MAPPING CLASS GROUPS, BRAID GROUPS AND GEOMETRIC REPRESENTATIONS

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1. Curves, Surfaces and Hyperbolic Geometry

1.1. **Simple closed curves.** There is a bijective correspondence

$$\left\{ \begin{array}{c} \text{Nontrivial} \\ \text{conjugacy classes} \\ \text{in } \pi_1(S) \end{array} \right\} \longleftrightarrow \left\{ \begin{array}{c} \text{Nontrivial free} \\ \text{homotopy classes of oriented} \\ \text{closed curves in } S \end{array} \right\}$$

Definition 1.1 (Primitive and multiple elements)**.** An element g of a group G is *primitive* if there does not exist any $h \in G$ so that $g = h^k$ for $|k| > 1$. The property of being a primitive is a conjugacy class invariant. In particular, it makes sense to say that a closed curve in a surface is primitive.
A closed curve in S is a multiple if it is a map $S^1 \to S$ that factors through the map $S^1 \xrightarrow{\times n} S^1$ for $n > 1$, i.e., there exists a map $\tilde{\alpha}\colon S^1 \to S$ such that the following diagram commutes:

$$\begin{tikzcd} S^1 \arrow[r, "\times n"] \arrow[rr, bend left, dashed, "\tilde{\alpha}"] & S^1 \arrow[r, "\alpha"] & S \end{tikzcd}$$

Definition 1.2 (Lifts)**.** We make a distinction between lifts: let $p\colon \tilde{S} \to S$ be a covering space. By a *lift* of a closed curve α to $\tilde{S}$ we will always mean the image of a lift $\mathbb{R} \to \tilde{S}$ of the map $\alpha \circ \pi$ where $\pi\colon \mathbb{R} \to S^1$ is the usual covering map. I.e., a lift of $\alpha\colon S^1 \to S$ is a map $\tilde{\alpha}\colon \mathbb{R} \to \tilde{S}$ such that the following diagram commutes

$$\begin{tikzcd} & & \tilde{S} \arrow[d, "p"] \\ \mathbb{R} \arrow[urr, "\tilde{\alpha}"] \arrow[r, "\pi"'] & S^1 \arrow[r, "\alpha"'] & S \end{tikzcd}$$

A lift is different from a *path lift* which is a proper subset of a lift. Namely, it would be the restriction of $\tilde{\alpha}$ to some interval of $\mathbb{R}$ of length 2π if the covering map π is of the form $t \mapsto e^{it}$.

Now suppose $p\colon \tilde{S} \to S$ is the universal cover and α is a simple closed curve in S that is not a multiple of another closed curve. In this case, there is a bijective correspondence between cosets in $\pi_1(S)$ of the infinite cyclic subgroup $\langle\alpha\rangle$ and the lifts of α. This can be seen as follows: first choose a basepoint $\alpha(1) = x_0 \in S$ and some $\tilde{x_0} \in p^{-1}(x_0)$. There exists a unique lift $\tilde{\alpha}$ of α such that

$$\begin{tikzcd} & & \tilde{S} \arrow[d, "p"] \\ \mathbb{R} \arrow[urr, "\tilde{\alpha}"] \arrow[r] & S^1 \arrow[r, "\alpha"] & S \end{tikzcd}$$

commutes and such that $\tilde{\alpha}(0) = \tilde{x} \in p^{-1}(\alpha \circ \pi(0))$ for some specific $\tilde{x}$ [1, Cor. 4.2]. But the set $p^{-1}(\alpha \circ \pi(0))$ is in bijective correspondence with the loops in $\pi_1(S)$ by the path lifting lemma. Now, under which path lifts are the lifts the same? The lifts of α to two points $\tilde{x}, \tilde{y} \in p^{-1}(\alpha \circ \pi(0))$ will be the same if $\alpha^k \cdot \tilde{x} = \tilde{y}$ where $\cdot$ denotes the monodromy action of $\pi_1(S)$ on the fiber. Now, there exist γ_x and γ_y in $\pi_1(S)$ such that $\gamma_x \cdot \tilde{x_0} = \tilde{x}$ and $\gamma_y \cdot \tilde{x_0} = \tilde{y}$, so $\alpha^k \gamma_x = \gamma_y$. Hence the lifts corresponding to γ_x and γ_y are the same if and only if $\alpha^k \gamma_x = \gamma_y$ for some k, i.e. if and only if $\gamma_x = \gamma_y$ in $\pi_1(S)/\langle\alpha\rangle$.

As usual, the group $\pi_1(S)$ acts on the set of lifts of α by deck transformations, and this action agrees with the usual left action of $\pi_1(S)$ on the cosets of $\langle\alpha\rangle$. The stabilizer of the lift corresponding to the coset $\gamma\langle\alpha\rangle$ is the cyclic group $\langle\gamma\alpha\gamma^{-1}\rangle$. See figure 1.

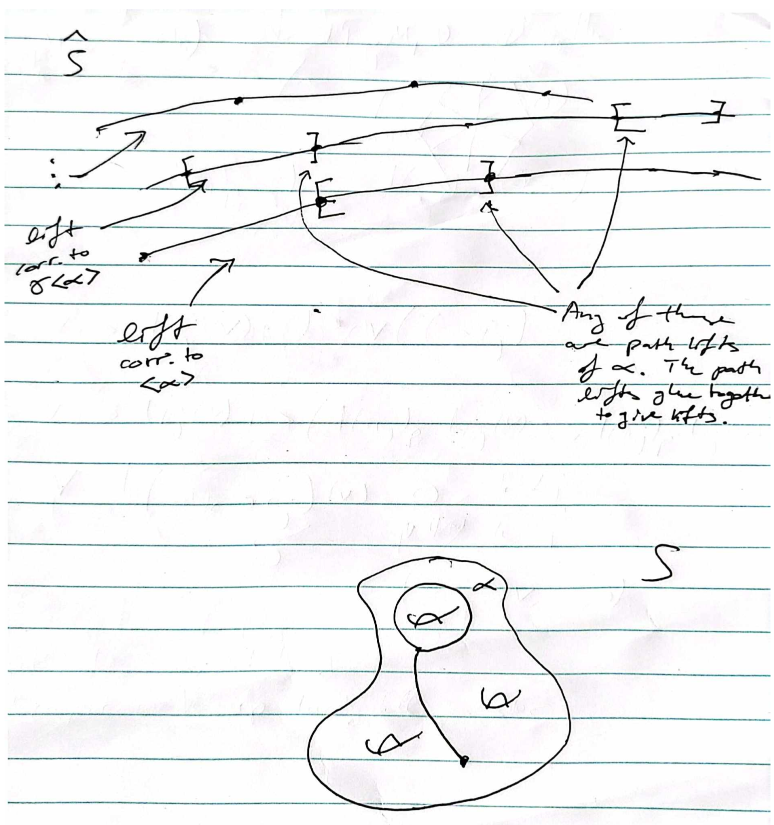


FIGURE 1.

Theorem 1.3. *When S admits a hyperbolic metric and α is a primitive element of $\pi_1(S)$, we have a bijective correspondence*

$$\left\{ \begin{array}{c} \textit{Elements of the conjugacy} \\ \textit{class of } \alpha \textit{ in } \pi_1(S) \end{array} \right\} \longleftrightarrow \left\{ \begin{array}{c} \textit{Lifts to } \tilde{S} \textit{ of the} \\ \textit{closed curve } \alpha \end{array} \right\}$$

More precisely, we claim that the map which sends the lift given by the coset $\gamma \langle \alpha \rangle$ to $\gamma\alpha\gamma^{-1}$ is bijective and well-defined.

Proof. To show that it is well-defined, suppose $\gamma \langle \alpha \rangle$ and $\beta \langle \alpha \rangle$ give the same lift. Then $\gamma = \beta\alpha^k$. So in particular,

$$\gamma\alpha\gamma^{-1} = \beta\alpha^k\alpha\alpha^{-k}\beta^{-1} = \beta\alpha\beta^{-1}$$

so they do correspond to the same element of the conjugacy class $[\alpha]$. It is clear that this is a surjective map. Now suppose that $\gamma\alpha\gamma^{-1} = \beta\alpha\beta^{-1}$. Then $\beta^{-1}\gamma\alpha\left(\beta^{-1}\gamma\right)^{-1} = \alpha$, so in particular, $\beta^{-1}\gamma \in C_{\pi_1(S)}(\alpha)$ which is a cyclic group generated by, say, θ. But then $\theta^l = \alpha$ since α is trivially in the centralizer of α; however, α is primitive, so l must be ± 1, but then α generates the centralizer of α, $C_{\pi_1(S)}(\alpha) = \langle \alpha \rangle$, and hence $\gamma = \beta\alpha^l$, so $\gamma \langle \alpha \rangle = \beta \langle \alpha \rangle$. □

Remark. If α is any multiple, then we still have a bijective correspondence between elements of the conjugacy class of α and the lifts of α. However, if α is not primitive and not a multiple, then there are more lifts of α than there are conjugates. Indeed, if $\alpha = \beta^k$, where $k > 1$, then $\beta \langle \alpha \rangle \neq \langle \alpha \rangle$ while $\beta\alpha\beta^{-1} = \alpha$.

Example 1.4. The above correspondence does not hold for the torus T^2 because each closed curve has infinitely many lifts, while each element of $\pi_1\left(T^2\right) \approx \mathbb{Z}^2$ is its own conjugacy class because $\pi_1\left(T^2\right)$ is abelian.

Geodesic representatives.

Proposition 1.5. *Let S be a hyperbolic surface. If α is a closed curve in S that is not homotopic into a neighborhood of a puncture, then α is homotopic to a unique geodesic closed curve γ.*

Corollary 1.6. *For compact hyperbolic surfaces, there is a bijective correspondence:*

$$\left\{ \begin{array}{c} \textit{Conjugacy classes} \\ \textit{in } \pi_1(S) \end{array} \right\} \longleftrightarrow \left\{ \begin{array}{c} \textit{Oriented geodesic} \\ \textit{closed curves in } S \end{array} \right\}$$

Simple closed curves.

Definition 1.7 (Simple curves)**.** A closed curve in S is *simple* if it is topologically embedded, i.e., if the map $S^1 \to S$ is injective.

By [1, Thm 11.8], any closed curve α can be approximated (arbitrarily close) by a smooth closed curve which is homotopic to α. Moreover, if α is simple, then the smooth approximation can be chosen to be simple. Smooth curves are advantageous because we can make use of notions such as transversality.
Simple closed curves are also natural to study because they represent primitive elements of $\pi_1(S)$.

Proposition 1.8. *Let α be a simple closed curve in a surface S. If α is not null homotopic, then each element of the corresponding conjugacy class in $\pi_1(S)$ is primitive.*

Example: simple closed curves on the torus.

Proposition 1.9. *The nontrivial homotopy classes of oriented simple closed curves in T^2 are in bijective correspondence with the set of primitive elements of $\pi_1\left(T^2\right) \approx \mathbb{Z}^2$ which is the set of elements $(p,q) \in \mathbb{Z}^2$ such that either $(p,q) = (0,\pm 1)$ or $(p,q) = (\pm 1, 0)$ or $\gcd(p,q) = 1$.*

Proof. Firstly, primitive elements of $\pi_1 T^2 \approx \mathbb{Z}^2$ are those (a,b) such that there does not exist (c,d) and $k \in \mathbb{Z}$ such that $|k| > 1$ and $(kc, kd) = (a,b)$. But this is equivalent to saying that either $\gcd(a,b) = 1$ or $(a,b) \in \{(\pm 1, 0), (0, \pm 1)\}$.

We now claim that for a nontrivial closed curve α in T^2, α is homotopic to a simple closed curve if and only if α represents a primitive element of $\pi_1 T^2 \approx \mathbb{Z}^2$.
Suppose $(p,q) = \alpha$ represents a primitive element of $\pi_1 T^2 \approx \mathbb{Z}^2$. Then if we choose the origin as basepoint, we can lift α to the straight-line path starting at the origin and ending at $(p,q) \in \mathbb{Z}^2$. The projected loop is simple since otherwise, we would have for $t, t' \in t, t' \in [0,1)$ with $t \neq t'$ that $(tp, tq) = (t'p, t'q) + (m,n)$ for $m, n \in \mathbb{Z}$. But then $\frac{p}{q} \in \mathbb{Z}$ contradicting $\gcd(p,q) = 1$ except when $q = \pm 1$. But then $\pm t = \pm t' + n$ necessarily gives $n = 0$ and $t = t'$, contradiction.

Conversely, suppose α is homotopic to a nontrivial simple closed curve which we will also denote α. A lift of α will consist of a collection of biinfinite disjoint topological lines. We can homotopy this collection into a collection of disjoint straight biinfinite lines, where the integer points on the lines are fixed during the homotopy. Since these collections and the homotopy are equivariant with respect to deck transformations, this descends to a homotopy of α. If the descended loop from the straight lines were not simple, we would have intersections in the universal cover - i.e. nonparallel lines which we do not have. This is the information of Lemma 1.11 below. As the straight-line respresentative is simple, we must therefore have that if α is represented by (p,q), we have that $\gcd(p,q) = 1$ or $(p,q) \in \{(\pm 1, 0), (0, \pm 1)\}$. $\square$

Closed geodesics.

Proposition 1.10. *Let S be a hyperbolic surface. Let α be a closed curve in S not homotopic into a neighborhood of a puncture. Let γ be the unique geodesic in the free homotopy class of α guaranteed by proposition 1.5. If α is simple, then γ is simple.*

Proof. Follows from the following lemma:

Lemma 1.11. *Let X be a topological space with a universal covering space $\tilde{X}$. A closed curve β in X is simple if and only if the following properties hold:*

1. *Each lift of β to $\tilde{X}$ is simple.*
2. *No two lifts of β intersect.*
3. *β is not a nontrivial multiple of another closed curve.*

$\square$

Intersection numbers. It is often useful to put an inner product on a vector space to check if two vectors are linearly independent. We can pursue something similar for surfaces.

Definition 1.12 (Transversality for curves)**.** If $\alpha \cap \beta$ is finite and, at every intersection, each curve locally separates the other curve, then we say that α and β are *transverse.*

Definition 1.13 (Algebraic intersection number)**.** Let α and β be a pair of transverse, oriented, simple closed curves in S. Their *algebraic intersection number* $\hat{i}\left(\alpha, \beta\right)$ is defined as the sum of the indices of the intersection points of α and β, where the intersection point is of index $+1$ when the orientation of intersection agrees with the orientation of S and is -1 otherwise.

Remark. The algebraic intersection number only depends on the homology classes of the curves and defines a symplectic form on homology.

Definition 1.14 (Geometric intersection number)**.** Let α, β be closed curves on a surface S. Their *geometric intersection number* is

$$i\left(\alpha, \beta\right) = \min_{\alpha' \simeq \alpha, \beta' \simeq \beta} \#\left(\alpha' \cap \beta'\right)$$

Intersection numbers are a useful general tool, and we will encounter them not only in applications of the Bigon criterion which we describe in a moment, but also in direct computations. One such computation will be the mapping class group of the torus T^2. For this, we will need an explicit expression for the intersection number of curves on the torus.

Example 1.15 (Intersection numbers on the torus)**.** By proposition 1.9, the nontrivial homotopy classes of oriented simple closed curves in T^2 are in bijective correspondence with the set of primitive elements of $\mathbb{Z}^2$. For two such homotopy classes (p, q) and p', q', we claim that

$$i\left(\left(p, q\right), \left(p', q'\right)\right) = \left|pq' - p'q\right|.$$

Suppose first that $(p, q) = (1, 0)$. Through a homotopy, we can assume that (p', q') is represented by a loop which first winds around the torus p' times horizontally without intersecting $(1, 0)$ and then q' times vertically. It then is clear that $i\left(\left(p, q\right), \left(p', q'\right)\right) = |q'| = |pq' - p'q|$. For the algebraic case, we choose $(1, 0)$ to be along the orientation direction. Then $\hat{i}\left(\left(p, q\right), \left(p', q'\right)\right) = q' = pq' - p'q$.
For the general case, suppose $\gcd(p, q) = 1$. Then by Bezout's lemma, there exist $a, b \in \mathbb{Z}$ such that $ap + bq = 1$. The system of equations

$$\begin{aligned} qd + pc &= 0 \\ ad - bc &= 1 \end{aligned}$$

has $(c, d) = (-q, p)$ as a solution. So letting

$$A = \begin{pmatrix} a & b \\ -q & p \end{pmatrix} \in \mathrm{SL}\left(2, \mathbb{Z}\right)$$

we get $A \begin{pmatrix} p \\ q \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$. Since A is a linear, orientation-preserving homeomorphism of $\mathbb{R}^2$ preserving $\mathbb{Z}^2$, it induces an orientation-preserving homeomorphism on the quotient $\mathbb{R}^2/\mathbb{Z}^2 \approx T^2$ whose action on the fundamental group $\pi_1\left(T^2\right) \approx \mathbb{Z}^2$ is given by A. Now, homeomorphisms preserve algebraic and geometric intersection numbers. Then

$$\begin{aligned} i\left(\left(p,q\right),\left(p',q'\right)\right) = i\left(A\left(p,q\right),A\left(p',q'\right)\right) &= i\left(\left(1,0\right),\left(ap'+bq',-qp'+pq'\right)\right) \\ &= \left|pq'-qp'\right| \end{aligned}$$

and likewise $\hat{i}\left(\left(p,q\right),\left(p',q'\right)\right) = pq' - qp'$.
The other primitive cases are checked easily.

