $k$-system $A$ of arcs on $S$, we may assume that $A$ consists of geodesics.

**2.2. Combinatorial complexes.** A map $X \to Y$ between CW complexes $X, Y$ is combinatorial if its restriction to each open cell of $X$ is a homeomorphism onto an open cell of $Y$. A CW complex $X$ is combinatorial if the attaching map of each cell in $X$ is combinatorial for some subdivision of the sphere. A cell of dimension 0 is
2-SYSTEMS OF ARCS ON SPHERES WITH PRESCRIBED ENDPOINTS

2.3. Square complexes. An $n$-cube is a copy of $[-1,1]^n$. A square complex $X$ is a combinatorial complex whose cells are $n$-cubes with $n \leq 2$; that is, $X$ is a combinatorial 2-complex each of whose 2-cells is attached via a combinatorial map from a 4-cycle into the 1-skeleton of $X$. The cells of $X$ are called cubes, and its 2-cells are called squares.

A midcube is a subspace of a cube $[-1,1]^n$ obtained by restricting one coordinate to 0. Let $U$ be a new square complex whose cells are midcubes of $X$ and whose attaching maps are restrictions of attaching maps in $X$ to midcubes. A dual curve $\alpha$ of a cube $c$ in $X$ is a connected component of $U$ containing a midcube of $c$. Note that if $c$ is a square, then it has exactly two dual curves. If $c$ is an edge, we say $\alpha$ is dual to $c$. We call $\alpha$ an arc if it is homeomorphic to an interval (possibly of length 0). There is a natural immersion $\alpha \to X$; if this map is an embedding, we say $\alpha$ is simple. In this case, we identify $\alpha$ with its image in $X$.

2.4. Annular diagrams. An annular diagram $A$ is a finite combinatorial cell decomposition of $S^2$ minus two disjoint open 2-cells (see Figure 3). The attaching map of each of these 2-cells is a boundary path of $A$.

We call $A$ a square annular diagram, or simply a diagram, if it is also a square complex (see Figure 4). A corner on a boundary path $P$ of a diagram $A$ is a vertex $v$ on $P$ of degree 2 that is contained in some square of $A$.

Let $c$ be a square of a diagram $A$ with boundary path $P$, and let $x$ be the center of $c$. Suppose the dual curves $\alpha, \beta$ of $c$ are dual to consecutive edges $a, b$ on $P$ with shared vertex $v$. Let $\gamma$ be the loop obtained from the subarcs of $\alpha, \beta$ joining $x$ and $P$ and the half-edges of $a, b$ containing $v$. If $\gamma$ is homotopic in $A$ to a constant path, then we call $c$ a cornsquare with outerpath $ab$.

A hexagon move on a diagram $A$ is the replacement of three squares forming a subdivided hexagon by an alternate three squares forming a subdivided hexagon (see Figure 5). A hexagon move can be visualized as a benign “sliding” operation on one of the dual curves of $A$, so that if $A'$ is obtained from $A$ by a hexagon move, there is a natural correspondence between the dual curves of $A$ and those of $A'$. Note that the number of squares of $A$ is preserved under hexagon moves.

A square annular diagram $A$ is a $k$-system annular diagram if its dual curves are simple arcs joining the boundary paths of $A$ and pairwise intersecting at most $k$ times in $A$. Note that the number of intersections between any pair of dual curves

Figure 3. An annular diagram. The boundary paths are indicated in red.
Figure 4. Square annular diagrams. Dual curves are dashed and colored. Corners are colored red. The bottom left (respectively, bottom right) diagram is a 2-system (respectively, 1-system) annular diagram. Note that the square at which the blue and orange dual curves meet in the bottom right diagram is a cornsquare with an outerpath on each boundary path, while the square at which the green and purple dual curves meet is not a cornsquare, even though the latter two dual curves are dual to consecutive edges on each boundary path.

Figure 5. A hexagon move and its effect on dual curves.

of $A$ is preserved under a hexagon move. Thus, if $A'$ is obtained from a $k$-system annular diagram $A$ by a hexagon move, then $A'$ is also a $k$-system annular diagram.

3. A 2-SYSTEM OF MAXIMUM SIZE

We provide an example of a 2-system of arcs of size $\binom{n}{3}$ joining a fixed pair of distinct punctures of an $n$-punctured sphere $S$. This collection was independently discovered by Assaf Bar-Natan.
Lemma 4.1. Rather technical and may be skipped on an initial reading.

Let $S$ be a pair of disjoint arcs in $S$ punctured at $p = (−1,0)$ and at the points $r_i = (i − \frac{1}{2},0)$ for $i = 1, \ldots, n − 2$. We construct a 2-system $A$ joining $p$ and the puncture $q$ at infinity.

Let $\alpha_{<−1}$ be the arc given by the ray \{(x,0) : x < −1\}. For $a,b,c \in \{0, 1, \ldots, n−2\}$ with $a < b < c$ or $0 < a < b = c = n−2$, let $\alpha_{abc}$ be the graph of the polynomial function $f_{abc} : (−1,∞) \to \mathbb{R}$ given by $x \mapsto (x+1)(x−a)(x−b)(x−c)$.

Note that for distinct triples $(a,b,c), (a′,b′,c′)$, the difference $f_{abc} − f_{a′b′c′}$ is a cubic polynomial, one of whose roots is $−1$. Thus, the $\alpha_{abc}$ pairwise intersect at most twice. Furthermore, the $\alpha_{abc}$ are pairwise non-homotopic [BN17, proof of Lemma 4.2], and $\alpha_{<−1}$ is not homotopic to any of the $\alpha_{abc}$ since the complement of $\alpha_{<−1} \cup \alpha_{abc}$ is a pair of punctured strips.