Definition 1.16 (Minimal position)**.** Two curves α and β are in *minimal position* if $\#\left(\alpha \cap \beta\right) = i\left(\alpha,\beta\right)$.

Bigons. We want a procedure to put curves into minimal position so we can compute intersection numbers.
For this, we need the notion of a *bigon*:

Definition 1.17 (Bigon)**.** Two transverse simple closed curves α and β in a surface S form a *bigon* if there is a topologically embedded disk in S (the bigon) whose boundary is the union of an arc of α and an arc of β intersecting in exactly two points.

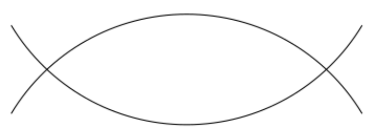


FIGURE 2. Local picture of a bigon

Lemma 1.18. *If transverse simple closed curves α and β in a surface S do not form any bigons, then in the universal cover of S, and pair of lifts $\tilde{\alpha}$ and $\tilde{\beta}$ of α and β intersect in at most one point.*

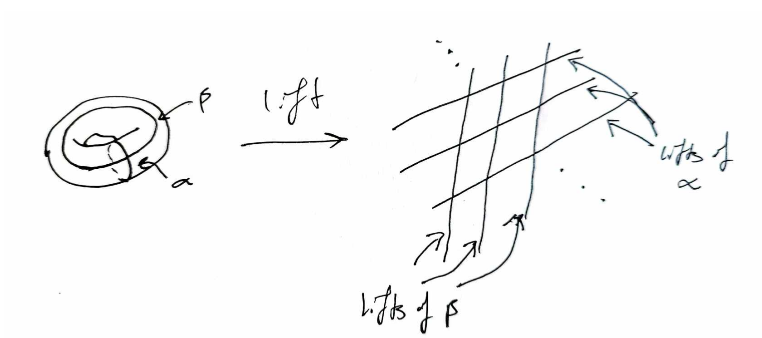


FIGURE 3. Lemma 1.18 illustrated

Proposition 1.19 (The bigon criterion)**.** *Two transverse simple closed curves in a surface S are in minimal position if and only if they do not form a bigon.*

Corollary 1.20. *Any two transverse simple closed curves that intersect exactly once are in minimal position.*

Homotopy versus isotopy for simple closed curves.

Definition 1.21 (Isotopy)**.** Two simple closed curves α and β are *isotopic* if there is a homotopy

$$H\colon S^1 \times [0,1] \to S$$

from α to β with the property that the closed curve $H\left(S^1 \times \{t\}\right)$ is simple for each $t \in [0,1]$.

Proposition 1.22 (Baer)**.** *Let α and β be two essential simple closed curves in a surface S. Then α is isotopic to β if and only if α is homotopoic to β.*

Proof. If α is isotopic to β then they are clearly also homotopic.

Suppose α and β are homotopic. Taking a tubular neighborhood around α, we can find a disjoint simple loop $\tilde{\alpha}$ which is homotopic to α but disjoint from it. Then β is homotopic to $\tilde{\alpha}$, and hence $i(\alpha,\beta) = i(\alpha,\tilde{\alpha}) = 0$. Performing an isotopy of α, we may assume that α is transverse to β . If α and β are not disjoint, then by the bigon criterion, they form a bigon. A bigon prescribes an isotopy that reduces intersection, so we may remove bigons by isotopy until α and β are disjoint.

why?

Suppose $\chi(S) < 0$. Lift α and β to $\tilde{a}$ and $\tilde{\beta}$ with the same endpoints in $\partial\mathbb{H}^2$. There is a hyperbolic isometry φ that leaves $\tilde{\alpha}$ and $\tilde{\beta}$ invariant and acts by translation on the lifts. As $\tilde{\alpha}$ and $\tilde{\beta}$ are disjoint, let R denote the region between them. We claim that the quotient surface $R' = R/\langle\varphi\rangle$ is an annulus. The fundamental group of R' is isomorphic to the group of deck transformations $\langle\varphi\rangle$ and is hence infinite cyclic. Furthermore, R' has two boundary components. □

Extension of isotopies.

Definition 1.23. An isotopy of a surface S is a homotopy $H\colon S \times I \to S$ such that for each $t \in [0,1]$, the map $H(S,t) : S \times \{t\} \to S$ is a homeomorphism. Given an isotopy between two simple closed curves in S, it will often be useful to promote this to an isotopy of S which we call an ambient isotopy of S.

Proposition 1.24. *Let S be any surface. If $F\colon S^1 \times I \to S$ is a smooth isotopy of simple closed curves, then there is an isotopy $H\colon S \times I \to S$ so that $H|_{S\times 0}$ is the identity and $H|_{F(S^1\times 0)\times I} = F$.*

Proof. [4, Ch 8, Thm 1.3] □

1.2. **Small digression on Hirsch chapter 8.**

Definition 1.25 (Isotopy in general and their tracks)**.** Let V and M be manifolds. An isotopy from V to M is a map $F\colon V \times I \to M$ such that for each $t \in I$, the map

$$F_t\colon V \to M, \quad x \mapsto F(x,t)$$

is an embedding.
The *track* of the isotopy F is the embedding

$$\hat{F}\colon V \times I \to M \times I, \quad (x,t) \mapsto (F(x,t),t)$$

Definition 1.26 (Isotopic embeddings and ambient isotopies)**.** If $F\colon V \times I \to M$ is an isotopy, we call the two embeddings F_0 and F_1 isotopic. If V is a submanifold of M and F_0 is the inclusion, we call F an isotopy of V in M. When $V = M$ and each F_t is a diffeomorphism, and $F_0 = \mathbb{1}_M$, then F is called an ambient isotopy.

Definition 1.27 (Support of isotopy)**.** The *support* $\operatorname{Supp} F \subset V$ of an isotopy $F\colon V \times I \to M$ is the closure of $\{x \in V : F(x,t) \neq F(x,0) \text{ for some } t \in I\}$.

Theorem 1.28 (Isotopy extension theorem)**.** *[4, Theorem 1.3, chapter 8] Let $V \subset M$ be a compact submanifold and $F\colon V \times I \to M$ an isotopy of V. If either $F(V \times I) \subset \partial M$ or $F(V \times I) \subset M - \partial M$, then F extends to an ambient isotopy of M having compact support.*

Insert proof?

1.3. **Arcs.**

Assume S is a compact surface, possibly with boundary and possibly with finitely many marked points in the interior. Denote the set of marked points by $\mathcal{P}$.

Definition 1.29. A *proper arc* in S is a map $\alpha\colon [0,1] \to S$ such that $\alpha^{-1}(\mathcal{P} \cup \partial S) = \{0,1\}$.

Definition 1.30. The arc α is *simple* if it is an embedding on its interior.

Remark. The homotopy class of a proper arc is taken to be the homotopy class within the class of proper arcs. Thus points on ∂S cannot move off the boundary during the homotopy.
A homotopy (or isotopy) of an arc is said to be *relative to the boundary* if its endpoints stay fixed throughout the homotopy. An arc in a surface S is *essential* if it is neither homotopic into a boundary component of S nor a marked point of S.

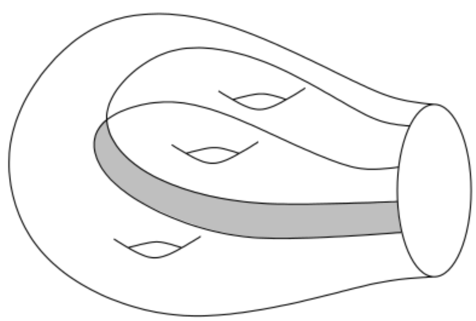


FIGURE 4. bigon-of-arcs.png

Note in this picture how if isotopies are considered relative to the boundary, then the two arcs are in minimal position, while if we consider general isotopies, then the half-bigon shows that they are not in minimal position as we can pull the top strand down under the bottom one along the boundary.

- The bigon criterion holds for arcs.
- Corollary 1.9 (geodesics are in minimal position) and prop 1.3 (existence and uniqueness of geodesic representatives) work for arcs in surfaces with punctures and/or boundary.
- Prop 1.10 (homotopy versus isotopy for curves) and theorem 1.13 (extension of isotopies) also work for arcs.

Change of coordinates principle.

Classification of simple closed curves.

Definition 1.31. Given a simple closed curve or a simple proper arc α in a surface S, the surface obtain by cutting S along α is a compact surface S_α equipped with an attaching map h (i.e.

(1) $S_\alpha/(x \sim h(x)) \approx S$
(2) the image of the distinguished boundary components under this quotient map is α.

Definition 1.32. We say that a simple closed curve α in the surface S is *nonseparating* if the cut surface S_α is connected, and *separating* if S_α is not connected.

Theorem 1.33. *If α and β are any two nonseparating simple closed curves in a surface S, then there is a homeomorphism $\varphi\colon S \to S$ with $\varphi(\alpha) = \beta$.*

Proof. The cut surface S_α and S_β have two boundary component corresponding to α and β, respectively. Now, suppose S_α has n_α vertices, m_α edges and t_α triangles in a triangulation. Then in obtaining S from S_α, we identify the vertices and edges, but no triangles are identified, so we get $n_S = n_\alpha - 3$ and $m_S = m_\alpha - 3$, but $t_S = t_\alpha$. Thus $\chi(S_\alpha) = \chi(S)$.
Since both S_α and S_β have the same Euler characteristic, number of boundary components and number of punctures, it follows that $S_\alpha \approx S_\beta$. Choose a homeomorphism $\varphi\colon S_\alpha \to S_\beta$ such that if h_α is the attaching map for S_α and h_β is the attaching map for S_β, then φ takes $\{x, h_\alpha(x)\}$ to $\{y, h_\beta(y)\}$ - i.e., the identification are respected under the map. This homeomorphism gives the desired homeomorphism of S taking α to β. If we want an orientation preserving homeomorphism, we can postcompose by an orientation-reversing homeomorphism fixing β if necessary. □

Theorem 1.34. *When S is closed, β is separating if and only if it is the boundary of some subsurface of S. Which is equivalent to the vanishing of the homology class of β in $H_1(S, \mathbb{Z})$.*

Remark. By the "classification of disconnected surfaces", there are finitely many separating simple closed curves in S up to homeomorphism.

Corollary 1.35. *There is an orientation-preserving homeomorphism of a surface taking one simple closed curve to another if and only if the corresponding cut surfaces (which may be disconnected) are homeomorphic.*

Definition 1.36 (Topological type)**.** The existence of a homeomorphism as in 1.35 is an equivalence relation. The equivalence class of a simple closed curve or a collection of simple closed curves is called its *topological type*.

A seprarating simple closed curve in the closed surface S_g divides S_g into two disjoint subsurfaces of genus k and $g-k$. The minimum of $\{k, g-k\}$ is called the genus of the separating simple closed curve. There are $\left\lfloor \frac{g}{2} \right\rfloor$ topological types of essential separating simple closed curves in a closed surface.

Question 1.37. Suppose α is any nonseparating simple closed curve on a surface S.

(1) Is there a simple closed curve γ in S so that α and γ *fill* S, i.e., such that α and γ are in minimal position and the complement of $\alpha \cup \gamma$ is a union of topological disks.

(2) Is there a simple closed curve δ in S with $i(\alpha,\beta)=0$? $i(\alpha,\beta)=1$? $i(\alpha,\beta)=k$?

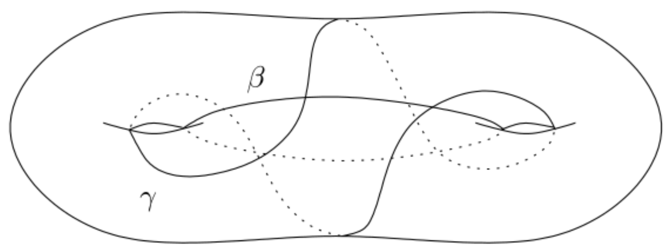


FIGURE 5. a

Figure **??** shows two filling simple closed curves on the genus 2 surface. By the classification of simple closed curves on a surface, there is a homeomorphism $\varphi\colon S_2 \to S_2$ such that $\varphi(\beta)=\alpha$. Then the image of γ under φ fills S_2 with α since filling is a topological property (show this).

Examples of change of coordinate principle.

(1) *Pairs of simple closed curves that intersect once are all of the same topological type.* Suppose α_1 and β_1 form such a pair on a surface S. Then β_1 must be an arc connecting the two boundary components in S_{α_1}. But the boundary component is homeomorphic to S^1, so removing a point leaves it connected. Thus removing β_1 leaves $(S_{\alpha_1})_{\beta_1}$ path-connected. Similarly, $(S_{\alpha_2})_{\beta_2}$ is path-connected for any other pair α_2 and β_2 that constitute a pair of simple closed curves that intersect once in S. By the classification of surfaces with boundary, $(S_{\alpha_1})_{\beta_1}$ is homeomorphic to $(S_{\alpha_2})_{\beta_2}$ which preserves equivalence classes on the boundary, and as we can construct this homeomorphism first for the β's and then for the α's, this homeomorphism descends to a self-homeomorphism of S taking the pair $\{\alpha_1,\beta_1\}$ to $\{\alpha_2,\beta_2\}$.

Three facts about homeomorphisms. Suppose $f\colon D\to D$ is an orientation-reversing map. Then f restricts to a map on $S^1\to S^1$, and if f is smooth considered as such a map, then the reversal of orientation implies that since the fiber of any point is a single point, the degree of f must be -1. But thus f is not isotopic to the identity as the identity has degree 1 and the isotopy would have to restrict to a homotopy on the boundary, but degree is a homotopy invariant for maps $S^n\to S^n$. However, the straight-line homotopy does give a homotopy between f and the identity.

On $A=S^1\times I$, the orientation-reversing map that fixes the S^1 factor and reflects the I factor is homotopic but not isotopic to the identity.

Theorem 1.38. *Let S be any compact surface and let f and g be homotopic homeomorphisms of S. Then f and g are isotopic unless they are one of the two examples described above (on $S=D^2$ and $S=A$). In particular, if f and g are orientation-preserving, then they are isotopic.*

Theorem 1.39. *Let S be a compact surface. Then every homeomorphism of S is isotopic to a diffeomorphism of S.*

Theorem 1.40 (Hamstrom)**.** *Let S be a compact surface, possibly minus a finite number of points from the interior. Assume that S is not homeomorphic to $S^2, \mathbb{R}^2, D^2, T^2$, the closed annulus, the once-punctured disk, or the once-punctured plane. Then the space $\mathrm{Homeo}_0(S)$ is contractible.*

2. Mapping class group basics

We will be defining the mapping class group as π_0 of a space of homeomorphisms, and as such, we must give this space a topology. For this, it turns out that we need the compact-open topology which we now describe.

The compact-open topology.

Definition 2.1. The *weak* or *compact-open* C^r topology on $C^r(M,N)$, where M and N are C^r manifolds, is generated by sets defined as follows: let $f \in C^r(M,N)$. Let $(U,\varphi),(V,\psi)$ be charts on M and N ; let $K \subset U$ be compact such that $f(K) \subset V$ and let $0 < \varepsilon \leqslant \infty$. Then a *weak subbasic neighborhood*

$$\mathcal{N}^r\left(f;(U,\varphi),(V,\psi),K,\varepsilon\right) \tag{ζ}$$

is the set of C^r maps $g\colon M \to N$ such that $g(K) \subset V$ and

$$\left\|D^k\left(\psi f \varphi^{-1}\right)(x) - D^k\left(\psi g \varphi^{-1}\right)(x)\right\| < \varepsilon$$

for all $x \in \varphi(K)$, for $k = 0,\ldots,r$. The *compact-open* C^r *topology* on $C^r(M,N)$ is generated by the set of weak subbasic neighborhoods, and defines the topological space $C^r_W(M,N)$. A neighborhood of f is then any set containing the intersection of a finite number of sets of the type (ζ).

We are interested in the subspace $\mathrm{Homeo}(S) \subset C^0_W(S,S)$, inheriting the subspace topology.

The compact-open topology might seem a bit confusing, but we have the following lemma [3, Prop A.14]:

Lemma 2.2. *Let X,Y,Z be Hausdorff topological spaces. Suppose Y is locally compact. Then a map $f\colon X \to C^0_W(Y,Z)$ is continuous if and only if the associated map $F\colon X \times Y \to Z$ defined by*

$$F(x,y) := f(x)(y)$$

is continuous.

2.1. Definitions and first examples.

Definition 2.3. Let S be a surface which is the connected sum of $g \geqslant 0$ tori with $b \geqslant 0$ disjoint open disks removed and $n \geqslant 0$ points removed from the interior. Let $\mathrm{Homeo}^+(S,\partial S)$ denote the group of orientation-preserving self-homeomorphisms of S that restrict to the identity on ∂S. We endow this group with the compact-open topology. The *mapping class group* of S, denoted $\mathrm{Mod}(S)$, is the group

$$\mathrm{Mod}(S) = \pi_0\left(\mathrm{Homeo}^+(S,\partial S)\right)$$

Remark. From Lemma 2.2, we see that a path $\gamma\colon I \to \mathrm{Homeo}^+(S,\partial S)$ is precisely equivalent to an isotopy $F\colon I \times S \to S$ from $\gamma(0)$ to $\gamma(1)$ (isotopy because at each time t, $\gamma(t)\colon S \to S$ is indeed a topological embedding as it is a homeomorphism). In fact, it's an isotopy of S. Here isotopies are required to fix boundaries.

If $\mathrm{Homeo}_0(S,\partial S)$ denotes the connected component of the identity in $\mathrm{Homeo}^+(S,\partial S)$, then we can equivalently write

$$\mathrm{Mod}(S) = \mathrm{Homeo}^+(S,\partial S)/\mathrm{Homeo}_0(S,\partial S).$$

Proposition 2.4.

$$\begin{aligned}\mathrm{Mod}(S) &= \pi_0\left(\mathrm{Homeo}^+(S,\partial S)\right)\\ &\approx \mathrm{Homeo}^+(S,\partial S)/\mathit{homotopy}\\ &\approx \pi_0\left(\mathrm{Diff}^+(S,\partial S)\right)\\ &\approx \mathit{Diff}^+(S,\partial S)/\sim\end{aligned}$$

where $\mathrm{Diff}^+(S,\partial S)$ *is the group of orientation preserving diffeomorphisms of* S *that are the identity on the boundary and* $\sim$ *can be taken to be either smooth homotopy relative to the boundary or smooth isotopy relative to the boundary.*

The Alexander Lemma. Here we will describe some of the simplest examples of mapping class groups following [2, Chapter 2.1]

Lemma 2.5 (Alexander lemma)**.** *The group* $\mathrm{Mod}\left(D^2\right)$ *is trivial.*

Proof. Let $\varphi\colon D^2 \to D^2$ be a homeomorphism with $\varphi|_{\partial D^2} = \mathrm{id}_{\partial D^2}$. Define

$$F(x,t) = \begin{cases}(1-t)\varphi\left(\frac{x}{1-t}\right), & 0 \leqslant |x| < 1-t\\ x, & 1-t \leqslant |x| \leqslant 1\end{cases}$$

for $0 \leqslant t < 1$, and let $F(x,1) = \mathrm{id}_{D^2}$. Then F is an isotopy from φ to the identity. The reason it is an isotopy is because at time t, $F(-,t)$ is a homeomorphism on the disk of radius $1-t$ where it is φ and outside this disk, it is the identity. On the boundary of this disk, both φ and the identity are the identity, so $F(-,t)$ is continuous by the pasting lemma, and thus a homeomorphism for each t.

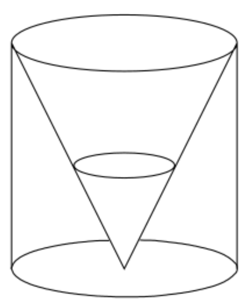


FIGURE 6. The Alexander trick. We envision F as performing the homeomorphism on the disk D^2 and embedding it at time t as a disk of radius $1-t$ as shown in the picture. Thus F will have support the cone as shown.

□

Remark. Also $0 \approx \mathrm{Mod}(D-\{0\}) \approx \mathrm{Mod}(S_{0,1}) \approx \mathrm{Mod}\left(S^2\right)$ using the Alexander trick again.

The mapping class group of the thrice-punctured sphere, $\mathrm{Mod}(S_{0,3})$. We will now present a couple other computations of some simple mapping class groups.

Proposition 2.6. *Any two essential simple proper arcs in* $S_{0,3}$ *with the same endpoints are isotopic. Any two essential arcs that both start and end at the same marked point of* $S_{0,3}$ *are isotopic.*

Proof. Let α and β be two simple proper arcs in $S_{0,3}$ connecting the same two distinct marked points. By isotopy, we may modify α so that it intersects transversally with β. Letting the last marked point become the point at infinity, we can consider α and β as being arcs in $\mathbb{R}^2 - \{p, q\}$ for the two marked points p, q. An example is illustrated below. Now, suppose the arcs are disjoint. Then, choosing an intersection point, we can follow the path to the other intersection point and obtain either a bigon, in which case we can remove it by isotopy, or a bigon with path segments inside. Now, suppose the there is some point of α inside the bigon. Then since this is part of the arc α, we can find a simple path connecting this point to two points of β. There could, however, be infinitely many such paths inside the bigon, preventing us choosing the innermost (think concentric semicircles). However, by transversality, the preimages of the intersection points form a 0-dimensional submanifold of I which is closed (as the preimage of a closed path segment of β) and discrete. But discrete subsets of compact spaces are finite. Hence we can choose the innermost such path of α. By isotopy, we can remove the bigon formed by this alpha. Continuing a finite amount of times, we remove the original bigon. After a finite amount of reiterations, we can therefore remove all bigons, and we get disjoint α and β.
Now suppose we remove $\alpha \cup \beta$. Then we get a disjoint union of a disk and a punctured disk (by the classification of surfaces - expound on this). Thus the embedded disk in $S_{0,3}$ gives an isotopy of α to β. □

Proposition 2.7. *The natural map*

$$\mathrm{Mod}\,(S_{0,3}) \to \Sigma_3$$

given by the action of $\mathrm{Mod}\,(S_{0,3})$ *on the set of marked points of* $S_{0,3}$ *is an isomorphism.*

Proof. The map is a surjective homomorphism since, for any choice of punctures $S_{0,3}$, we can, using the classification of surfaces, modify where the punctures are so that the desired permutation can easily be obtain from a rotation.

It thus suffices to show injectivity. So suppose φ is a homomorphism fixing the three marked points, call them p, q, and r. Choose an arc α in $S_{0,3}$ with distinct endpoints, say p and q. Since φ fixes the marked points, proposition 2.6 gives that $\varphi \circ \alpha$ is isotopic to α, or equivalently, that α is isotopic to $\varphi^{-1} \circ \alpha$, say through an isotopy $F\colon I \times I \to S_{0,3}$. By theorem 1.28, we can extend F to an ambient isotopy, and by composing with φ, we get an isotopy from φ to a homeomorphism which fixes α pointwise.

Now cut $S_{0,3}$ along α so as to obtain a disk with one marked point. Since φ preserves the orientations of $S_{0,3}$ and of α, it follows that φ induces a homemomorphism $\overline{\varphi}$ of this disk which is the identity on the boundary.
But $\mathrm{Mod}\,(S_{0,1}) \approx 0$, so $\overline{\varphi}$ is homotopic to the identity. And this homotopy induces a homotopy from φ to the identity. □

Exercise 2.8. Show similarly that $\mathrm{Mod}\,(S_{0,2}) \approx \mathbb{Z}/2\mathbb{Z}$.

Solution. Let α, β be arcs with the same distinct marked endpoints. Equivalently to before, we can reduce bigons by isotopy until α and β are disjoint. Then removing $\alpha \cup \beta$ we would get two disjoint disks (firstly, $\alpha \cup \beta$ make up a closed simple curve which is trivial since $H_1\left(S^1\right) = \{0\}$ and thus separating. Therefore we get a disconnected space with as many vertices as edges whose Euler characteristic must add to $2 = \chi\left(S^2\right)$, so it must precisely have 1 face each, i.e., they are disks) which will descend to give the desired isotopy in $S_{0,2}$.

So assume no intersection. Let φ be an orientation preserving homeomorphism fixing the marked points. Then $\varphi(\alpha)$ is isotopic to α, so φ is isotopic to a homeomorphism which fixes α pointwise, call it ψ. This induces a homeomorphism on $S^2 - \alpha$ which is a disk that is the identity on the boundary, and hence isotopic to the identity homeomorphism on the disk since $\mathrm{Mod}\left(D^2\right) \approx \{0\}$. This isotopy gives an isotopy of ψ to the identity. The composition of all these isotopies gives an isotopy of φ with the identity. Hence the map is injective.

Theorem 2.9. *The homomorphism*

$$\sigma\colon \mathrm{Mod}\left(T^2\right) \to \mathrm{SL}\left(2, \mathbb{Z}\right)$$

given by the action on $H_1(T;\mathbb{Z}) \approx \mathbb{Z}^2$ is an isomorphism.

Proof. Any homeomorphism φ of T^2 induces an isomorphism on homology: $\varphi_*\colon \mathbb{Z}^2 \approx H_1(T^2) \to H_1\left(T^2\right) \approx \mathbb{Z}^2$.

Additional notes on the proof: □

why can we for any element $f \in \mathrm{Mod}\left(T^2\right)$ choose a representative φ that fixes a basepoint for T^2?

Corollary 2.10. *Since $H_1(S_{1,1};\mathbb{Z}) \approx \mathbb{Z}^2$, there is a homomorphism $\sigma\colon \mathrm{Mod}(S_{1,1}) \to SL(2,\mathbb{Z})$ which is determined which isomorphism the homomorphism induces in homology. This map is an isomorphism.*

Exercise 2.11. Prove this explicitly.

The mapping class group of $S_{0,4}$. Consider the torus T^2 as $I^2/\sim$ under the usual identification. Then consider the linear map $\iota\colon \mathbb{R} \to \mathbb{R}$ by $\iota = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} = -I \in SL(2,\mathbb{Z})$ which rotates about the origin by π radians.

The map is equivarient with respect to the quotient map so it induces a map $I^2/\sim \to I^2/\sim$ and we wish to take the quotient space that identifies fibers of this map. This is equivalent to taking the quotient space of $\mathbb{R}^2$ induced by the following actions: for $(a,b) \in \mathbb{R}^2$,

(1) sending (a,b) to $(a+2k, b)$ for $k \in \mathbb{Z}$,
(2) sending (a,b) to $(a, b+2t)$ for $t \in \mathbb{Z}$,
(3) or sending (a,b) to $(-a,-b)$.

We claim the quotient of $[0,2] \times I$ under this action is a fundamental domain for the action. Clearly, the action is transitive. Now if $(a,b),(c,d) \in (0,2) \times I$ are in the same orbit, then

$$a = (-1)^\alpha c + 2k$$
$$b = (-1)^\alpha d + 2t$$

for some $k,t \in \mathbb{Z}$. But then if $b + d = 2t$, we get $b + d \in 2\mathbb{Z} \cap (0,2) = \varnothing$, so α must be even, and $b = d$. But then $a - c \in 2\mathbb{Z} \cap (-2,2) = \{0\}$, so $a = c$ and $b = d$. The identifications on the boundary become as in figure 7 which becomes S^2.

We identify the quotient by $S_{0,4}$ where the 4 marked points are the 4 fixed points under the involution, namely, the images of the center of I^2, the midpoints of the edges and corner vertices. This is clearly also a 2-fold cover of the sphere.

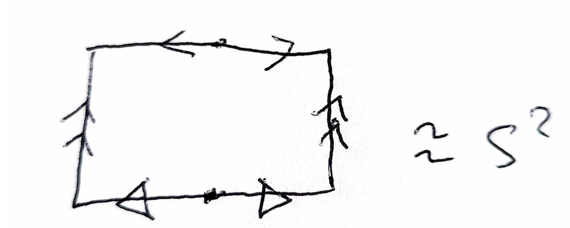


FIGURE 7.

Now, since for any $A \in \mathrm{SL}(2,\mathbb{Z})$, $A(-I) = (-I)A$, each element of $\mathrm{Mod}\left(T^2\right)$ induces an element of $\mathrm{Mod}\left(S_{0,4}\right)$ by descending to the quotient.

Proposition 2.12. *The hyperelliptic involution induces a bijection between the set of homotopy classes of essential simple closed curves in T^2 and the set of homotopy classes of essential simple closed curves in $S_{0,4}$.*

Proof. Notes:

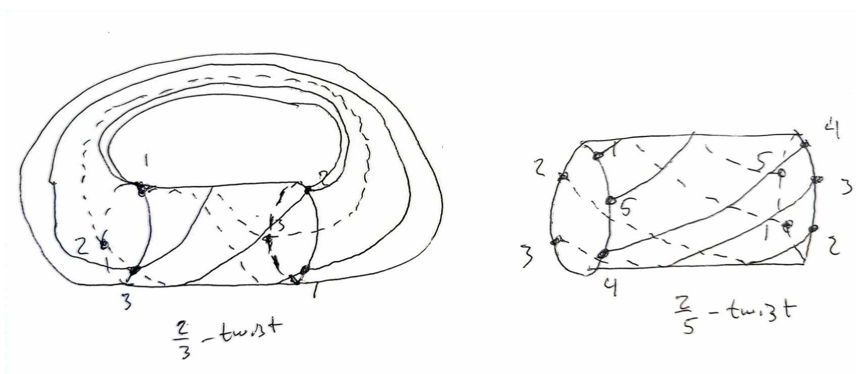


FIGURE 8. Twists along the meridian circle on the torus

Why is the preimage of a (p,q)-curve in $S_{0,4}$ in T^2 a $(2p,2q)$-curve? □

Proposition 2.13. $\mathrm{Mod}\left(S_{0,4}\right) \approx \mathrm{PSL}\left(2,\mathbb{Z}\right) \ltimes (\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z})$.

Lemma 2.14. *If the short exact sequence of groups*

$$1 \to N \to G \to H \to 1$$

has a right inverse for $G \to H$, then G is naturally isomorphic to $N \ltimes H$.

Proof. Let $f\colon N \to G, g\colon G \to H$ and $h\colon H \to G$ be the inverse. Then f and g are injective. Suppose $z \in f(N) \cap h(H)$. Then there exists a $v \in N$ and $u \in H$ such that $f(v) = z = h(u)$, so $u = g\left(h(u)\right) = g(z) = g(f(v)) = 0$, so $z = 0$. Since $f(N)$ is the kernel of g, it is normal in G, so $f(N)h(H)$ forms a subgroup of G. Now suppose $p \in G - f(N)h(H)$. Then since $g\left(p - h(g(p))\right) = 0$, there exists $n \in N$ such that $p = f(n) + h(g(p)) \in f(N)h(H)$, contradiction. So $G = f(N)h(H)$, giving $G = f(N) \ltimes h(H) \approx N \ltimes H$. □

Proof. To show 2.13, it thus suffices to find a homomorphism $\mathrm{Mod}\left(S_{0,4}\right) \to \mathrm{PSL}\left(2, \mathbb{Z}\right)$ with a right inverse, and show that the kernel is $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$.
Notes on the proof: for the involutions ι_1, ι_2, we can lift them to homeomorphisms of T^2 by the lifting theorem [1, Thm 4.1]. □

But why would these necessarily have to be homeomorphisms that rotate one of the factors of $T^2 \approx S^1 \times S^1$ by π?

2.1.1. *The Alexander method.*

Proposition 2.15 (Alexander method)**.** *Let S be a compact surface, possibly with marked points, and let $\varphi \in \mathrm{Homeo}^+\left(S, \partial S\right)$. Let $\gamma_1, \ldots, \gamma_n$ be a collection of essential simple closed curves and simple proper arcs in S with the following properties.*

(1) The γ_i are pairwise in minimal position.
(2) The γ_i are pairwise nonisotopic.
(3) For distinct i, j, k, at least one of $\gamma_i \cap \gamma_j, \gamma_i \cap \gamma_k$, or $\gamma_j \cap \gamma_k$ is empty.
(i) If there is a permutation σ of $\{1, \ldots, n\}$ so that $\varphi\left(\gamma_i\right)$ is isotopic to $\gamma_{\sigma(i)}$ relative to ∂S for each i, then $\varphi\left(\cup\gamma_i\right)$ is isotopic to $\cup\gamma_i$ relative to ∂S.
If we regard $\cup\gamma_i$ as a (possibly disconnected) graph Γ in S, with vertices at the intersection points and at the endpoints of arcs, then the composition of φ with this isotopy gives an automorphism φ_* of Γ.
(ii) Suppose now that $\{\gamma_i\}$ fills S. If φ_* fixes each vertex and each edge of Γ with orientations, then φ is isotopic to the identity. Otherwise, φ has a nontrivial power that is isotopic to the identity.