Now fix $M > 0$ such that $M > |f_{abc}(x)|$ for all $x \in (−1,n−2)$. For each $i,j \in \{1, \ldots, n−2\}$ with $i < j$, let $\alpha_{ij}$ be the union of the following horizontal and vertical segments: the segment joining $(-1,0)$ and $(-1,M)$, the segment joining $(−1,M)$ and $(i−\frac{1}{2}+\frac{1}{4},M)$, the segment joining $(i−\frac{1}{2}+\frac{1}{4},M)$ and $(i−\frac{1}{2}+\frac{1}{4},−M)$, the segment joining $(u−\frac{1}{2}+\frac{1}{4},−M)$ and $(-2,−M)$, the segment joining $(-2,−M)$ and $(-2,M+1)$, the segment joining $(-2,M+1)$ and $(j−\frac{1}{2}−\frac{1}{4},M+1)$, and the vertical ray travelling down from $(j−\frac{1}{2}−\frac{1}{4},M+1)$. Note that each $\alpha_{ij}$ intersects $\alpha_{<−1}$ exactly once and each $\alpha_{abc}$ exactly twice (see Figure 6). Furthermore, each $\alpha_{ij}$ is in minimal position with $\alpha_{<−1}$ by Corollary 2.2; since $\alpha_{<−1}$ is disjoint from the $\alpha_{abc}$, this shows that none of the $\alpha_{ij}$ is homotopic to any of the $\alpha_{abc}$.

We claim that the $\alpha_{ij}$ are pairwise non-homotopic. Indeed, for $k \in \{1, \ldots, n−3\}$, let $\gamma_k$ be the horizontal arc joining the punctures at $x = k−\frac{1}{2}$ and $x = k+\frac{1}{2}$, and note that $\alpha_{ij}$ and $\gamma_k$ are in minimal position by Corollary 2.2. Since no two of the $\alpha_{ij}$ share the same number of intersection points with each of the $\gamma_k$, the $\alpha_{ij}$ must be pairwise non-homotopic.

We claim further that the $\alpha_{ij}$ pairwise intersect at most twice. Indeed, if $i,j,i′,j′ \in \{1, \ldots, n−2\}$ with $i \leq i′$, then the number of intersection points between $\alpha_{ij}, \alpha_{i′j′}$ is determined by the order of $j,j′,i,i′$. If $i′ < j \leq j′$, then $\alpha_{ij}$ and $\alpha_{i′j′}$ are disjoint (see Figure 7, top). If $i′ < j′ < j$, then $\alpha_{ij}$ and $\alpha_{i′j′}$ intersect once (see Figure 7, middle). Otherwise, $j \leq i′$, and there are two points of intersection between $\alpha_{ij}$ and $\alpha_{i′j′}$ (see Figure 7, bottom). Thus, the family $A$ consisting of $\alpha_{<−1}$, the $\alpha_{abc}$, and the $\alpha_{ij}$ is a 2-system of size $1 + (n−3) + \binom{n−1}{3} + \binom{n−2}{2} = \binom{n}{3}$.

4. Properties of $r$-homotopic arcs intersecting at most twice

Let $p,q,r$ be distinct punctures of a punctured sphere $S$, and let $A$ be a 2-system of arcs on $S$ joining $p$ and $q$. Let $S$ be the surface obtained from $S$ by forgetting $r$, and for each arc $\alpha \in A$, let $\bar{\alpha}$ be the homotopy class of the corresponding arc on $S$. In order to bound the size of $A$ from above, we will need to examine to what extent the map $\alpha \mapsto \bar{\alpha}$ is injective. In this section, we collect some facts about the fibers of this map. Together, the results of this section show that we can extend $A$ so that the size of each fiber is $1$ larger than the number of pairs of disjoint arcs in that fiber.

The main results of this section are Lemmas 4.4, 4.5, and 4.6. The proofs are rather technical and may be skipped on an initial reading.

**Lemma 4.1.** Let $p,q,r$ be distinct punctures of a punctured sphere $S$, and let $\alpha_1, \alpha_2$ be a pair of $r$-homotopic arcs joining $p$ and $q$ and intersecting at most twice. If
Figure 6. The arcs $\alpha_{abc}$ on the 5-punctured sphere, together with arc $\alpha_{<1}$, drawn in blue, arc $\alpha_{23}$, drawn in violet, and arc $\gamma_1$, drawn in green.

Figure 7. The $\alpha_{ij}$ pairwise intersect at most twice.

The $\alpha_i$ are in minimal position, then they are in one of the configurations shown in Figure 8, up to relabeling $p$ and $q$. 
Figure 8. The possible configurations of a pair of $r$-homotopic arcs in minimal position and intersecting at most twice, up to relabeling $p$ and $q$.

Proof. If $\alpha_1, \alpha_2$ are disjoint, then they bound a strip whose only puncture is $r$ (see Figure 8, top left). Otherwise, by Corollary 2.2, $\alpha_1, \alpha_2$ bound a half-bigon or bigon $R$ whose only puncture is $r$. If $\alpha_1, \alpha_2$ intersect exactly once, then $R$ is a half-bigon and, since the $\alpha_i$ are $r$-homotopic, all punctures of $S$ distinct from $p, q, r$ lie in the other half-bigon formed by $\alpha_1, \alpha_2$ (see Figure 8, top right).

If the $\alpha_i$ intersect twice and $R$ is a half-bigon, then the $\alpha_i$ do not form a bigon, since otherwise they would not be $r$-homotopic (see Figure 9). Thus, in this case, the $\alpha_i$ must be as in the bottom right diagram of Figure 8, and since the $\alpha_i$ are $r$-homotopic, all punctures of $S$ distinct from $p, q, r$ must lie in the other half-bigon formed by the $\alpha_i$.

Otherwise, $R$ is a bigon, and the $\alpha_i$ also bound a pair of punctured half-bigons. These half-bigons must contain all the remaining punctures of $S$ since the $\alpha_i$ are $r$-homotopic (see Figure 8, bottom left).

The corollary of the following lemma will be useful in the proofs of Lemmas 4.4 and 4.5. The former tells us that, in a particular context, if we have a portion of an arc then we can trace out the remainder of that arc.

Lemma 4.2. Let $D$ be a disc with at least 2 punctures in its interior and at least 1 puncture on its boundary, and let $\alpha$ be an arc joining an interior puncture $p$ of $D$ to a puncture $x$ on $\partial D$. If $\beta$ is another arc joining $p$ and $x$ such that $\alpha$ and $\beta$ bound a strip containing all interior punctures of $D$ distinct from $p$, then $\beta$ is homotopic to exactly one of the arcs $\alpha_1, \alpha_2$ shown in Figure 10 (left).