Lemma 2.16. *Let S be a compact surface, possibly with marked points, and let $\gamma_1, \ldots, \gamma_n$ be a collection of essential simple closed curves and simple proper arcs in S that satisfy the three properties from proposition 2.15. If $\gamma_1', \ldots, \gamma_n'$ is another such collection so that γ_i' is isotopic to γ_i relative to ∂S for each i, then there is an isotopy of S relative to ∂S that takes γ_i' to γ_i for all i simultaneously and hence takes $\cup\gamma_i$ to $\cup\gamma_i'$.*

Remark. I put lemma 4.16 here since it's a slight generalization of (i) above and is used in the proof of Alexander's method too.

3. Dehn Twists

Let S be an oriented surface and let α be a simple closed curve in S. Let N be a tubular neighborhood of α and choose an orientation preserving homeomorphsim $\varphi\colon A \to N$. We then obtain a homeomorphism $T_\alpha\colon S \to S$, called a *Dehn twist about α*, as follows:

$$T_\alpha(x) = \begin{cases} \varphi \circ T \circ \varphi^{-1} & \text{if } x \in N \\ x & \text{if } x \in S - N \end{cases}.$$

"By the uniqueness of regular neighborhoods, the isotopy class of T_α does not depend on the choice of N or the choice of homeomorphism φ. Nor does T_α depend on the choice of simple closed curve α within its isotopy class."

See theorem 1.8 in Hempel

Dehn twists on the torus. Via the isomorphism $\mathrm{Mod}\left(T^2\right) \to \mathrm{SL}\left(2, \mathbb{Z}\right)$ from 2.9, the Dehn twists about the $(1,0)$-curve and the $(0,1)$-curve in $\mathrm{Mod}\left(T^2\right)$ correspond to the matrices

$$\begin{pmatrix} 1 & -1 \\ 0 & 1 \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix}$$

3.0.1. *Dehn twist facts.*

This section is needed for the Birman-Hilden theorem

Proposition 3.1. *Let a be the isotopy class of a simple closed curve α in a surface S. If α is not homotopic to a point or a puncture of S, then the Dehn twist T_a is a nontrivial element of* $\mathrm{Mod}(S)$.

Proposition 3.2. *Let a and b be arbitrary isotopy classes of essential simple closed curves in a surface and let k be an arbitrary integer. We have*

$$i\left(T_a^k(b), b\right) = |k|\, i\,(a, b)^2 .$$

Proposition 3.3. *Let α and β be simple closed curves in a surface. Suppose that α and β are in minimal position. Given a third simple closed curve γ, there exists a simple closed curve γ' that is homotopic to γ and that is in minimal position with respect to both α and β.*

Proposition 3.4. *Let $a_1, \ldots, a_n$ be a collection of pairwise disjoint isotopy classes of simple closed curves in a surface S and let $M = \Pi_{i=1}^n T_{a_i}^{e_i}$. Suppose that $e_i > 0$ for all i or $e_i < 0$ for all i. If b and c are arbitrary isotopy classes of simple closed curves in S, then*

$$\left| i\,(M(b), c) - \sum_{i=1}^{n} |e_i|\, i(a_i, b) i(a_i, c) \right| \leqslant i(b, c).$$

Definition 3.5 (Pairs of filling curves)**.** We say a pair of isotopy classes $\{a, b\}$ of simple closed curves in a surface S *fill* if any pair of minimal position representatives fill (i.e., the complement of the representatives in the surface is a collection of disks and once-punctured disks). This is equivalent to saying that for every isotopy class c of essential simple closed curves in the surface, either $i\,(a, c) > 0$ or $i(b, c) > 0$.

Proposition 3.6. *Let $g, n \geqslant 0$ and assume $\chi\,(S_{g,n}) < 0$. Then there exists a pair of simple closed curves in $S_{g,n}$ that fill $S_{g,n}$.*

The equivalence is intuitive since otherwise, it would be contained in one of the disks and hence not be essential, and the converse is similarly seen.

3.0.2. *Basic facts about Dehn twists.* Throughout this section, a and b denote arbitrary (unoriented) isotopy classes of simple closed curves.

Lemma 3.7. $T_a = T_b \iff a = b$.

Lemma 3.8. *For any $f \in \mathrm{Mod}(S)$ and any isotopy class a of simple closed curves in S, we have*

$$T_{f(a)} = f T_a f^{-1}.$$

Corollary 3.9. *For any $f \in \mathrm{Mod}(S)$ and any isotopy class a of simple closed curves in S, we have*

$$f \text{ commutes with } T_a \iff f(a) = a.$$

Corollary 3.10. *If a and b are nonseparating simple closed curves in S, then T_a and T_b are conjugate in* $\mathrm{Mod}(S)$.

Lemma 3.11. *For any two isotopy classes a and b of simple closed curves in a surface S, we have*

$$i(a, b) = 0 \iff T_a(b) = b \iff T_a T_b = T_b T_a.$$

Proposition 3.12. *The above results have the following analogues for powers of Dehn twists: for $f \in \mathrm{Mod}(S)$, we have*

$$fT_a^j f^{-1} = T_{f(a)}^j$$

and so f commutes with T_a^j if and only if $f(a) = a$. Also, for nontrivial Dehn twists T_a, T_b and nonzero integers j, k, we have

$$T_a^j = T_b^k \iff a = b \text{ and } j = k$$
$$T_a^j T_b^k = T_b^k T_a^j \iff i(a,b) = 0.$$

3.0.3. *The center of the mapping class group.*

Theorem 3.13. *For $g \geqslant 3$, $Z(G)$, for any finite index subgroup $G \leqslant \mathrm{Mod}(S_g)$, is trivial. In particular, $Z(\mathrm{Mod}(S_g))$ is trivial for $g \geqslant 3$.*

3.0.4. *Relations between two Dehn twists.*

Proposition 3.14 (Braid relation)**.** *If a and b are isotopy classes of simple closed curves with $i(a,b) = 1$, then*

$$T_a T_b T_a = T_b T_a T_b.$$

Equivalently, this read $T_a T_b(a) = b$.

Question 3.15. Does the converse also work? I.e., if two Dehn twists satisfy the braid relation algebraically, do the corresponding curves necessarily have intersection number equal to 1?

Proposition 3.16. *If a and b are distinct isotopy classes of simple closed curves and the Dehn twists T_a and T_b satisfy $T_a T_b T_a = T_b T_a T_b$, then $i(a,b) = 1$.*

Groups generated by two Dehn twists.

Theorem 3.17. *Let a and b be two isotopy classes of simple closed curves in a surface S. If $i(a,b) \geqslant 2$, then $\langle T_a, T_b \rangle \approx F_2$, where F_2 is the free group of rank 2.*

Proof. The slick proof makes use of this basic but nice lemma from geometric group theory:

Lemma 3.18 (Ping pong lemma)**.** *Let G be a group acting on a set X. Let $g_1, \ldots, g_n$ be elements of G. Suppose that there are nonempty, disjoint subsets $X_1, \ldots, X_n$ of X with the property that, for each i and each $j \neq i$, we have $g_i^k(X_j) \subset X_i$ for every nonzero integer k. Then the group generated by the g_i is a free group of rank n.*

Exercise 3.19. Complete the proof.

□

3.1. **Cutting, capping and including.**

3.1.1. *Including.* When S is a closed subsurface of a surface S', we can define a natural homomorphism $\eta\colon \mathrm{Mod}(S) \to \mathrm{Mod}(S')$ as follows. For $f \in \mathrm{Mod}(S)$, we represent it by some $\varphi \in \mathrm{Homeo}^+(S, \partial S)$. Then, if $\hat{\varphi} \in \mathrm{Homeo}^+(S', \partial S')$ denotes the element that agrees with φ on S and is the identity outside of S, we define $\eta(f)$ to be the class of $\hat{\varphi}$. The map η is well defined because any homotopy between two elements of $\varphi \in \mathrm{Homeo}^+(S, \partial S)$ gives a homotopy between the corresponding elements of $\mathrm{Homeo}^+(S', \partial S')$ (the homotopy is simply relative to $S' - S$).

The goal is to find $\ker \eta$.

Lemma 3.20. *Let $\alpha_1, \ldots, \alpha_n$ be a collection of homotopically distinct simple closed curves in a surface S, each not homotopic to a point in S. Let β and β' be simple closed curves in S that are both disjoint from $\cup \alpha_i$ and are homotopically distinct from each α_i. If β and β' are isotopic in S, then they are isotopic in $S - \cup \alpha_i$.*

Theorem 3.21 (The kernel of the inclusion homomorphism)**.** *Let S be a closed subsurface of a surface S'. Assume that S is not homeomorphic to a closed annulus and that no component of $S' - S$ is an open disk. Let $\eta\colon \mathrm{Mod}(S) \to \mathrm{Mod}(S')$ be the induced map. Let $\alpha_1, \ldots, \alpha_m$ denote the boundary components of S that bound once-punctured disks in $S' - S$ and let $\{\beta_1, \gamma_1\}, \ldots, \{\beta_n, \gamma_n\}$ denote the pairs of boundary components of S that bound annuli in $S' - S$. Then the kernel of η is the free abelian group*

$$\ker \eta = \left\langle T_{\alpha_1}, \ldots, T_{\alpha_m}, \ldots, T_{\beta_1} T_{\gamma_1}^{-1}, \ldots, T_{\beta_n} T_{\gamma_n}^{-1} \right\rangle .$$

In particular, i no connected component of $S' - S$ is an open annulus, an open disk, or an open once-marked disk, then η is injective.

3.1.2. *The capping homomorphism.* One useful special case of theorem 3.21 is the case where $S' - S$ is a once-punctured disk. We say that S' is the surface obtained from S by *capping* one boundary component. In this case, we have

Proposition 3.22 (The capping homomorphism)**.** *Let S' be the surface obtained from a surface S by capping the boundary component β with a once-marked disk; call the marked point in this disk p_0. Denote by $\mathrm{Mod}(S, \{p_1, \ldots, p_k\})$ the subgroup of $\mathrm{Mod}(S)$ consisting of elements that fix the punctures $p_1, \ldots, p_k$, where $k \geqslant 0$. Let $\mathrm{Mod}(S', \{p_0, \ldots, p_k\})$ denote the subgroup of $\mathrm{Mod}(S')$ consisting of elements that fix the marked points $p_0, \ldots, p_k$ and then let $\mathcal{C}ap\colon \mathrm{Mod}(S, \{p_1, \ldots, p_k\}) \to \mathrm{Mod}(S', \{p_0, \ldots, p_k\})$ be the induced homomorphism. Then the following sequence is exact:*

$$1 \to \langle T_\beta \rangle \to \mathrm{Mod}(S, \{p_1, \ldots, p_k\}) \xrightarrow{\mathcal{C}ap} \mathrm{Mod}\left(S', \{p_0, \ldots, p_k\}\right) \to 1$$

Remark. In the case where S' is capped by an unmarked disk, the kernel is isomorphic to $\pi_1(TS')$, i.e., the fundamental group of the tangent bundle of S'.

4. Braid Groups

Definition 4.1 (Braids)**.** Let $p_1, \ldots, p_n$ be distinguished points in $\mathbb{C}$. A *braid* is a collection of n paths $f_i\colon [0,1] \to \mathbb{C} \times [0,1], 1 \leqslant i \leqslant n$, called *strands*, and a permutation $\overline{f} \in \Sigma_n$ such that the following hold:

- the strands $f_i([0,1])$ are disjoint
- $f_i(0) = p_i$
- $f_i(1) = p_{\overline{f}(i)}$
- $f_i(t) \in \mathbb{C} \times \{t\}$.

Usually we picture this by its *braid diagram* which is the projection of the images of the strands to the plane $\mathbb{R} \times [0,1]$ (with indications as to which strands pass over and under which others).

Definition 4.2. The *braid group on n strands*, denoted B_n, is the group of isotopy classes of braids.

Remark. Here an isotopy of the braid is a collection of isotopies $(h_1(x,t),\ldots,h_n(x,t))$ where h_i is an isotopy of f_i and such that $(h_1(-,t),\ldots,h_n(-,t))$ is a braid for each $t \in [0,1]$.

Definition 4.3. The product of the braid $(f_i(t))$ and the braid $(g_i(t))$ is the braid $(h_i(t))$, where

$$h_i(t) = \begin{cases} f_i(2t), & t \in \left[0, \frac{1}{2}\right] \\ g_{\overline{f}(i)}(2t-1), & t \in \left[\frac{1}{2}, 1\right] \end{cases}.$$

For $1 \leqslant i \leqslant n-1$, let $\sigma_i \in B_n$ denote the braid whose only crossing is the $(i+1)$ st strand passing in front of the i th strand.
We claim that the group B_n is generated by the elements $\sigma_1,\ldots,\sigma_{n-1}$. This claim follows from the fact that any braid β can be isotoped so that its finitely many corssings occur at different horizontal levels.

4.1. **Fundamental groups of configuration spaces.**

Definition 4.4. Let S be a surface and let $C^{ord}(S,n)$ denote the configuration space of n distinct, ordered points in S, given by $C^{ord}(S,n) = \times_n S - \mathrm{BigDiag}(\times_n S)$ where $\mathrm{BigDiag}(\times_n S) = \{(x_1,\ldots,x_n) \in \times_n S \mid \exists 1 \leqslant i < j \leqslant n \colon x_i = x_j\}$.

Now, the symmetric group Σ_n acts on $\times_n S$ by permuting the coordinates. This action preserves $\mathrm{BigDiag}(\times_n S)$ and thus induces an action of Σ_n by homeomorphisms on $C^{ord}(S,n)$. Since the action of Σ_n permutes the n coordinates and since these coordinates are always distinct for points in $C^{ord}(S,n)$, we see that this action is free. The quotient space

$$C(S,n) = C^{ord}(S,n)/\Sigma_n$$

is just the configuration space of n distinct, *unordered* points in S.
Now we note the following lemma [5, Cor 12.27] and proposition [5, Prop 12.22]

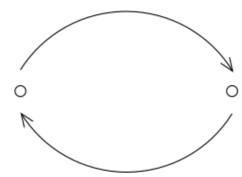
Lemma 4.5. *Let M be a connected n-manifold on which a discrete group Γ acts continuously, freely, and properly. Then M/Γ is an n-manifold.*

Proposition 4.6. *Every continuous action of a compact topological group on a Hausdorff space is proper*

Since $C(S,n)$ is the quotient of a manifold by a continuous free action of a finite group (hence compact), it follows that $C(S,n)$ is a manifold.
Since each strand of a braid is a map $f_i \colon I \to \mathbb{C} \times I$ with $f_i(t) \in \mathbb{C} \times \{t\}$, we can think of each f_i as a map $I \to \mathbb{C}$, so that a braid essetially becomes a path $I \to \mathbb{C}^n$ with equal end points, i.e., a loop, where each t is mapped to the point whose ith coordinate is $I \xrightarrow{f_i} \mathbb{C} \times \{t\} \xrightarrow{\text{proj}} \mathbb{C}$. By assumption, the strands are disjoint, so each t is mapped to a point in $C^{\text{ord}}(\mathbb{C},n)$, and essentially, forgetting the strand index, we can regard this as a map $I \to C(\mathbb{C},n)$. Said in a different way, if we consider a slice $\mathbb{C} \times \{t\}$ and intersect it with any braid, then we get a point in $C(\mathbb{C},n)$, so the whole braid, which can be seen as a path in $C(\mathbb{C},n)$ between these intersections, gives an element of $\pi_1(C(\mathbb{C},n))$, and this gives the isomorphism

$$B_n \approx \pi_1(C(\mathbb{C},n))$$

In this case, the generator σ_i of B_n corresponds to the element of $\pi_1(C(\mathbb{C},n))$ given by the loop of n-point configurations in $\mathbb{C}$ where the i th and $(i+1)$ st points switch places by moving in a clockwise fashion, and the other $n-2$ points remain fixed.



4.1.1. *The torsion of a braid group.* Since we just saw that $B_n \approx \pi_1(C(\mathbb{C},n))$, and $C(\mathbb{C},n)$ is a finite-dimensional CW-complex that is $K(B_n,1)$, we get that B_n is torsion-free [3, Prop 2.45]

4.2. **Mapping Class Group of a punctured disk.**

Question 4.7. Is there any relationship between braid groups and mapping class groups?

The answer is that if we let D_n be a closed disk D^2 with n marked points, then

$$B_n \approx \mathrm{Mod}(D_n) = \pi_0\left(\mathrm{Homeo}^+(D_n, \partial D_n)\right).$$

To see this, let φ be a representative of some element in $\mathrm{Mod}(D_n)$ which leaves the set of marked points invariant under φ - i.e., if $\{x_0,\ldots,x_n\} \subset D_n$ are the n marked points, then $\varphi(\{x_0,\ldots,x_n\}) = \{x_0,\ldots,x_n\}$. Note that we do not regard these marked points as punctures because we will not want to consider isotopies which "move" these marked points around which is not allowed when the marked points represent punctures. We see that φ is simply a homeomorphism of D^2 fixing ∂D^2 pointwise, so by the Alexander lemma, φ is isotopic to the identity. Now, throughout such an isotopy, the marked points must again be send to themselves, albeit they might move around through in the interior of D^2 (which we identify with $\mathbb{C}$) throughout the isotopy. Thus this isotopy produces a loop of these marked points, i.e., it produces a loop in $C(\mathbb{C},n)$. So we have produced a braid.

Question 4.8. Does this association give a well-defined homomorphism $B_n \to \mathrm{Mod}(D_n)$ and would this be an isomorphism?

The answer is yes, and since σ_i generate B_n, the images generate $\mathrm{Mod}(D_n)$. Now, the image of σ_i will be the homotopy class of a homeomorphism of D_n that has support a twice-punctured disk and is described on this support by figure 9.

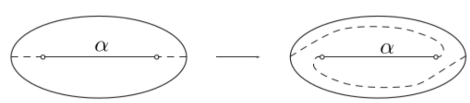


FIGURE 9. A half-twist

The way to think about this is that while fixing the boundary pointwise, we take the two punctures and swap their places by moving them in semicircles to the other puncture's position and the movement of the remaining points can be thought of as if this were carried out on a surface made of rubber.

We denote such a half-twist as H_α, and we can think of α as either a simple closed curve with two punctures in its interior or a simple proper arc connecting two punctures.

4.3. **The Birman Exact Sequence.** Let S be any surface, possibly with punctures (but no marked points) and let (S,x) denote the surface obtained from S by marking a point x in the interior of S. There is a natural homomorphism

$$\mathcal{F}orget\colon \mathrm{Mod}\,(S,x) \to \mathrm{Mod}(S)$$

called the forgetful map which is realized by forgetting that the point x is marked. This map is surjective as any homeomorphism of S can be modified by isotopy to fix x . The group $\mathrm{Mod}(S,x)$ is isomorphic to the subgroup G of $\mathrm{Mod}\,(S-x)$ why?
consisting of homeomorphisms preserving the puncture coming from x.
The forgetful map can then be interpreted as the map $G \to \mathrm{Mod}(S)$ obtained by "filling in" the puncture x. I.e., $\mathcal{F}orget$ is the map induced by the inclusion $S-x \hookrightarrow S$.

4.3.1. *Analyzing the kernel of $\mathcal{F}orget$.* Let $f \in \mathrm{Mod}(S,x)$ be an element of the kernel of $\mathcal{F}orget$ and let φ be a homeomorphism representing f. We can think of φ as a homeomorphism $\overline{\varphi}$ of S.
Since $\mathcal{F}orget(f) = 1$, there is an isotopy from $\overline{\varphi}$ to $\mathbb{1}_S$. During this isotopy, the image of the point x traces out a loop α in S based at x. Now we will introduce the $\mathcal{P}ush$ map: given a loop α in S based at x, we can consider $\alpha\colon [0,1] \to S$ as an isotopy $h\colon \{x\} \times I \to S$ with $h(x,0) = h(x,1) = x$ and extend this to the whole surface using 1.28 (here, $V = \{x\}$), denote this by $h\colon S \times I \to S$ also. Let $\varphi(x) = h(x,1)$ be the homeomorphism of S obtained at the end of the isotopy. Taking its isotopy class in $\mathrm{Mod}\,(S,x)$, we get $[\varphi] =: \mathcal{P}ush(\alpha) \in \mathrm{Mod}\,(S,x)$. Think of $\mathcal{P}ush(\alpha)$ as placing your finger on x and pushing x along α, draggin the rest of the surface along as you go (indeed, locally, this is what must happen).
The question of whether this mapping class is independent of the choice of isotopy extension as well as the choice of α within its homotopy class. I.e., whether $\mathcal{P}ush$ defines a well-defined map

$$\mathcal{P}ush\colon \pi_1\,(S,x) \to \mathrm{Mod}\,(S,x)\,.$$

For that, we show look at the Birman exact sequence.

Theorem 4.9 (Birman exact sequence)**.** *Let S be a surface with $\chi(S) < 0$, possibily with punctures and/or boundary. Let (S,x) be the surface obtained from S by marking a point x in the interior of S. Then the following sequence is exact:*

$$1 \to \pi_1\,(S,x) \overset{\mathcal{P}ush}{\to} \mathrm{Mod}\,(S,x) \overset{\mathcal{F}orget}{\to} \mathrm{Mod}(S) \to 1.$$

Lemma 4.10. *$\mathcal{P}ush\colon \pi_1\,(S,x) \to \mathrm{Mod}(S,x)$ is injective when $\chi(S) < 0$.*

Proof. Let φ represent $\mathcal{P}ush\,(\alpha) \in \mathrm{Mod}\,(S,x)$. Then φ is a map $(S,x) \to (S,x)$, so in particular, we have an induced homomorphism $\varphi_*\colon \pi_1\,(S,x) \to \pi_1\,(S,x)$. This homomorphism is the inner automorphism $I_\alpha(\gamma) = \alpha\gamma\alpha^{-1}$. Now, for $\chi(X) < 0$, why?
the center of $\pi_1(S)$ is trivial, so I_α is nontrivial whenever $\alpha \neq c_x$. If φ had been

homotopic to the identity, their induced homomorphisms would be equal, so we conclude that $\mathcal{P}ush\,(\alpha)$ is nontrivial whenever α is nontrivial. ☐

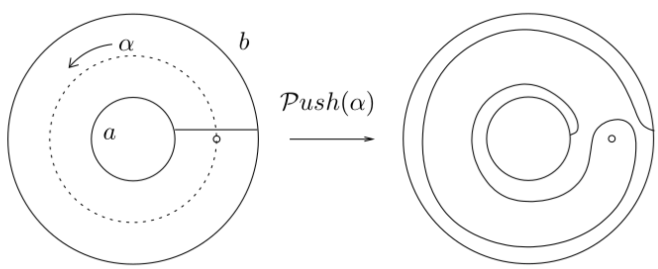
4.3.2. *Push maps along loops in terms of Dehn twists.* Let $\alpha \in \pi_1(S, x)$ be simple. Let $S^1 \times [0,2]$ be an annulus about α with $S^1 \times \{1\}$ identified with α with $(0,1)$ identified with the marked point x. We orient $S^1 \times [0,2]$ with the standard orientations on S^1 and $[0,2]$.
Let $F\colon A \times I \to A$ be the isotopy given by

$$F((\theta, r), t) = \begin{cases} (\theta + 2\pi r t, r), & 0 \leqslant r \leqslant 1 \\ (\theta + 2\pi(2-r)t, r), & 1 \leqslant r \leqslant 2. \end{cases}$$

By 1.28, we can extend F to an ambient isotopy of S. Restricting F to $\{x\} \times [0,1]$, we get

$$F((0,1), t) = (2\pi t, 1),$$

so F pushes x around the core of the annulus. Now, the homeomorphism (representing $\mathcal{P}ush\,(\alpha)$) φ of (S, x) given by $F((\theta, r), 1)$ is a product of two Dehn twists, $T_a T_b^{-1}$ where a is the closed curve identified with $S^1 \times \{0\}$ and b is the closed curve identified with $S^1 \times \{2\}$.



Remark (Naturality). For any $h \in \mathrm{Mod}(S, x)$ and any $\alpha \in \pi_1(S, x)$, we have

$$\mathcal{P}ush\,(h_*(\alpha)) = h\mathcal{P}ush\,(\alpha)\,h^{-1}.$$

Write out proof

Proof. Now write a proof of the Birman exact sequence. ☐

4.4. **Generalized Birman Exact Sequence.** We now return to Question 4.8. We wish to show that $\pi_1(C(\mathbb{C}, n)) \approx \mathrm{Mod}(D_n)$.

Definition 4.11 (n-stranded surface braid group of S)**.** For an arbitrary surface S, we call $\pi_1(C(S, n))$ the n-stranded surface braid group of S.

Let S be a compact finite-type surface without marked points. Let $(S, \{x_1, \ldots, x_n\})$ denote S with n marked points $x_1, \ldots, x_n$ in the interior. Equivalently to the construction in the proof of the Birman exact sequence, there is a fiber bundle

Prove that this is a fiber bundle

$$\mathrm{Homeo}^+((S, \{x_1, \ldots, x_n\}), \partial S) \to \mathrm{Homeo}^+(S, \partial S) \to C(S^\circ, n)$$

where S° is the interior of S and $\mathrm{Homeo}^+((S, \{x_1, \ldots, x_n\}), \partial S)$ is the group of orientation-preserving homeomorphisms of S that preserve the set $\{x_1, \ldots, x_n\}$ (allowing permutations, however) and fix the boundary of S pointwise.

Theorem 4.12 (Birman exact sequence generalized)**.** *Let S be a surface without marked points and with $\pi_1\left(\mathrm{Homeo}^+(S,\partial S)\right)=1$. The following sequence is exact:*

$$1\to\pi_1\left(C\left(S,n\right)\right)\overset{\mathcal{P}ush}{\to}\mathrm{Mod}\left(S,\{x_1,\ldots,x_n\}\right)\overset{\mathcal{F}orget}{\to}\mathrm{Mod}(S)\to 1.$$

Corollary 4.13. *When $S=D^2$, this gives the exact sequence*

$$1\to\underbrace{\pi_1\left(C\left(D^2,n\right)\right)}_{B_n}\to\mathrm{Mod}\left(D_n\right)\to\underbrace{\mathrm{Mod}\left(D^2\right)}_{1}\to 1.$$

Hence $B_n\approx\mathrm{Mod}\left(D_n\right)$.

4.5. **Algebraic Structure of the Braid Group.**

4.6. **The pure braid group.** Recall that by definition of a braid group, we are given a collection of n points $p_1, \ldots, p_n$, n paths $f_i \colon I \to \mathbb{C} \times I$ and a permutation $\overline{f} \in \Sigma_n$ such that $f_i(0) = p_i$ and $f_i(1) = p_{\overline{f}(i)}$. We can thus define a homomorphism $B_n \to \Sigma_n$ by sending $f \mapsto \overline{f}$.

Definition 4.14. We define the *pure braid group* PB_n as the kernel of the homomorphism $B_n \to \Sigma_n$ given by $f \mapsto \overline{f}$.

We obtain the short exact sequence

$$1 \to PB_n \to B_n \to \Sigma_n \to 1.$$

So a pure braid is a braid where each strand begins and ends at the same point of $\mathbb{C}$.

Exercise 4.15. Show that

$$PB_n \approx \pi_1 \left(C^{ord} \left(\mathbb{C}, n \right) \right) \approx \mathrm{PMod}(D_n)$$

4.7. **Braid group and symmetric mapping class groups.**

4.7.1. *The construction of the homomorphism.* Let S_g^1 be a surface of genus g with one boundary component. Define a homomorphism $\psi\colon B_n \to \operatorname{Mod}\left(S_g^1\right)$ for $n \leqslant 2g+1$ as follows. Choose a chain of simple closed curves $\{\alpha_i\}$ in S_g^1, that is, a collection of simple closed curves satisfying $i\left(\alpha_i, \alpha_{i+1}\right) = 1$ for all i and $i\left(\alpha_i, \alpha_j\right) = 0$ otherwise. We then define ψ via $\psi\left(\sigma_i\right) = T_{\alpha_i}$. This is well defined if and only if T respects all the relations in B_n. Now, if σ_i and σ_j are given with $|i-j| \geqslant 2$, then $\sigma_i\sigma_j = \sigma_j\sigma_i$ and indeed also $i\left(\alpha_i, \alpha_j\right) = 0$ so by the disjointness relation for Dehn twists (fact 3.9), we get that T respects this commutativity.
Similarly, we have that $\sigma_i\sigma_{i+1}\sigma_i$, for all i, is mapped to $T_{\alpha_i}T_{\alpha_{i+1}}T_{\alpha_i}$ which, by the braid relation on Dehn twists and the assumption that $i\left(\alpha_i, \alpha_{i+1}\right) = 1$ for all i, is equivalent to $T_{\alpha_{i+1}}T_{\alpha_i}T_{\alpha_{i+1}}$, so the braid relation in B_n is respected under ψ.

Question 4.16. Can we say whether ψ is injective?

4.8. **The Birman-Hilden Theorem.** Let ι be the order 2 element of $\operatorname{Homeo}^+\left(S_g^1\right)$ as shown in figure 10 and let $\operatorname{SHomeo}^+\left(S_g^1\right)$ be the centralizer in $\operatorname{Homeo}^+\left(S_g^1, \partial S_g^1\right)$ of ι:

$$\operatorname{SHomeo}^+\left(S_g^1\right) = C_{\operatorname{Homeo}^+\left(S_g^1, \partial S_g^1\right)}\left(\iota\right).$$

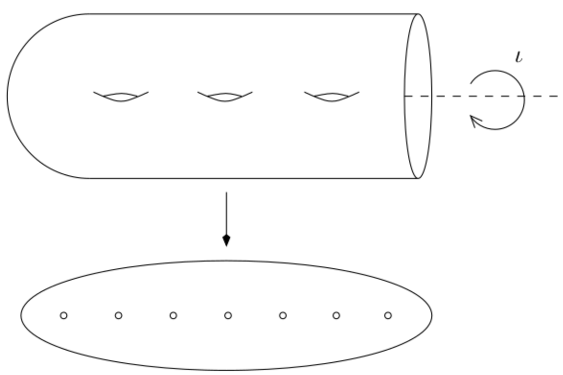


FIGURE 10. The Birman-Hilden double cover

Definition 4.17. The group $\operatorname{SHomeo}^+\left(S_g^1\right)$ is called the group of orientation-preserving symmetric homeomorphisms of S_g^1. The symmetric mapping class group is the group

$$\operatorname{SMod}(S_g^1) = \operatorname{SHomeo}^+\left(S_g^1\right)/\text{isotopy},$$

i.e, the subgroup of $\operatorname{Mod}\left(S_g^1\right)$ that is the image of $\operatorname{SHomeo}^+\left(S_g^1\right)$. In particular, $\operatorname{SMod}\left(S_g^1\right)$ is not the same as $\pi_0\left(\operatorname{SHomeo}^+\left(S_g^1\right)\right)$ as isotopies are allowed to pass through all homeomorphisms in $\operatorname{SMod}\left(S_g^1\right)$, but not in the latter.

The homeomorphism ι has $2g+1$ fixed points in S_g^1. The quotient of S_g^1 by $\langle\iota\rangle$ is a topological disk D_{2g+1} with $2g+1$ cone points of order 2, with each cone point coming from a fixed point of ι. Since the elements of $\operatorname{SHomeo}^+\left(S_g^1\right)$ commute with

ι, they descend to homeomorphisms of the quotient disk, and by the commutativity, they must preserve the set of $2g+1$ fixed points of ι, and so there is a homomorphism

$$\mathrm{SHomeo}^+\left(S_g^1\right) \to \mathrm{Homeo}^+\left(D_{2g+1}, \partial D_{2g+1}\right)$$

by sending φ to $\pi \circ \varphi$ where $\pi\colon S_g^1 \to D_{2g+1}$ is the quotient map. If $\varphi \mapsto \pi \circ \varphi = \mathbb{1}_{D_{2g+1}}$, then $\varphi \in \langle \iota \rangle$, and since $\iota \notin \mathrm{SHomeo}^+\left(S_g^1\right)$, we have $\varphi = 1$.

Question 4.18. Why does any element of $\mathrm{Homeo}^+\left(D_{2g+1}\right)$ lift to $\mathrm{SHomeo}^+\left(S_g^1\right)$?

Definition 4.19. We say two homeomorphisms $\varphi, \psi \in \mathrm{SHomeo}^+\left(S_g^1\right)$ are symmetrically isotopic whenever $[\varphi] = [\psi]$ in $\pi_0\left(\mathrm{SHomeo}^+\left(S_g^1\right)\right)$. Note that here, $\mathrm{SHomeo}^+\left(S_g^1\right)$ inherits the subspace topology from $\mathrm{Homeo}^+\left(S_g^1\right)$ (actually, is this true?...)

If we have this, we get the isomorphism

$$\begin{aligned}
\mathrm{SHomeo}^+\left(S_g^1\right)/\text{symmetric isotopy} &= \pi_0\left(\mathrm{SHomeo}^+(S_g^1)\right) \\
&\approx \pi_0\left(\mathrm{Homeo}^+\left(D_{2g+1}, \partial D_{2g+1}\right)\right) \\
&= \mathrm{Mod}\left(D_{2g+1}\right) \\
&\approx B_{2g+1}.
\end{aligned}$$

We want to show that if two symmetric homeomorphisms of S_g^1 are isotopic, then they must be symmetrically isotopic, since then we will derive the Birman-Hilden theorem which we now state.

4.9. **The Birman-Hilden Theorem.**

Theorem 4.20 (Birman-Hilden)**.** $\mathrm{SMod}\left(S_g^1\right) \approx B_{2g+1}$.