Proof. Suppose that the $x$-end of $\beta$ lies to the right of $\alpha$. Then we may homotope $\alpha_1$ so that it bounds an empty strip with $\beta$, as in Figure 10 (right). Thus, in this
If $\alpha_1, \alpha_2$ are in minimal position, intersect exactly twice, and form a bigon that does not contain $r$, then they cannot be $r$-homotopic.

The fact that the bigon and half-bigons bounded by the $\alpha_i$ prior to forgetting $r$ are punctured, and the fact that the arcs on the right are in minimal position, are consequences of Corollary 2.2.

Case 1: $\alpha$ and $\beta$ intersect exactly once. Cutting $S$ along $\alpha_0, \beta_0$ yields two punctured strips. Let $D$ be the strip containing $q$. Note that $x_1$ is now a puncture on $\partial D$, and that $\alpha_1$ and $\beta_1$ are arcs joining $q$ and $x_1$ and bounding a strip containing all the interior punctures of $D$ distinct from $q$. Thus, by Lemma 4.2, the homotopy type of $\beta_1$ is uniquely determined, since only one of the arcs described in Lemma 4.2 produces a $\beta$ that intersects $\alpha$ transversally at $x_1$ (in fact,
By Lemma 4.2, given segments $\beta_0$ and $\beta_1$ of $\beta$, there are at most 2 homotopy classes of arcs joining $q$ and $x_2$ to which $\beta_2$ can belong. One such homotopy class produces a $\beta$ that intersects $\alpha$ non-transversally at $x_2$, as shown above.

the only other candidate homotopy class of $\beta_1$ produces a $\beta$ that is homotopic to $\alpha$).

Case 2: $\alpha$ and $\beta$ form a bigon. Let $D$ be the square containing the puncture $q$ obtained by cutting $S$ along $\alpha_0, \beta_0, \alpha_1, \beta_1$. Now $x_2$ is a puncture on $\partial D$, and $\alpha_2, \beta_2$ are arcs joining $q$ and $x_2$ and bounding a strip containing all the interior punctures of $D$ distinct from $q$, so we may apply Lemma 4.2 as in Case 1. Again, only one of the two homotopy classes to which $\beta_2$ must belong by Lemma 4.2 produces a $\beta$ that intersects $\alpha$ transversally at $x_2$ (see Figure 11).

Case 3: $\alpha$ and $\beta$ intersect exactly twice but do not form a bigon. Let $D$ be the strip containing $q$ obtained by cutting $S$ along $\alpha_0, \beta_0$. Since $x_1$ is a puncture on $\partial D$, and $\alpha_1, \beta_1$ are arcs joining $x_1, x_2$ and bounding a strip containing all interior punctures of $D$ distinct from $x_2$, the homotopy type of $\beta_1$ is uniquely determined by Lemma 4.2 as in the previous cases. Now let $D'$ be the strip containing $q$ obtained by cutting $D$ along $\alpha_1, \beta_1$. Since $x_2$ is a puncture on $\partial D'$, and $\alpha_2, \beta_2$ are arcs joining $q, x_2$ and bounding a strip containing all interior punctures of $D'$ distinct from $q$, the homotopy type of $\beta_2$ is uniquely determined by Lemma 4.2. □

Lemma 4.4. Let $p, q, r$ be distinct punctures of an $n$-punctured sphere $S$, with $n \geq 4$. Let $A_r$ be a maximal 2-system of $r$-homotopic arcs on $S$ joining $p$ and $q$. If $A_r$ contains intersecting arcs $\alpha_1, \alpha_2 \in A_r$ in minimal position that do not form a bigon, then $A_r$ is as in Figure 12, up to homotopy and relabeling $p$ and $q$.

Proof. Let $H$ be the half-bigon formed by the $\alpha_i$ containing $r$, and assume that $H$ is adjacent to $p$ (see Figures 13, 14, left). Let $\beta \in A_r$.

Case 1: The $\alpha_i$ intersect exactly once. Let $x$ be their unique point of intersection. If $\beta$ is disjoint from the $\alpha_i$, then $\beta$ is homotopic to arc $\beta_1$ in Figure 13 (right). Now suppose $\beta$ is not disjoint from the $\alpha_i$, and let $z$ be the first point of intersection of $\beta$ and the $\alpha_i$ as $\beta$ travels from $p$ to $q$. Suppose that $z$ lies on $\alpha_1$, and that $\alpha_1, \beta$ are in minimal position. If the $p$-end of $\beta$ lies in $H$, then $\beta$ forms a half-bigon with $\alpha_1$ whose only puncture is $r$, since otherwise $\alpha_1$ and $\beta$ would form an empty half-bigon, contradicting our assumption that $\alpha_1, \beta$ are in minimal position (Corollary 2.2). Thus, by Lemma 4.1 and Corollary 4.3, $\beta$ is either homotopic to $\alpha_2$ or to arc $\beta_2$ in Figure 13 (right). If the $p$-end of $\beta$ lies outside $H$,
then \( z \) cannot lie on the segment \((px)_{\alpha_1}\), since otherwise \( \beta \) and \( \alpha_1 \) would form an empty half-bigon. Thus, \( z \) lies on \((xq)_{\alpha_1}\), and so \( \beta \) again forms a half-bigon with \( \alpha_1 \) whose only puncture is \( r \). Thus, by Corollary 4.3, \( \beta \) is again homotopic to one of \( \alpha_2, \beta_2 \). Note that, by the above, \( A_r \) cannot contain an additional arc \( \beta' \) in minimal position with \( \alpha_2 \) and intersecting \( \alpha_2 \) first as \( \beta' \) travels from \( p \) to \( q \). This is because the reflection of \( \beta_2 \) across the vertical diameter in Figure 13 (right) intersects \( \beta_2 \) thrice.