Example 4.21. Taking $g = 1$, we will find $\mathrm{Mod}\left(S_g^1\right)$. Note that by Corollary 9.12, $\iota \in C\left(\mathrm{Homeo}^+\left(S_g^1\right)\right)$, so $\mathrm{Mod}\left(S_1^1\right) = \mathrm{SMod}\left(S_g^1\right)$, and now it is easy to see that

$$\mathrm{Mod}\left(S_1^1\right) = \mathrm{SMod}\left(S_g^1\right) \approx B_3 \approx \mathrm{Mod}\left(D_3\right)$$

Remark. The Birman-Hilden theorem also holds for surfaces with two symmetric boundary components that are interchanged by ι, see figure 11. Hence

$$\mathrm{SMod}\left(S_g^2\right) \approx B_{2g+2}.$$

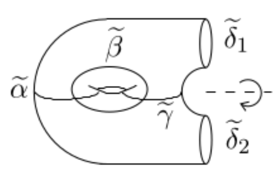


FIGURE 11. Symmetric boundary components interchanged by ι.

4.10. **Proof of the Birman-Hilden Theorem.**

Definition 4.22. A closed curve α in S_g is symmetric if $\iota(\alpha) = \alpha$ as sets.

Lemma 4.23. *Let $g \geqslant 2$ and let α and β be two symmetric nonseparating simple closed curves in S_g. If α and β are isotopic, then they are symmetrically isotopic.*

Proof. Let $\overline{\alpha}$ and $\overline{\beta}$ denote the images of α and β in $S_{0,2g+2} \approx S_g / \langle\iota\rangle$. Now, $\overline{\alpha}$ and $\overline{\beta}$ must be simple proper arcs in $S_{0,2g+2}$ (look at it geometrically - in particular, remember α and β are symmetric).
Let's look at an example to get a picture. If α and β are symmetric choices of the usual generating loops in the homology of a torus, these will correspond to one loop being the "innermost" meridian loop while we choose the other loop to be a longitudinal loop whose plan of existence is normal to the axis of rotation. See figure 12.

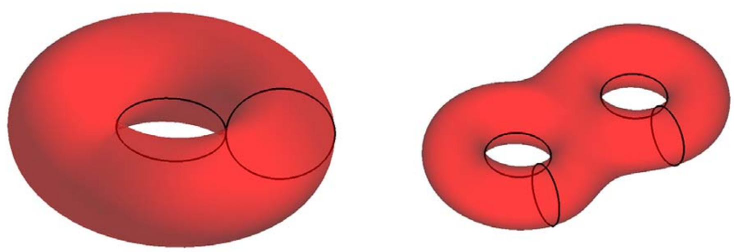


FIGURE 12. Basis for homology groups of torus and double torus

Imagine in this figure now we cut the surface into a "lower" and "upper" half. Looking at the resulting paths of our loops, we indeed get arcs for the longitudinal loops and loop on the boundary for the meridian loops.
Now, an isotopy between these arcs will lift to a symmetric isotopy between α and β.
I.e., if H is an isotopy between α and β, then there exist an induced map $\tilde{H}$ such that

$$\begin{tikzcd} & S_g \arrow[d] \\ I^2 \arrow[ur, "\tilde{H}"] \arrow[r, "H"'] & S_g/\langle\iota\rangle \end{tikzcd}$$

commutes since I^2 is simply connected, path-connected and locally path-connected [1, Cor 4.2].
We can modify α by a symmetric isotopy so that it is transverse to β. We claim that α cannot be disjoint from β. Indeed, for then $\overline{\alpha}$ and $\overline{\beta}$ are disjoint including endpoints. But such arcs cannot correspond to isotopic curves in S_g: we can choose an arc $\overline{\gamma}$ that passes through an odd number of endpoints of $\overline{\alpha}$ and an even number of endpoints of $\overline{\beta}$. This will then lift to a loop γ in S_g with $i(\alpha, \gamma)$ odd and $i(\beta, \gamma)$ even, contradicting α isotopic to β.
Now, since α is isotopic to β and $\alpha \cap \beta \neq \varnothing$, the bigon criterion gives that α and β form a bigon B. Assume B is the innermost bigon. As α and β are fixed (they are symmetric) by ι, we have that $\iota(B)$ is another innermost bigon in the graph $\alpha \cup \beta$.

But ι reverses the orientation of non-separating closed curves (while preserving orientations of separating closed curves), so since the bigon B lies to one side of α, $\iota(B)$ must lie on the other side of α.

It follows that the image of B in $S_{0,2g+2}$ is an innermost bigon $\overline{B}$ between $\overline{\alpha}$ and
why? $\overline{\beta}$. Furthermore, since $\iota(B) \neq B$, there are no fixed points of ι in B and hence no marked points of $S_{0,2g+2}$ in $\overline{B}$.
Now, considering the boundary of the bigon $\overline{B}$, it can have zero, one or two of its vertices on marked points of $S_{0,2g+2}$. In the first two cases, we can modify $\overline{\alpha}$ by
why? isotopy in order to remove the bigon , reducing the intersection number of $\overline{\alpha}$ and $\overline{\beta}$. In the last case, since $\overline{B}$ is innermost, we see that $\overline{\alpha} \cup \overline{\beta}$ is a simple loop bounding
why? a disk , and we can push $\overline{\alpha}$ onto $\overline{\beta}$. Removing bigons inductively, we see that $\overline{\alpha}$ is isotopic to $\overline{\beta}$, and this isotopy lifts to a symmetric isotopy between α and β.

□

Proposition 4.24. *Let $g \geqslant 2$ and let $\varphi, \psi \in \mathrm{SHomeo}^+(S_g)$. If φ and ψ are isotopic, then they are symmetrically isotopic.*

Proof of the Birman-Hilden theorem. We have a commutative diagram

$$\begin{tikzcd}
\mathrm{SHomeo}^+(S_g) \arrow[r, two heads] & \mathrm{Homeo}^+\left(S_{0,2g+2}, \partial S_{0,2g+2}\right) \arrow[rr] \arrow[dr] & & \mathrm{Mod}\left(S_{0,2g+2}\right) \\
& & \mathrm{SMod}(S_g) \arrow[ur] &
\end{tikzcd}$$

We wish to find the kernel of the map $\mathrm{SMod}(S_g) \to \mathrm{Mod}\left(S_{0,2g+2}\right)$. Suppose $f \in \mathrm{SMod}(S_g)$ is mapped to 0. Since the composition $\mathrm{SHomeo}^+(S_g) \to \mathrm{Homeo}^+\left(S_{0,2g+2}\right) \to \mathrm{Mod}\left(S_{0,2g+2}\right)$ is a surjective homomorphism, we can choose a representative $\varphi \in \mathrm{SHomeo}^+\left(S_g\right)$. Let $\overline{\varphi}$ be the image in $\mathrm{Homeo}^+\left(S_{0,2g+2}\right)$. Then $\overline{\varphi}$ is isotopic to the identity, say $H\colon I^2 \to \mathrm{Homeo}^+\left(S_{0,2g+2}\right)$. Then this lifts to a symmetric isotopy $\tilde{H}\colon I^2 \to \mathrm{SHomeo}^+\left(S_g\right)$ making the following diagram commute

$$\begin{tikzcd}
& I^2 \arrow[dl, "\tilde{H}"'] \arrow[dr, "H"] & & & \\
\mathrm{SHomeo}^+(S_g) \arrow[rr, two heads] & & \mathrm{Homeo}^+\left(S_{0,2g+2}, \partial S_{0,2g+2}\right) \arrow[rr] \arrow[dr] & & \mathrm{Mod}\left(S_{0,2g+2}\right) \\
& & & \mathrm{SMod}(S_g) \arrow[ur] &
\end{tikzcd}$$

Now, $\tilde{H}$ is an isotopy of φ to either the identity or ι, so

$$\mathrm{SMod}\left(S_g\right) / \langle [\iota] \rangle \approx \mathrm{Mod}\left(S_{0,2g+2}\right).$$

□

Remark. We can generalize the proof of the Birman-Hilden theorem a bit to the case of S_g^1 quite simply: the quotient of S_g^1 by the hyperelliptic involution $\iota\colon S_g^1 \to S_g^1$ is a disk with $2g+1$ marked points. Since $\iota\colon S_g^1 \to S_g^1$ is not an element of $\mathrm{Homeo}^+\left(S_g^1, \partial S_g^1\right)$, it does not represent an element of $\mathrm{SMod}(S_g^1)$, and so we get

$$\mathrm{SMod}\left(S_g^1\right) \approx \mathrm{Mod}\left(D_{2g+1}\right) \approx B_{2g+1}.$$

5. Braided monoidal categories

The Birman-Hilden homomorphism is an example of a geometric representation:

Definition 5.1 (Geometric representation)**.** A geometric representation of a group G is any homomorphism $G \to \mathrm{Mod}(S)$ for some surface S.

Write up connection between braided monoidal categories and geometric representations

5.1. **Monoidal categories.**

We first introduce the notion of a monoidal category.

Definition 5.2 (Monoidal category)**.** A monoidal category is a tuple $V = (V, \otimes, I, a, l, r)$ consisting of a category V, a functor $\otimes \colon V \times V \to V$ called the monoidal product, and object $I \in V$ called the unit, and natural isomorphisms

$$\begin{aligned} a\colon \ (- \otimes -) \otimes - \ &\overset{\sim}{\Longrightarrow} \ - \otimes (- \otimes -) \\ l\colon \ I \otimes - \ &\overset{\sim}{\Longrightarrow} \ - \\ r\colon \ - \otimes I \ &\overset{\sim}{\Longrightarrow} \ - \end{aligned}$$

called the associativity, left unit and right unit constraints, respectively. Additionally, we require that for all objects $A, B, C, D \in V$, the following two diagrams commute:

$$\begin{tikzcd}[column sep=small] & & (A \otimes B) \otimes (C \otimes D) \arrow[drr, "a"] & & \\ ((A \otimes B) \otimes C) \otimes D \arrow[urr, "a"] \arrow[dr, "a \otimes D"'] & & & & A \otimes (B \otimes (C \otimes D)) \\ & (A \otimes (B \otimes C)) \otimes D \arrow[rr, "a"'] & & A \otimes ((B \otimes C) \otimes D) \arrow[ur, "A \otimes a"'] & \end{tikzcd}$$

and

$$\begin{tikzcd} (A \otimes I) \otimes B \arrow[rr, "a"] \arrow[dr, "r \otimes B"'] & & A \otimes (I \otimes B) \arrow[dl, "A \otimes l"] \\ & A \otimes B & \end{tikzcd}$$

The monoidal category is called strict when all the natural isomorphisms are identity morphisms for all objects.

Definition 5.3 (Monoidal functor)**.** If $\mathcal{V}$ and $\mathcal{W}$ are monoidal categories, then we define a *monoidal functor* to be a tuple $F = (F, \varphi_2, \varphi_0) : \mathcal{V} \to \mathcal{W}$ consisting of a functor $F \colon \mathcal{V} \to \mathcal{W}$, a family of natural isomorphisms

$$\varphi_{2,A,B} \colon FA \otimes FB \xrightarrow{\sim} F(A \otimes B),$$

and an isomorphism $\varphi_0 \colon I \xrightarrow{\sim} FI$ such that the following three diagrams commute:

$$\begin{tikzcd} (FA \otimes FB) \otimes FC \arrow[r, "a"] \arrow[d, "\varphi_2 \otimes FC"'] & FA \otimes (FB \otimes FC) \arrow[d, "FA \otimes \varphi_2"] \\ F(A \otimes B) \otimes FC \arrow[d, "\varphi_2"'] & FA \otimes F(B \otimes C) \arrow[d, "\varphi_2"] \\ F((A \otimes B) \otimes C) \arrow[r, "Fa"'] & F(A \otimes (B \otimes C)) \end{tikzcd}$$

$$\begin{tikzcd} FA \otimes I \arrow[r, "r"] \arrow[d, "FA\otimes\varphi_0"'] & FA \\ FA \otimes FI \arrow[r, "\varphi_2"'] & F(A \otimes I) \arrow[u, "Fr"'] \end{tikzcd} \qquad \begin{tikzcd} I \otimes FA \arrow[r, "l"] \arrow[d, "\varphi_0\otimes l"'] & FA \\ FI \otimes FA \arrow[r, "\varphi_2"'] & F(I \otimes A) \arrow[u, "Fl"'] \end{tikzcd}$$

A monoidal functor is called *strict* when each of the isomorphisms $\varphi_{2,A,B}$ and φ_0 are all identities.

Definition 5.4. A morphism $\theta\colon F \implies G$ of monoidal functors is a natural transformation $\theta\colon F \implies G$ such that the following diagrams commute:

$$\begin{tikzcd} FA \otimes FB \arrow[r, "\varphi_2"] \arrow[d, "\theta_a\otimes\theta_b"'] & F(A \otimes B) \arrow[d, "\theta_{A\otimes B}"] \\ GA \otimes GB \arrow[r, "\varphi_2"'] & G(A \otimes B) \end{tikzcd} \qquad \begin{tikzcd} & FI \arrow[dd, "\theta_I"] \\ I \arrow[ur, "\varphi_0"] \arrow[dr, "\varphi_0"'] & \\ & GI \end{tikzcd}$$

Definition 5.5 (Braiding)**.** A braiding for a monoidal category V consists for a natural family of isomorphisms

$$c = c_{A,B} \colon A \otimes B \xrightarrow{\sim} B \otimes A$$

in V such that the following diagrams commute

$$\begin{tikzcd} & (B \otimes A) \otimes C \arrow[r, "a"] & B \otimes (A \otimes C) \arrow[dr, "B\otimes c"] & \\ (A \otimes B) \otimes C \arrow[ur, "c\otimes C"] \arrow[dr, "a"'] & & & B \otimes (C \otimes A) \\ & A \otimes (B \otimes C) \arrow[r, "c"'] & (B \otimes C) \otimes A \arrow[ur, "a"'] & \end{tikzcd}$$

and

$$\begin{tikzcd} & A \otimes (C \otimes B) \arrow[r, "a^{-1}"] & (A \otimes C) \otimes B \arrow[dr, "c\otimes B"] & \\ A \otimes (B \otimes C) \arrow[ur, "A\otimes c"] \arrow[dr, "a^{-1}"'] & & & (C \otimes A) \otimes B \\ & (A \otimes B) \otimes C \arrow[r, "c"'] & C \otimes (A \otimes B) \arrow[ur, "a^{-1}"'] & \end{tikzcd}$$

Proposition 5.6. *In a braided monoidal category, the following diagram commutes*

$$\begin{tikzcd}
(A\otimes B)\otimes C \arrow[r, "a"] \arrow[d, "c\otimes C"'] & A\otimes (B\otimes C) \arrow[r, "A\otimes c"] \arrow[ddd, dashed, no head, "c"] & A\otimes (C\otimes B) \arrow[r, "a^{-1}"] \arrow[ddd, dashed, no head, "c"] & (A\otimes C)\otimes B \arrow[d, "c\otimes B"] \\
(B\otimes A)\otimes C \arrow[d, "a"'] & & & (C\otimes A)\otimes B \arrow[d, "a"] \\
B\otimes (A\otimes C) \arrow[d, "B\otimes c"'] & & & C\otimes (A\otimes B) \arrow[d, "C\otimes c"] \\
B\otimes (C\otimes A) \arrow[r, "a^{-1}"'] & (B\otimes C)\otimes A \arrow[r, "c\otimes A"'] & (C\otimes B)\otimes A \arrow[r, "a"'] & C\otimes (B\otimes A)
\end{tikzcd}$$

Proof. Write up proof □

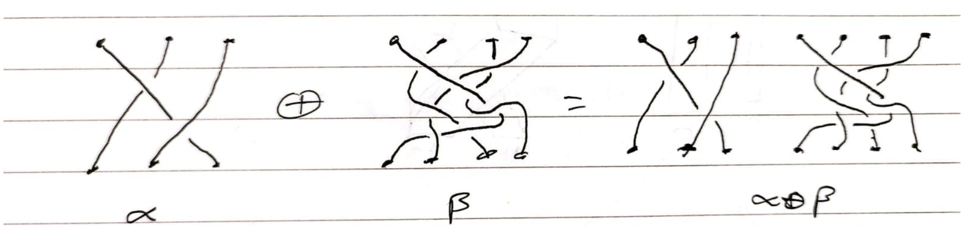
Example 5.7 (Braids and labelled braids on strings)**.** We define the braid groupoid to be the category $\mathcal{B}$ whose objects are the natural numbers and whose morphisms are given by

$$B\,(m,n) = \begin{cases} B_n, & m = n \\ \varnothing, & m \neq n \end{cases}$$

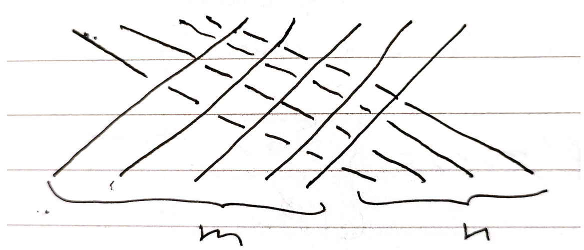
where composition of morphisms is defined to be the product of the braids (i.e., concatenation).
We can then equip $\mathcal{B}$ with a strinct monoidal structure by letting $\otimes\colon B_m \times B_n \to B_{m+n}$ be given by addition of braids which is described algebraically by

$$\sigma_i \otimes \sigma_j = \sigma_i \sigma_{m+j}\,(= \sigma_{m+j}\sigma_i)$$

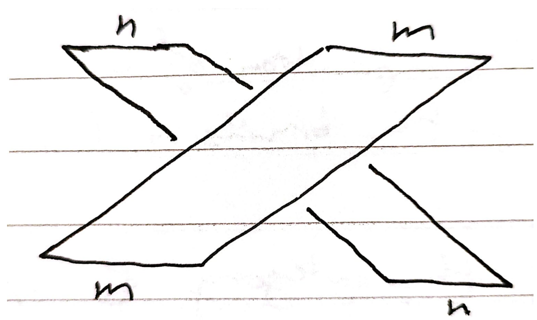
pictured as



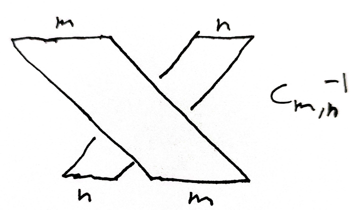
Furthermore, we can give $\mathcal{B}$ a braiding c given by $c = c_{m,n}\colon \underbrace{m\otimes n}_{=m+n} \mapsto \underbrace{n\otimes m}_{=n+m}$ which, on morphisms, can be illustrated by concatenating from, say above, with the following braid



or, illustrated differently, as



Then this is clearly an isomorphism since it has the inverse



5.2. **Yang-Baxter operators.**

Definition 5.8 (Yang-Baxter operator)**.** Let $T\colon \mathcal{A} \to \mathcal{V}$ be a functor from a category $\mathcal{A}$ to a monoidal category $\mathcal{V}$. A *Yang-Baxter operator on* T is a natural family of isomorphisms

$$y = y_{A,B}\colon TA \otimes TB \xrightarrow{\sim} TB \otimes TA$$

such that the following diagram commutes.

$$\begin{tikzcd}
(TA \otimes TB) \otimes TC \arrow[r, "a"] \arrow[d, "y \otimes TC"'] & TA \otimes (TB \otimes TC) \arrow[r, "TA \otimes y"] & TA \otimes (TC \otimes TB) \arrow[r, "a^{-1}"] & (TA \otimes TC) \otimes TB \arrow[d, "y \otimes TB"] \\
(TB \otimes TA) \otimes TC \arrow[d, "a"'] & & & (TC \otimes TA) \otimes TB \arrow[d, "a"] \\
TB \otimes (TA \otimes TC) \arrow[d, "TB \otimes y"'] & & & TC \otimes (TA \otimes TB) \arrow[d, "TC \otimes y"] \\
TB \otimes (TC \otimes TA) \arrow[r, "a^{-1}"'] & (TB \otimes TC) \otimes TA \arrow[r, "y \otimes TA"'] & (TC \otimes TB) \otimes TA \arrow[r, "a"'] & TC \otimes (TB \otimes TA)
\end{tikzcd}$$

Remark. When $\mathcal{A} = \mathbb{1}$, we say that y is a Yang-Baxter operator on $X = T(\mathcal{A}) \in \mathcal{V}$ if it is a Yang-Baxter operator on $T\colon \mathbb{1} = \mathcal{A} \to \mathcal{V}$.

Let $(\mathcal{X}, \otimes, I)$ be a monoidal category with $\tau \in \mathrm{Aut}_{\mathcal{X}}(X \otimes X)$ a Yang-Baxter operator in $\mathcal{X}$. Suppose $\mathcal{X}$ acts on a category $\mathcal{M}$ via a functor $\mathcal{M} \times \mathcal{X} \to \mathcal{M}$ which we also denote by $\otimes$. Then there is an action of the braid groupoid $\alpha_\tau\colon \mathcal{M} \times B \to \mathcal{M}$ given on objects by $\alpha_\tau(A, n) = A \otimes X^{\otimes n}$ and determined on morphisms by $\alpha_\tau(f, \sigma_i) = f \otimes \mathrm{id}_{X^{\otimes i-1}} \otimes \tau \otimes \mathrm{id}_{X^{\otimes n-i-1}}$.

Example 5.9. If $\mathcal{X} = (\mathcal{X}, \otimes, \mathcal{I})$ admits a braiding b, then $\tau = b_{X,X} \in \mathrm{Aut}_{\mathcal{X}}(X \otimes X)$ is a Yang-Baxter operator for any object X. The thing that needs verifying here is that the big Yang-Baxter diagram in definition 5.8 is satisfied, but this follows directly from proposition 5.6.

We want to show that the category of strong monoidal functors from the braid groupoid into $\mathcal{X}$ is equivalent to a naturally defined category of Yang-Baxter operators in $\mathcal{X}$.

Proposition 5.10. *For any strict monoidal category $\mathcal{V}$ and any Yang-Baxter operator y on $T\colon \mathcal{A} \to \mathcal{V}$, there exists a unique strict tensor functor $T'\colon \mathcal{B} \wr \mathcal{A} \to \mathcal{V}$ such that $T' \circ z = y$ and the following diagram commutes:*

$$\begin{tikzcd}
\mathcal{A} \arrow[r, "\iota"] \arrow[dr, "T"'] & \mathcal{B} \wr \mathcal{A} \arrow[d, "T'"] \\
& \mathcal{V}
\end{tikzcd}$$

Proposition 5.11. *For any strict monoidal category $\mathcal{V}$ and any Yang-Baxter τ on an element $X \in V$, there exists a unique strict monoidal functor $\Phi_{X,\tau}\colon \mathcal{B} \to \mathcal{V}$ such that $\Phi_{X,\tau} \circ z = y$.*

Proof and construction. Define $\Phi_{X,\tau}\colon \mathcal{B} \to \mathcal{V}$ on objects by $\Phi_{X,\tau}(n) = X^{\otimes n}$. For $0 \leqslant i < n$, define

$$y_i = X^{\otimes(i-1)} \otimes y \otimes X^{\otimes(n-i-1)}\colon X^{\otimes n} \to X^{\otimes n}.$$

These satisfy the braid group relations. Thus we obtain a monoid homomorphism $\Phi_{X,\tau,n}\colon \mathcal{B}_n \to \mathcal{V}(X^{\otimes n}, X^{\otimes n})$ taking σ_i to y_i for all $0 \leqslant i < n$. Clearly $\Phi_{X,\tau}$ is the unique strict monoidal functor with these properties. $\square$

More explicit details.

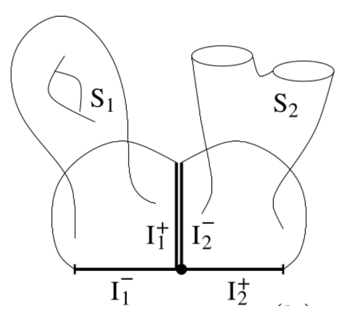
Definition 5.12. If $\mathcal{V}$ and $\mathcal{W}$ are monoidal categories, we define $\mathcal{M}on\,(\mathcal{V}, \mathcal{W})$ to be the category whose objects are monoidal functors $F\colon \mathcal{V} \to \mathcal{W}$ and whose morphisms are morphisms $\psi\colon F \implies G$ of monoidal functors.
If $\mathcal{V}, \mathcal{W}$ are braided monoidal categories, we write $\mathcal{BM}on\,(\mathcal{V}, \mathcal{W})$ for the full subcategory of $\mathcal{M}on\,(\mathcal{V}, \mathcal{W})$ consisting of the braided monoidal functors.

5.3. **Braided monoidal category of decorated and bidecorated surfaces.**

Definition 5.13 (Decorated surface)**.** A decorated surface is a pair (S, I) where S is a compact connected surface with at least one boundary component and $I\colon [-1, 1] \hookrightarrow \partial S$ is a parametrised interval in its boundary.

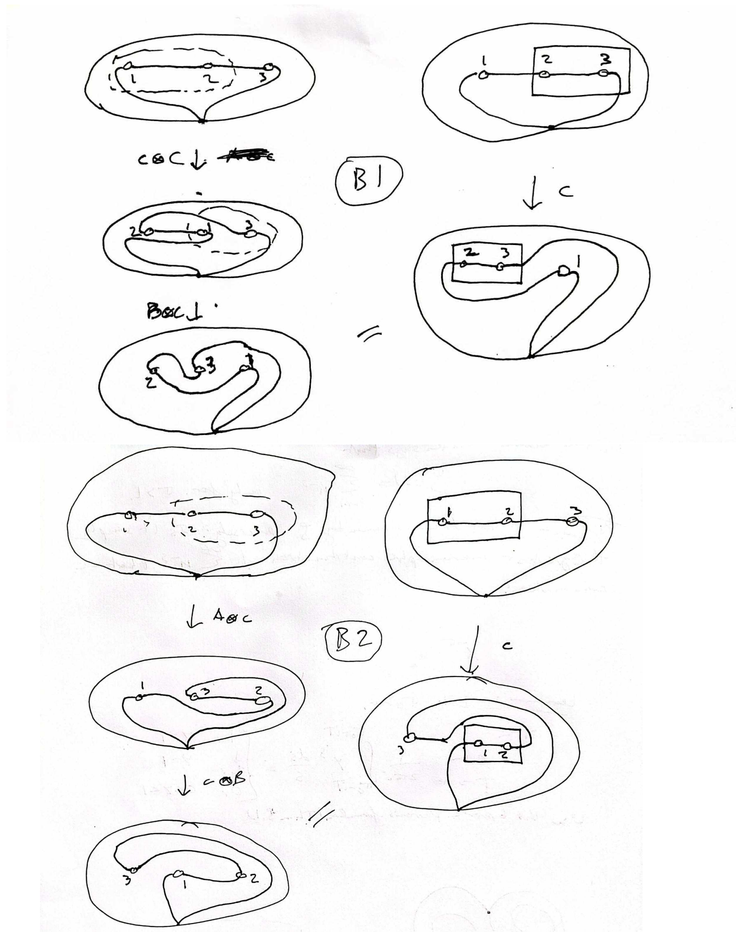
Definition 5.14 ($\mathcal{M}_1$)**.** Let $\mathcal{M}_1$ denote the groupoid where the objects are decorated surfaces and morphisms are isotopy classes of diffeomorphisms restricting to the identity on a neighborhood of I.

We now construct a braided monoidal structure on $\mathcal{M}_1$: given decorated surfaces (S_1, I_1) and (S_2, I_2), define $(S_1, I_1) \otimes (S_2, I_2) := (S_1 \# S_2, I_1 \# I_2)$ to be the surface obtained by gluing S_1 and S_2 along the right half-interval $I_1^+ \in \partial S_1$ and the left half-interval $I_2^- \in \partial S_2$, defining $I_1 \# I_2 = I_1^- \cup I_2^+$.



Furthermore, we define the unit object to be $I := \left(D^2, I\right)$. For it to be a strict unit, we define $\left(S_1 \# D^2, I_1 \# I\right) := (S_1, I_1)$ and $\left(D^2 \# S_2, I \# I_2\right) := (S_2, I_2)$.

We define a braiding c on $(S_1 \# S_2, I_1 \# I_2)$ as the half-Dehn twist which satisfies that $c\colon (S_1 \# S_2, I_1 \# I_2) \xrightarrow{\sim} (S_2 \# S_1, I_2 \# I_1)$ is a natural isomorphism because we it has the opposite half-Dehn twist as the inverse. It is natural because the induced map will simply be the one induced by the naturality square.
The B1 and B2 diagrams can be verified pictorially as follows:



We will also consider a different monoidal category of surfaces. Informally, a bidecorated surface is a surface with two intervals marked in its boundary.
To give a precise definition, we first define certain surfaces X_i that will be convenient for the monoidal structure, we set $X_1 = D^2 \subset \mathbb{C}$ to be the unit disk, and then define embeddings $\iota_1^0, \iota_1^1 \colon I \to X_1$ by

$$\iota_1^0(t) = e^{i\left(\frac{\pi}{4}+t\frac{\pi}{2}\right)} \quad \text{and} \quad \iota_1^1(t) = e^{i\left(5\frac{\pi}{4}+t\frac{\pi}{2}\right)}.$$

We denote by $\overline{\iota_1^i} \colon I \to X_1$ the reverse map $t \mapsto \iota_1^i(1-t)$ for $i = 0, 1$. Then we recursively define X_{m+1} for $m \geqslant 1$ by

$$X_{m+1} := \frac{X_m \sqcup X_1}{\iota_m^i(t) \sim \overline{\iota_1^i}} \quad \text{for } t \in \left[\frac{1}{2}, 1\right]$$

and we define

$$\iota_{m+1}^i(t) = \begin{cases} \iota_m^i(t), & \text{if } t \leqslant \frac{1}{2} \\ \iota_1^i(t), & \text{else} \end{cases}.$$

In this process, the marked intervals will live in different boundary components every second time. The process for each of the two situations is illustrated below in figures 13 and 14.

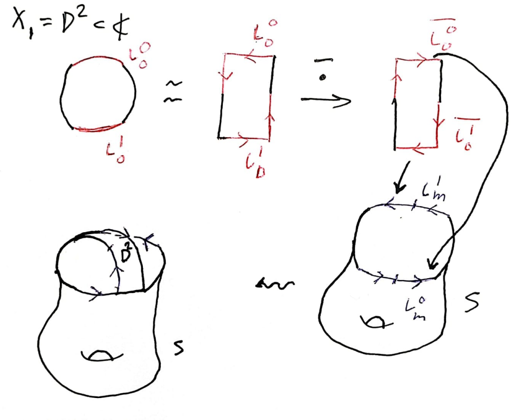


FIGURE 13. Marked intervals in single boundary components.

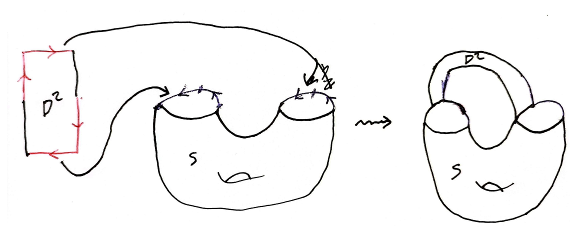


FIGURE 14. Marked intervals in different boundary components.

Lemma 5.15. *For $m \geqslant 1$, $X_m \approx S_{g,r}$ where*

$$(g, r) = \begin{cases} \left(\frac{m}{2} - 1, 2\right), & m \text{ even} \\ \left(\frac{m-1}{2}, 1\right), & m \text{ odd} \end{cases}.$$

Proof. Firstly, X_m is clearly connected, and we have

$$\chi(X_m) = \chi(X_{m-1}) - 1$$

since, for example, the Δ-structure on our surface X_m can be chosen to be that for X_{m-1} with the boundary subdivided into four 2-simplices with four vertices, adding an additional two 2-simplices and then a disk. By induction, we then get $\chi(X_m) = \chi(X_1) - (m-1) = 2 - m$.
Now, by the classification of surfaces with boundary and genus, we simply need to know how many boundary components X_{m+1} has. But as can be seen from the figures, if m is odd, we will have one boundary component, while if m is even, we will have two boundary components. □

Definition 5.16 (Bidecorated surface)**.** A bidecorated surface is a tuple (S, m, φ) where S is a surface, $m \geqslant 1$ is an integer, and

$$\varphi \colon \partial X_m \sqcup \left(\sqcup_k S^1\right) \xrightarrow{\sim} \partial S$$

is a homeomorphism, giving a parametrization of the boundary of S. We think of (S, m, φ) as a surface with two parametrized arcs

$$I_0 := \varphi \circ \iota_m^0 \quad \text{and} \quad I_1 := \varphi \circ \iota_m^1$$

in its boundary, and k additional parametrized boundaries.

Definition 5.17 ($\mathcal{M}_2$)**.** Let $\mathcal{M}_2$ denote the monoidal groupoid where objects are bidecorated surfaces together with a formal unit U. The Hom set between two bidecorated surfaces (S, m, φ) and (S', m', φ') is empty if $m \neq m'$ or S and S' are nonhomeomorphic. Otherwise, the Hom set consists of all mapping classes of homeomorphisms that preserve the boundary parametrizations:

$$\mathrm{Hom}_{\mathcal{M}_2}\left((S, m, \varphi), \left(S', m, \varphi'\right)\right) = \pi_0 \mathrm{Homeo}_\partial\left(S, S'\right) = \pi_0\left\{f \in \mathrm{Homeo}\left(S, S'\right) \mid f \circ \varphi = \varphi'\right\}$$

where $\mathrm{Homeo}\left(S, S'\right)$ has the compact-open topology, and $\mathrm{Homeo}_\partial\left(S, S'\right)$ the subspace topology.