**Case 2: The \( \alpha_i \) intersect exactly twice.** Let \( x, y \) be the points of intersection of the \( \alpha_i \) in the order that \( \alpha_1 \) traverses them as it travels from \( p \) to \( q \). In this case, \( \beta \) intersects at least one of the \( \alpha_i \) since \( p, q \) are in distinct components of the complement of \( \alpha_1 \cup \alpha_2 \). Let \( z \) be the first point of intersection of \( \beta \) and the \( \alpha_i \) as \( \beta \) travels from \( p \) to \( q \). We suppose again that \( z \) lies on \( \alpha_1 \), and that \( \alpha_1, \beta \) are in minimal position. If the \( p \)-end of \( \beta \) lies in \( H \), then, as in Case 1, \( \beta \) forms a half-bigon with \( \alpha_1 \) whose only puncture is \( r \). Thus, by Corollary 4.3, \( \beta \) is either homotopic to \( \alpha_2 \) or to arc \( \beta_1 \) in Figure 14 (right). If the \( p \)-end of \( \beta \) lies outside \( H \), then, as in Case 1, \( z \) cannot lie on the segment \((px)_{\alpha_1}\). Thus, \( z \) lies on \((xy)_{\alpha_1}\). But then \( \beta \) again forms a half-bigon with \( \alpha_1 \) whose only puncture is \( r \), and so \( \beta \) is either homotopic to \( \alpha_2 \) or to \( \beta_1 \) as before. Similarly, if \( \beta \) is in minimal position with \( \alpha_2 \) and intersects \( \alpha_2 \) first as it travels from \( p \) to \( q \), then \( \beta \) is either homotopic to \( \alpha_1 \) or to arc \( \beta_2 \) in Figure 14 (right). \( \square \)
Lemma 4.5. Let \( p, q, r \) be distinct punctures of an \( n \)-punctured sphere \( S \), with \( n \geq 4 \). Let \( \mathcal{A}_r \) be a maximal 2-system of \( r \)-homotopic arcs on \( S \) joining \( p \) and \( q \). If \( \mathcal{A}_r \) contains arcs \( \alpha_1, \alpha_2 \in \mathcal{A}_r \) in minimal position that form a bigon, then \( \mathcal{A}_r \) is as in Figure 15, up to homotopy and relabeling \( p \) and \( q \).

Proof. Let \( H \) be the half-bigon adjacent to \( p \) formed by the \( \alpha_i \). Let \( x, y \) be the points of intersection of the \( \alpha_i \) in the order that \( \alpha_1 \) traverses them as it travels from \( p \) to \( q \). Let \( \beta \in \mathcal{A}_r \), and assume \( \alpha_1, \alpha_2, \beta \) are in minimal position.

If \( \beta \) is disjoint from the \( \alpha_i \), then \( \beta \) is homotopic to the blue arc in Figure 15. Now suppose \( \beta \) is not disjoint from the \( \alpha_i \), and let \( z_1, z_2, \ldots \) be the points of intersection of \( \beta \) and the \( \alpha_i \) in the order that \( \beta \) traverses them as it travels from \( p \) to \( q \). We assume that \( z_1 \) lies on \( \alpha_1 \). Note that, by Lemma 4.4, \( \beta \) forms a bigon (containing only the puncture \( r \)) with each of the \( \alpha_i \) that it intersects.

Case 1: \( z_1 \) lies on the segment \((yq)_{\alpha_1}\). In this case, \( \alpha_1 \) and \( \beta \) form a half-bigon whose only puncture is \( r \). As remarked above, this is impossible.

Case 2: \( z_1 \) lies on the segment \((xy)_{\alpha_1}\). In this case, \( z_2 \) does not lie on \((xy)_{\alpha_2}\). Otherwise, since \( \alpha_2 \) and \( \beta \) are in minimal position, they would form a half-bigon whose only puncture is \( r \) (as in Case 1 of Lemma 4.4), but this is impossible. Thus, \( z_2 \) lies on \((xy)_{\alpha_1}\), and so \( \beta \) is homotopic to \( \alpha_2 \) by Corollary 4.3.

Case 3: \( z_1 \) lies on the segment \((px)_{\alpha_1}\). In this case, since \( \alpha_1, \beta \) are in minimal position, \( \beta \) forms a half-bigon \( H' \) with \( \alpha_1 \) adjacent to \( p \) and containing at least one of the punctures of \( H \).

Observe that \( z_2 \) cannot lie on the segment \((yq)_{\alpha_2}\), since otherwise \( \alpha_2 \) and \( \beta \) would form a half-bigon containing \( r \). We also have that \( z_2 \) cannot lie on \((xy)_{\alpha_1}\), since otherwise \( \alpha_1 \) and \( \beta \) would not form a bigon. Furthermore, if \( z_2 \) lies on \((px)_{\alpha_2}\), then so must \( z_3 \), since otherwise \( \alpha_1 \) and \( \beta \) would not form a bigon. But if \( z_2 \) and \( z_3 \) both lie on \((px)_{\alpha_2}\), then \( \alpha_2 \) and \( \beta \) form a bigon that does not contain \( r \), which is impossible.

Now, if \( H' \) contains all the punctures of \( H \), then \( z_2 \) cannot lie on \((xy)_{\alpha_2}\) since \( \alpha_2, \beta \) are in minimal position, and if \( z_2 \) lies on \((yq)_{\alpha_1}\), then \( \beta \) is homotopic to \( \alpha_2 \) by Corollary 4.3. Thus, we may assume that \( H' \) contains some but not all of the punctures of \( H \).

Under this assumption, \( z_2 \) cannot lie on \((yq)_{\alpha_1}\), since otherwise \( \beta \) would be homotopic to the purple arc Figure 16 (left) by Corollary 4.3, and so \( \beta \) would
Lemma 4.6. Let $p, q$ be distinct punctures of an $n$-punctured sphere $S$, with $n \geq 4$. Let $\alpha_1, \alpha_2, \beta$ be arcs on $S$ joining $p, q$ in one of the configurations shown in Figure 17. Then an arc $\gamma$ joining $p, q$ that is in minimal position with $\beta$ and intersects $\beta$ at least thrice must intersect $\alpha_1$ or $\alpha_2$ at least thrice.

Proof. Set $x_0 = p$, and let $x_1, x_2, x_3$ be the first 3 points of intersection of $\beta$ and $\gamma$ in the order that $\gamma$ traverses them as $\gamma$ travels from $p$ to $q$. For $i = 0, 1, 2$, let $\beta_i = (x_i, x_{i+1})_{\beta}, \gamma_i = (x_i, x_{i+1})_{\gamma}$, and let $R_i$ be the region not containing $p$ bounded by $\beta_i, \gamma_i$. If $\gamma_0$ does not intersect the $\alpha_i$, then $R_0$ contains no punctures, and so $\beta, \gamma$ are not in minimal position by Lemma 2.1, contradicting our assumption. Thus, $\gamma_0$ has at least one point of intersection with the $\alpha_i$. Similarly, $R_1, R_2$ must each contain at least one puncture of $S$, and so each of $\gamma_1, \gamma_2$ has at least 2 points of intersection with the $\alpha_i$. Thus, $\gamma$ has at least 3 points of intersection with $\alpha_1$ or $\alpha_2$. \qed
5. 1-System annular diagrams

In this section, we prove Theorem 1.5, which will be useful in the inductive step of the proof of Lemma 1.4.

**Lemma 5.1.** Let $S$ be a twice-punctured sphere and $p, q$ its punctures. Let $\mathcal{A}$ be a finite collection of simple arcs joining $p$ and $q$ and pairwise intersecting at most once. If there is a pair of intersecting arcs of $\mathcal{A}$, then there is a pair of arcs of $\mathcal{A}$ forming a half-bigon $H$ adjacent to $p$ such that no other arc of $\mathcal{A}$ has its $p$-end in $H$.

**Proof.** Pick $\alpha, \beta \in \mathcal{A}$ such that $\alpha$ and $\beta$ intersect, and let $H$ be the half-bigon adjacent to $p$ formed by $\alpha, \beta$. If $H$ is as in the statement of the lemma, then we are done. Otherwise, there is an arc $\beta' \in \mathcal{A}$ whose $p$-end lies in $H$. Since the $q$-end of $\beta'$ is outside $H$, the arc $\beta'$ must intersect one of $\alpha, \beta$, say $\alpha$. We now repeat the above steps with arcs $\alpha, \beta'$. Since there are finitely many arcs in $\mathcal{A}$, this process must terminate. \(\square\)

The following corollary follows immediately.

**Corollary 5.2.** Let $A$ be a 1-system annular diagram, and $P$ a boundary path of $A$. If $A$ has at least one square, then $A$ has a cornsquare with outerpath on $P$.

We now proceed to the proof of Theorem 1.5.

**Proof of Theorem 1.5.** We proceed by induction on the number of squares of $A$. If $A$ has no squares, then $A$ is a cycle. Now suppose $A$ has at least one square, that there is a boundary path $P$ of $A$ without a corner, and that the theorem holds for any annular square complex with fewer squares than $A$. Since $A$ contains a square, $A$ contains a cornsquare with outerpath on $P$ by Corollary 5.2. Thus, we may produce a corner on $P$ via a series of hexagon moves [Wis12, Figure 3.17]. Note that a single hexagon move cannot produce two corners on $P$; otherwise there would be a dual curve beginning and terminating at $P$ (see Figure 18).

We perform hexagon moves until the first corner $v$ on $P$ is produced. Note that each neighbor of $v$ has degree at least 4. Indeed, since $P$ had no corners, we had to have performed at least one hexagon move to obtain $v$, but a neighbor of $v$ of degree 3 would correspond to a corner prior to performing that move, contradicting our assumption that $v$ is the first corner produced on $P$ (see Figure 19). Thus, by deleting $v$ as well as the two edges and the square incident to $v$, we obtain a 1-system annular diagram with one fewer square than $A$ and without any corners on one of its boundary paths, contradicting the induction hypothesis. \(\square\)
Corollary 5.3. Let \( p, q \) be punctures of a punctured sphere \( S \), and let \( \mathcal{A} \) be a 1-system of arcs joining \( p \) and \( q \) such that \( |\mathcal{A}| \geq 2 \) and the arcs of \( \mathcal{A} \) are pairwise in minimal position. There is a puncture \( s \) of \( S \) distinct from \( p, q \) that is \( p \)-isolated by \( \mathcal{A} \). If \( \mathcal{A} \) contains a pair of intersecting arcs, then \( s \) can be chosen so that the component \( H \) of \( S - \bigcup \mathcal{A} \) containing \( s \) is a half-bigon.

**Proof.** The dual square complex \( A \) to \( \mathcal{A} \) is an annular square complex as in Theorem 1.5. Let \( P \) be the boundary path corresponding to \( p \). Note that \( A \) has at least 2 vertices since \( |\mathcal{A}| \geq 2 \), and that \( A \) has at least one square if and only if \( \mathcal{A} \) contains at least one pair of intersecting arcs. If \( A \) is a cycle, then we may take \( H \) to be the strip corresponding to any vertex of \( A \). Otherwise, \( A \) has a corner \( v \) on \( P \), and we may take \( H \) to be the half-bigon corresponding to \( v \). In either case, \( H \) is punctured since the arcs of \( \mathcal{A} \) are pairwise non-homotopic and in minimal position. \( \square \)

6. Proof of Lemma 1.4

In this section, we prove Lemma 1.4, which essentially constitutes the inductive step in the proof of Theorem 1.3. We will need the following:

**Lemma 6.1.** [Erd46] A set of pairwise intersecting straight line segments between \( \ell \) points on a circle in \( \mathbb{R}^2 \) has size at most \( \ell \).

**Proof of Lemma 1.4.** We fix a complete hyperbolic metric on \( S \) of area \( 2\pi(n-2) \). We may assume that \( \mathcal{P}, \mathcal{Q} \) are nonempty, and that the arcs of \( \mathcal{P} \cup \mathcal{Q} \) are pairwise in minimal position. We divide the proof into steps:

**Step 0. The arcs of \( \mathcal{P} \) (and hence the arcs of \( \mathcal{Q} \)) are consecutive at \( r \).** Indeed, suppose \( \alpha, \alpha' \in \mathcal{P} \) are distinct, and suppose there is an arc \( \beta \in \mathcal{Q} \) whose \( r \)-end lies in the strip or half-bigon \( H \) bounded by \( \alpha, \alpha' \) and adjacent to \( r \). Since \( \beta \) does not intersect \( \alpha, \alpha' \), the puncture \( q \) must lie in \( H \). Since no arc of \( \mathcal{Q} \) intersects \( \alpha, \alpha' \), it follows that the \( r \)-end of every arc of \( \mathcal{Q} \) must also lie in \( H \).
We fix an orientation on $S$. This induces a cyclic order $C$ of the arcs of $\mathcal{P} \cup \mathcal{Q}$ around $r$. By Step 0, this order in turn induces a linear order $<$ on $\mathcal{P}$, where the minimum and maximum arcs of $\mathcal{P}$ are those with a successor or predecessor in $\mathcal{Q}$ under $C$.

We proceed by induction. If $n = 3$, then, up to homotopy, there is a unique arc joining $r$ to each of $p, q$, and the statement of the lemma holds. Now let $n \geq 4$, and assume the lemma holds if $S$ has fewer punctures. If $\mathcal{P}$ consists of a single arc then the lemma is trivially satisfied since $|\mathcal{Q}| \leq \binom{n-1}{2}$ by Theorem 1.2. Thus, we may assume that $|\mathcal{P}| \geq 2$.

**Step 1.** There is a puncture $s$ of $S$ distinct from $p, q, r$ that is $p$-isolated by $\mathcal{P} \cup \mathcal{Q}$. Indeed, if the arcs of $\mathcal{P}$ are pairwise disjoint, then since $|\mathcal{P}| \geq 2$, we have that $S - \mathcal{P}$ consists of at least two punctured strips adjacent to $p$ and $r$, and so we may take $s$ to be a puncture of any such strip that does not contain $q$ (see Figure 20, left). Otherwise, by Corollary 5.3, there is a puncture $s$ distinct from $p, r$ that is $p$-isolated by $\mathcal{P}$ such that the component of $S - \bigcup \mathcal{P}$ containing $s$ is a half-bigon (see Figure 20, right). In this case, $s$ is necessarily distinct from $q$ since we are assuming $\mathcal{Q}$ to be nonempty, and so there is at least one arc disjoint from the arcs of $\mathcal{P}$ joining $q$ and $r$.

Let $\tilde{S}$ be the surface obtained from $S$ by forgetting the puncture $s$ (endowed with a complete, finite-area hyperbolic metric), and for each arc $\alpha \in \mathcal{P} \cup \mathcal{Q}$, let $\tilde{\alpha}$ be the corresponding arc on $\tilde{S}$. Let $\tilde{\mathcal{P}}, \tilde{\mathcal{Q}}$ be the collection of all $\tilde{\alpha}$ for $\alpha \in \mathcal{P}, \mathcal{Q}$, respectively. We tighten the arcs of $\tilde{\mathcal{P}} \cup \tilde{\mathcal{Q}}$ to geodesics, thereby identifying arcs that correspond to $s$-homotopic arcs on $S$.

The orientation on $S$ induces an orientation on $\tilde{S}$. As above, this gives us a linear order $\prec$ on $\tilde{\mathcal{P}}$.

**Step 2.** Two distinct arcs in $\mathcal{Q}$ cannot be $s$-homotopic. Otherwise, they would form a strip adjacent to $q, r$ or a half-bigon adjacent to one of $q, r$ whose only puncture is $s$, which cannot happen since the component of $S - \bigcup (\mathcal{P} \cup \mathcal{Q})$ containing $s$ is adjacent to $p$. Thus, we may identify $\tilde{\mathcal{Q}}$ with $\mathcal{Q}$.

**Step 3.** Arcs in $\mathcal{P}$ that are $s$-homotopic must be consecutive at $r$. Indeed, suppose that $\alpha, \alpha' \in \mathcal{P}$ are $s$-homotopic. If $\alpha, \alpha'$ bound a strip whose only puncture is $s$, then the $r$-end of any arc $\beta \in \mathcal{P}$ distinct from $\alpha, \alpha'$ cannot lie inside this strip,
since otherwise $\beta$ and one of $\alpha, \alpha'$ would necessarily form a half-bigon adjacent to $r$ whose only puncture is $s$, contradicting the fact that $s$ is $p$-isolated.

Otherwise, $\alpha$ and $\alpha'$ form a half-bigon adjacent to $p$ whose only puncture is $s$, and a half-bigon adjacent to $r$ containing all punctures of $S$ except $p, r, s$. Thus, any arc $\alpha''$ in $P$ distinct from $\alpha, \alpha'$ with $r$-end outside the latter half-bigon must be disjoint from $\alpha, \alpha'$, in which case $\alpha, \alpha', \alpha''$ are in fact $s$-homotopic.

**Step 4.** For any $\alpha, \alpha' \in P$, if $\alpha < \alpha'$ then $\bar{\alpha} \preceq \bar{\alpha'}$. Indeed, if $\bar{\alpha} > \bar{\alpha'}$, then $\alpha, \alpha'$ form a half-bigon adjacent to $r$ whose only puncture is $s$. This cannot happen since $s$ is $p$-isolated.

We now extend $P$ and $R$ as follows. Suppose $P$ contains intersecting $s$-homotopic arcs $\alpha, \alpha'$. Then, as discussed in Step 3, an arc $\alpha''$ disjoint from $\alpha, \alpha'$ joining $p$ and $r$ is $s$-homotopic to $\alpha, \alpha'$ and is between $\alpha, \alpha'$ with respect to the linear order on $P$. If $\alpha''$ is not homotopic to an arc in $P$, then we add $\alpha''$ to $P$ (otherwise, name the latter arc $\alpha''$). If there is an arc $\beta \in Q$ such that $(\alpha, \beta), (\alpha', \beta) \in R$ but $(\alpha'', \beta) \notin R$, we then add the pair $(\alpha'', \beta)$ to $R$. Since $\alpha''$ is disjoint from all arcs in $P \cup Q$, we have not violated any of the conditions of the lemma. We do this for each pair of intersecting $s$-homotopic arcs $\alpha, \alpha'$.

Let $\bar{R}$ be the image of $R$ under the map $P \times Q \to P \times Q, (\alpha, \beta) \mapsto (\bar{\alpha}, \beta)$. It is clear that $\bar{R}$ satisfies condition $(i)$, and it follows from Step 4 that $\bar{R}$ satisfies $(ii)$ as well, so that $|\bar{R}| \leq \binom{n-2}{2}$. It remains to show that $|\bar{R}| - |\bar{R}| \leq n - 2$.

Let $I$ be the subset of $\bar{R}$ consisting of elements with more than one pre-image under the map $R \to \bar{R}$.

**Step 5.** If $(\bar{\alpha}, \beta), (\bar{\alpha'}, \beta') \in I$ with $\beta \neq \beta'$, then $\beta, \beta'$ are disjoint. Indeed, let $(\alpha_1, \beta), (\alpha_2, \beta)$ be pre-images of $(\alpha, \beta)$, and $(\alpha_1', \beta'), (\alpha_2', \beta')$ pre-images of $(\alpha', \beta')$ with $\alpha_1 \neq \alpha_2, \alpha_1' \neq \alpha_2'$. Suppose that $\beta$ and $\beta'$ intersect. Note that we cannot have $(\alpha_1, \alpha_2) = (\alpha_1', \alpha_2')$, since otherwise either $(\alpha_1, \beta), (\alpha_2, \beta')$ or $(\alpha_1, \beta'), (\alpha_2, \beta)$ would be intersecting pairs of arcs in $R$ whose cyclic order around $r$ is not alternating, contradicting assumption $(ii)$.

Now suppose $(\alpha_1, \alpha_2) \cap \{\alpha_1', \alpha_2'\} \neq \emptyset$. Then there are 3 distinct arcs among $\alpha_1, \alpha_2, \alpha_1', \alpha_2'$ that are $s$-homotopic. Assume without loss of generality that these arcs are $\alpha_1, \alpha_2, \alpha_1'$. Observe that $\alpha_1'$ cannot intersect $\alpha_i$ for $i = 1, 2$, since otherwise $(\alpha_i, \beta), (\alpha_1', \beta')$ would intersect more than once, contradicting assumption $(i)$. Thus, $\alpha_1$ intersects $\alpha_2$, but then $\alpha_1'$ lies between $\alpha_1$ and $\alpha_2$ at $r$, and so there is an $i \in \{1, 2\}$ such that $(\alpha_1, \beta), (\alpha_1', \beta')$ contradict assumption $(ii)$.

We conclude that $\alpha_1, \alpha_2, \alpha_1', \alpha_2'$ are distinct; in particular, since at most 3 distinct arcs in $P$ can be $s$-homotopic, we must have $\bar{\alpha} \neq \bar{\alpha'}$. Thus, by Step 3, the order of $\alpha_1, \alpha_2, \alpha_1', \alpha_2'$ at $r$ is neither alternating nor nested. By the latter, we mean that $\alpha_1, \alpha_2$ do not both lie between $\alpha_1', \alpha_2'$ in the linear order on $P$, and vice versa. Since each of the pairs of arcs $\alpha_1, \alpha_2$ and $\alpha_1', \alpha_2'$ bound a strip or half-bigon containing $s$, we must have that $\alpha_i, \alpha_j'$ intersect for some $i, j \in \{1, 2\}$, but then $(\alpha_1, \beta), (\alpha_1', \beta')$ intersect more than once, contradicting assumption $(i)$.

**Step 6.** If $(\bar{\alpha}, \beta), (\bar{\alpha'}, \beta') \in I$ with $\bar{\alpha} \neq \bar{\alpha'}, \bar{\beta} \neq \bar{\beta'}$, then the cyclic order of $(\alpha, \beta), (\alpha', \beta')$ at $r$ is alternating. Indeed, suppose otherwise, and let $(\alpha_1, \beta), (\alpha_2, \beta)$ be pre-images of $(\bar{\alpha}, \beta)$, and $(\alpha_1', \beta'), (\alpha_2', \beta')$ pre-images of $(\alpha', \beta')$
with \( \alpha_1 \neq \alpha_2, \alpha'_1 \neq \alpha'_2 \). Then, by Step 3, the order of \( \alpha_1, \alpha_2, \alpha'_1, \alpha'_2 \) at \( r \) is neither alternating nor nested. Thus, as in Step 5, \( \alpha_i, \alpha'_j \) must intersect for some \( i, j \in \{1, 2\} \), but then \( (\alpha_i, \beta), (\alpha'_j, \beta') \) are two intersecting pairs of arcs in \( R \) whose cyclic order around \( r \) is not alternating, contradicting assumption \((ii)\) (see Figure 21).

Let \( H_q \) be the image of \( I \) under the projection map \( \bar{P} \times Q \to Q \). Let \( H_s \) be the collection of all geodesic arcs \( a \) joining \( r \) and \( s \) such that \( a \) is contained in a strip bounded by a pair of distinct, disjoint \( s \)-homotopic arcs in \( \bar{P} \).

Let \( \mathcal{H} = H_s \cup H_q \), and let \( \mathcal{I}' \subset H_s \times H_q \) be the set of all \( (a, \beta) \in H_s \times H_q \) such that \( (\alpha, \beta) \in I \) for an arc \( \alpha \) bounding a strip corresponding to \( a \). We extended \( \mathcal{R} \) so that the map \( \mathcal{R} \to \bar{\mathcal{R}} \) is injective outside a set of cardinality \(|\mathcal{I}'|\). Thus, to complete the proof, it suffices to show that \(|\mathcal{I}'| \leq n - 2\).

**Step 7.** The complement of \( \mathcal{H} \) consists of punctured strips and a single square, possibly with no punctures. Indeed, the arcs of \( H_s \) are disjoint by construction [Prz15, proof of Theorem 1.7], and the arcs of \( H_q \) are disjoint by Step 5, so that the complement of each of \( H_s, H_q \) consists of punctured strips. By Step 0, the arcs in \( H_q \) (and hence the arcs in \( H_s \)) are consecutive at \( r \). Thus, \( H_s \) is contained in a single strip of \( S - H_q \) and vice versa. Let \( \beta, \beta' \) be the arcs in \( H_q \) bounding the unique strip of \( S - H_q \) containing \( H_s \), and let \( \gamma, \gamma' \) be the arcs in \( H_s \) bounding the unique strip of \( S - H_s \) containing \( H_q \) (note that we do not exclude the possibility that \( \beta = \beta' \) or \( \gamma = \gamma' \)). Then the complement of \( \mathcal{H} \) consists of the remaining strips of \( S - H_q, S - H_s \) and a square bounded by \( \beta, \beta', \gamma, \gamma' \).

**Step 8.** \(|\mathcal{H}| \leq n - 1\). Indeed, \(|\mathcal{H}| \) is 2 larger than the number of strips of \( S - \mathcal{H} \), so it suffices to show that there are at most \( n - 3 \) of these strips. This is true by Step 7 since \( S \) has area \( 2\pi(n - 2) \), and a punctured strip and a square each have area at least \( 2\pi \).

**Step 9.** \(|\mathcal{I}'| \leq n - 2\). To show this, we intersect \( \mathcal{H} \) with a small circle \( C \) centered at \( r \). Each element of \( \mathcal{I}' \) is determined by a pair of points of this intersection, and we connect them by a straight line segment. We also draw a line segment between

![Figure 21. An illustration of Step 6. Here, the pairs \((\alpha_1, \beta)\) and \((\alpha'_1, \beta')\) contradict assumption \((ii)\).](image)
20 SAMI DOUBA

Figure 22

the outermost points on $C$ corresponding to elements of $\mathcal{H}_q$. By Step 6, these line segments are pairwise intersecting, so by Lemma 6.1, $|I'| + 1 \leq |H| \leq n - 1$. □

7. Proof of Theorem 1.3

Proof of Theorem 1.3. We proceed by induction on $n$. The case $n = 3$ is trivial. Now let $n \geq 4$, and assume the theorem holds if $S$ has fewer punctures. Let $r$ be a puncture of $S$ distinct from $p, q$. Let $\tilde{S}$ be the $(n - 1)$-punctured sphere obtained from $S$ by forgetting $r$. For each arc $\alpha \in \mathcal{A}$, let $\tilde{\alpha}$ be the corresponding arc on $\tilde{S}$, and let $\tilde{\mathcal{A}} = \{\tilde{\alpha} : \alpha \in \mathcal{A}\}$. We tighten the arcs of $\mathcal{A}$ to geodesics. Note that $\tilde{\mathcal{A}}$ is a 2-system on $\tilde{S}$, and so $|\tilde{\mathcal{A}}| \leq \binom{n-1}{3}$ by the induction hypothesis. Thus, it is enough to show that $|\mathcal{A}| - |\tilde{\mathcal{A}}| \leq \binom{n-1}{2}$. To that end, we examine the extent to which the map $\pi : \mathcal{A} \to \tilde{\mathcal{A}}$, $\alpha \mapsto \tilde{\alpha}$ is injective.

By Lemmas 4.4, 4.5, and 4.6, we may add arcs to $\mathcal{A}$ so that for each $\alpha \in \mathcal{A}$,

$|\pi^{-1}(\tilde{\alpha})| - 1 = |\{\{\alpha_1, \alpha_2\} \in \pi^{-1}(\tilde{\alpha}) : \alpha_1, \alpha_2 \text{ distinct and disjoint}\}|$

Let $\mathcal{P}$ (resp., $\mathcal{Q}$) be the collection of all geodesic arcs $\alpha$ on $S$ starting at $r$ and ending at $p$ (resp., ending at $q$) such that $\alpha$ is contained entirely in a strip bounded by a pair of distinct, disjoint $r$-homotopic arcs in $\mathcal{A}$. Let $\mathcal{R} \subseteq \mathcal{P} \times \mathcal{Q}$ be the relation consisting of all pairs $(\alpha, \beta)$ such that both $\alpha$ and $\beta$ lie in a single such strip. We claim that $\mathcal{P}, \mathcal{Q}, \mathcal{R}$ satisfy the conditions of Lemma 1.4, so that $|\mathcal{R}| \leq \binom{n-1}{2}$. Since $|\mathcal{R}| = |\mathcal{A}| - |\tilde{\mathcal{A}}|$, this completes the proof.

We first note that for $(\alpha, \beta), (\alpha', \beta') \in \mathcal{R}$ corresponding to pairs of disjoint $r$-homotopic arcs $\gamma_1, \gamma_2 \in \mathcal{A}$ and $\gamma'_1, \gamma'_2 \in \mathcal{A}$, respectively, we have for some $i, j \in \{1, 2\}$ that $r$ produces at least one point of intersection between $\gamma_i, \gamma'_j$. Each point of intersection between the arcs $\alpha, \beta, \alpha', \beta'$ produces an additional point of intersection between $\gamma_i, \gamma'_j$. It follows that there is at most one point of intersection between any two pairs of arcs in $\mathcal{R}$.

We now show that no arc in $\mathcal{P}$ intersects an arc in $\mathcal{Q}$. Indeed, suppose we have $(\alpha, \beta), (\alpha', \beta') \in \mathcal{R}$ such that $\alpha$ intersects $\beta'$. By the above, $\alpha$ intersects $\beta'$ exactly once and that is the only point of intersection between the pairs of arcs $(\alpha, \beta), (\alpha', \beta')$. But then we can find two arcs in $\mathcal{A}$ that intersect thrice, as shown in Figure 22 (left).
Finally, if there are two intersecting pairs of arcs in $\mathcal{R}$ whose cyclic order around $r$ is not alternating, then we can also find two arcs in $\mathcal{A}$ that intersect thrice, as shown in Figure 22 (right).

References


Department of Mathematics and Statistics, McGill University, Montreal, Quebec, Canada

E-mail address: sami.douba@mail.mcgill.ca