The monoidal structure $\#$ on $\mathcal{M}_2$ is defined as follows. The object U is by definition a unit, and for the remaining objects, we define

$$(S, m, \varphi) \# \left(S', m', \varphi'\right) := \left(\frac{S \sqcup S'}{I_i(t) \sim \overline{I_i'}(t), t \in \left[\frac{1}{2}, 1\right]}, m + m', \varphi \# \varphi'\right)$$

for $i = 0, 1$, and where

$$\varphi \# \varphi' \colon \partial X_{m+m'} \sqcup \left(\sqcup_{k+k'} S^1\right) \hookrightarrow \partial\left(S \# S'\right)$$

is obtained using the canonical identification $\partial X_{m+m'} \approx \left(\partial X_{n - \iota_m\left(\frac{1}{2}, 1\right)}\right) \cup \left(\partial X_{m'} - \iota_{m'}\left(0, \frac{1}{2}\right)\right)$.
Now we will construct a Yang-Baxter element in $\mathcal{M}_2$ as follows. Let $D^{\# m} = D_1 \# \ldots \# \left(D_i \# D_{i+1}\right) \# \ldots \# D_m$, where subscripts are used to enumerate the disks. The underlying surface, by construction, will be X_m. Let a_i defnote the isotopy class of a curve in the interior $D_i \# D_{i+1} \approx S^1 \times I$ that is parallel to its boundary components, see figure 5.3.

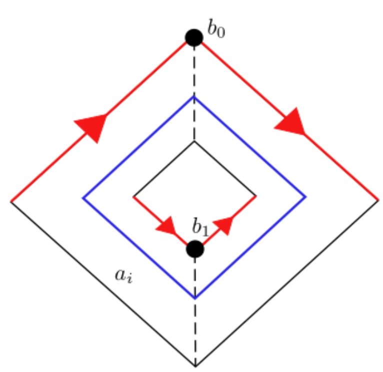


FIGURE 15. The curve a_i in $D_i \# D_{i+1}$

Lemma 5.18. *The curves $a_1, \ldots, a_{m-1}$ form a chain in $D^{\# m}$.*

Proof. The curve a_i has image contained in $D_i \# D_{i+1}$, so it can only intersect a_{i-1} and a_{i+1} nontrivially. So it suffices to look at the subsurface of $D^{\# m}$ corresponding to $D_i \# D_{i+1} \# D_{i+2}$.

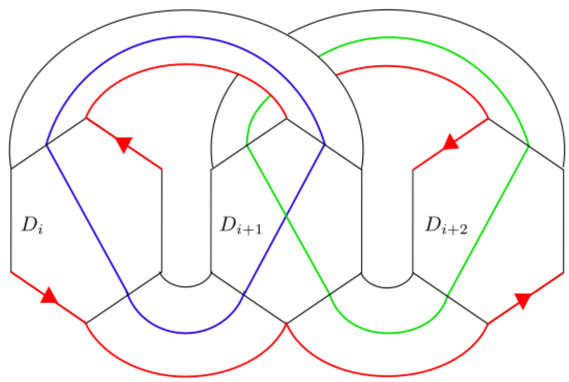


FIGURE 16. Intersection of a_i and a_{i+1} in $D_i \# D_{i+1} \# D_{i+2}$.

□

Now by Lemma 3.11 and Proposition 3.14 (the braid relation), we get that the braid group relations hold for the Dehn twists $T_i \in \mathrm{Aut}_{\mathcal{M}_2}\left(D^{\# m}\right)$ where T_i is the Dehn twist along the curve a_i in $D^{\# m}$, i.e.,

$$\begin{aligned} T_i T_{i+1} T_i &= T_{i+1} T_i T_{i+1} && \forall i \\ T_i T_j &= T_j T_i && \text{for } |i-j|>1 \end{aligned}$$

Hence the same relations hold for the inverses T_i^{-1}.

If we add a disk to either side of $D^{\# m}$, we get

$$T_i \# \mathrm{id}_D = T_i \quad \text{and} \quad \mathrm{id}_D \# T_i = T_{i+1}$$

in $\mathrm{Aut}_{\mathcal{M}_2}\left(D^{\# m+1}\right)$. Hence this gives the relation

$$\left(T_1^{-1} \# \mathrm{id}_D\right)\left(\mathrm{id}_D \# T_1^{-1}\right)\left(T_1^{-1} \# id_D\right) = \left(\mathrm{id}_D \# T_1^{-1}\right)\left(T_1^{-1} \# \mathrm{id}_D\right)\left(\mathrm{id}_D \# T_1^{-1}\right)$$

in $\mathrm{Aut}_{\mathcal{M}_2}\left(D^{\# 3}\right)$, meaning that T_1^{-1} is a Yang-Baxter element. This yields a monoidal functor

$$\Phi = \Phi_{D, T_1^{-1}} \colon (B, \otimes) \to (\mathcal{M}_2, \#)$$

uniquely determined up to monoidal natural isomorphism by $\Phi(n) = D^{\# n}$ and $\Phi_{D, T_1^{-1}, n}(\sigma_1) = D^{\# i-1} \# T_1^{-1} \# D^{\# n-i-1} = T_i^{-1} \in \mathrm{Aut}_{\mathcal{M}_2}\left(D^{\# m}\right) = \pi_0 \mathrm{Homeo}_\partial\left(X_m\right)$. But by the Birman-Hilden theorem, the homomorphisms $\Phi_{D, T_1^{-1}, m} \colon B_m \to \mathrm{Aut}_{\mathcal{M}_2}\left(D^{\# m}\right)$ are injective.

5.4. **Braiding inducing geometric representation.** Putting the things above together, we have that a Yang-Baxter operator $\tau \in \mathrm{Aut}_{\mathcal{X}}(X \otimes X)$ gives a collection of homomorphisms $\varphi_{X,\tau} \colon B_n \to \mathrm{Aut}_{\mathcal{X}}\left(X^{\otimes n}\right)$. There are two standard ways to embed braid groups in mapping class groups of surfaces and we will describe how they both come from Yang-Baxter elements in appropriate categories of surfaces.

5.4.1. *The bidecorated case.*

6. Geometric Representations of the Braid Group on non-orientable surfaces

A connected orientable (respectively nonorientable) surface of genus g with b boundary components will be denoted by $S_{g,b}$ (respectively $N_{g,b}$).
Now, recall that the Möbius band, which are also called crosscaps), are the mapping cylinders on the map $z \mapsto z^2$ (see figure 6)

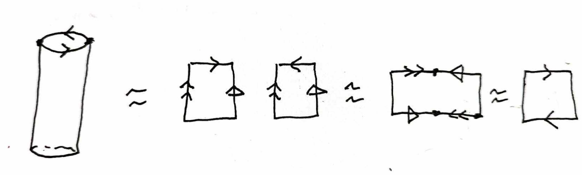


Figure 17. Möbius band

In this case, any of the two curves making up the half-circles which get identified can be cut along, rendering a connected surface. Thus gluing on a Möbius strip along the boundary, we obtain a surface of one higher genus.

We can then obtain $N_{g,b}$ from $S_{0,g+b}$ by gluing g Möbius bands along g distinct boundary components of $S_{0,g+b}$.

Definition 6.1 (Geometric representation)**.** A geometric representation of a group G is any homomorphism $G \to \mathrm{Mod}(S)$ for some surface S.

Example 6.2. The homomorphism $\psi\colon B_n \to \mathrm{Mod}(S_g^1)$ defined in the Birman-Hilden isomorphism is an example of a geometric representation of the braid group.

We will introduce three types of geometric representations of the braid group: the standard twist representation, the crosscap transposition representation, and lastly, transvection.

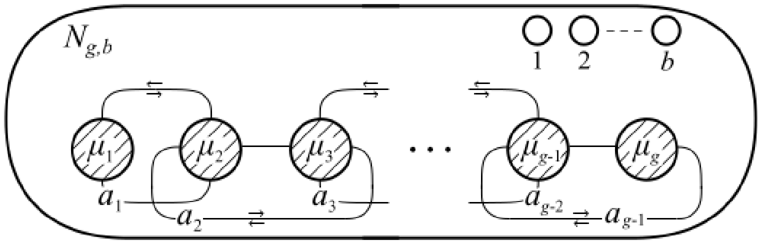
We call a curve two-sided (resp. one-sided) if its regular neighborhood is an annulus (resp a Möbius band). A sequence $C\,(a_1, \ldots, a_{n-1})$ of two-sided curves in S is called a chain of nonseparating curves if $i\,(a_i, a_{i+1}) = 1$ for $1 \leqslant i \leqslant n-2$ and $i\,(a_i, a_j) = 0$ for $|i-j| > 0$.

6.0.1. *The standard twist representation.*

Lemma 6.3. *If we fix an orientation of a regular neighborhood of the union of the curves a_i, then C determines the standard twist representation $\rho_C\colon B_n \to \mathrm{PMod}(S)$ defined by*

$$\rho_C\,(\sigma_i) = t_{a_i}, \quad i = 1, \ldots, n-1,$$

where t_{a_i} is the right-handed Dehn twist about a_i with respect to the orientation.



6.0.2. *The crosscap transposition representation.* Let $N = N_{g,b}$ be nonorientable. A sequence $C = (a_1, \ldots, a_{n-1})$ of separating curves in N is called *a chain of separating curves* if

(1) a_i bounds a one-holed Klein bottle for $i = 1, \ldots, n-1$,
(2) $i\,(a_i, a_{i+1}) = 2$ for $i = 1, \ldots, n-2$,
(3) $i\,(a_i, a_j) = 0$ for $|i - j| > 1$.

Here a_i bounding a one-holed Klein bottle means that if we collapse a_i to a point, we obtian a sphere with two crosscaps which is equivalent to the Klein bottle (see figure 6.0.2)

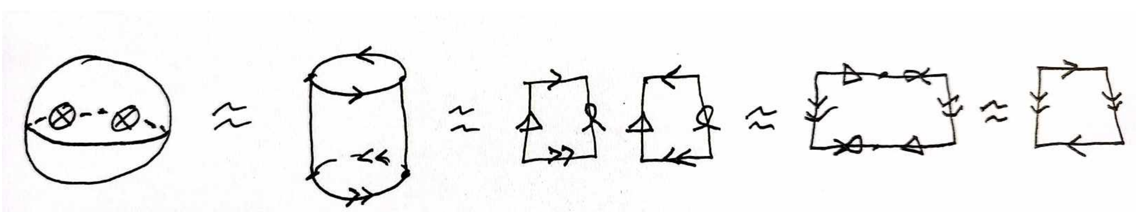


FIGURE 18. Klein-bottle as the sphere with two crosscaps

Let K_i be the one-hoeld Klein bottle bounded by a_i. Then $K_i \cap K_{i+1}$ will be a Möbius strip for $i = 1, \ldots, n-2$, and we denote its core curve by μ_{i+1}. Let μ_1 and μ_n be the core curves of $K_1 - K_2$ and $K_{n-1} - K_{n-2}$, respectively. Fix an orientation of a regular neighborhood of the union of the a_i. Let T_{a_i} be the right-handed Dehn twist about $a_i$and let u_i be the *crosscap transpostion* supported in K_i, swapping μ_i and μ_{i+1} such that $u_i^2 = T_{a_i}$ (essentially a half-Dehn twist but for crosscaps instead of punctures).

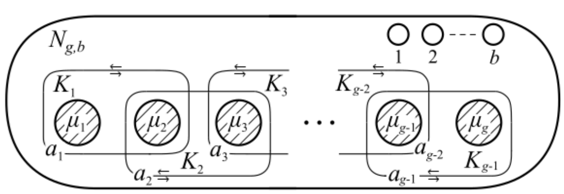


FIGURE 19. A chain of separating curves in $N_{g,b}$.

Lemma 6.4. *The mapping $\theta_C \colon B_n \to \mathrm{PMod}(N)$ by $\theta_C(\sigma_i) = u_i$ for $i = 1, \ldots, n-1$, defines a homomorphisms called crosscap transposition representation.*

6.0.3. *Transvection.*

Definition 6.5 (Transvection)**.** Given a homomorphism $\rho \colon B_n \to \mathrm{PMod}(S)$ and an element $\tau \in \mathrm{PMod}(S)$ such that τ commutes with $\rho(\sigma_i)$ for $1 \leqslant i \leqslant n-1$, we define a homomorphism $\rho^\tau \colon B_n \to \mathrm{Mod}(S)$, called a *transvection* of ρ, by

$$\rho^\tau(\sigma_i) = \tau\rho(\sigma_i), \quad i = 1, \ldots, n-1.$$

A homomorphism $\rho \colon B_n \to \mathrm{PMod}(S)$ is called *cyclic* if $\rho(B_n)$ is a cyclic group.

6.1. The main theorems.

Theorem 6.6. *Let $n \geqslant 14$ and let $N = N_{g,b}$ with $g \leqslant 2\left\lfloor \frac{n}{2} \right\rfloor + 1$ and $b \geqslant 0$. Then any homomorphism $\rho \colon B_n \to \mathrm{PMod}(N)$ is either cyclic, or is a transvection of a standard twist representation, or is a transvection of a crosscap transposition representation.*

Theorem 6.7. *Theorem 6.6 still holds when $\mathrm{PMod}(N)$ is replaced by $\mathrm{Mod}(N, \partial N)$.*

Note that $\mathrm{Mod}(N, \partial N) \nleqslant \mathrm{PMod}(N)$ as, for example, the Dehn twist about a boundary curve is non-trivial in $\mathrm{Mod}(N, \partial N)$, but becomes trivial in $\mathrm{PMod}(N)$.

7. The Burau Representations of the Braid Group

Let $\Lambda = \mathbb{Z}\left[t, t^{-1}\right]$ and $n \geqslant 2$. Over Λ, consider the $n \times n$-matrix

$$U_i = \begin{pmatrix} I_{i-1} & 0 & 0 & 0 \\ 0 & 1-t & t & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & I_{n-i-1} \end{pmatrix}.$$

So letting $U = \begin{pmatrix} 1-t & t \\ 1 & 0 \end{pmatrix}$, U_i becomes a block matrix on identity matrices and U.

Proposition 7.1. *Each U_i is invertible, and the U_i for $i \in \{1, \ldots, n\}$, for $n \geqslant 2$, satisfy the braid relations.*

Proof. By the Cayley-Hamilton theorem, any 2×2-matrix M over the ring Λ satisfies $M^2 - \operatorname{tr}(M)M + \det(M)I_2 = 0$. For $M = U$, we get $U^2 - (1-t)\,U - tI_2 = 0$. Clearly, also $I_n^2 - (1-t)I_n - tI_n = 0$ for all n, so we find that $U_i^2 - (1-t)U_i - tI_n = 0$ for all i, giving $U_i\,(U_i - (1-t)I_n) = tI_n$, so U_i is invertible with inverse

$$U_i^{-1} = t^{-1}\,(U_i - (1-t)I_n) = \begin{pmatrix} I_{i-1} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & t^{-1} & 1-t^{-1} & 0 \\ 0 & 0 & 0 & I_{n-i-1} \end{pmatrix}.$$

Now, for all i, j with $j - i \geqslant 2$, we have

$$\begin{aligned} U_iU_j &= \begin{pmatrix} I_{i-1} & 0 & 0 & 0 \\ 0 & 1-t & t & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & I_{n-i-1} \end{pmatrix} \begin{pmatrix} I_{j-1} & 0 & 0 & 0 \\ 0 & 1-t & t & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & I_{n-j-1} \end{pmatrix} \\ &= \begin{pmatrix} I_{i-1} & & & & & & \\ & 1-t & t & & & & \\ & 1 & 0 & & & & \\ & & & I_{j-i-2} & & & \\ & & & & 1-t & t & \\ & & & & 1 & 0 & \\ & & & & & & I_{n-j-3} \end{pmatrix} \\ &= \begin{pmatrix} I_{j-1} & 0 & 0 & 0 \\ 0 & 1-t & t & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & I_{n-j-1} \end{pmatrix} \begin{pmatrix} I_{i-1} & 0 & 0 & 0 \\ 0 & 1-t & t & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & I_{n-i-1} \end{pmatrix} \end{aligned}$$

□

8. Glossary

Definition 8.1 (Equivariant maps)**.** Suppose a group G acts on spaces X and Y, and let $f\colon X \to Y$ be a map. Then f is said to be equivariant if $f(g \cdot x) = g \cdot f(x)$ for all $x \in X$ and all $g \in G$.

Definition 8.2 (Closed surface)**.** A *closed surface* is a surface that is compact and without boundary.

Definition 8.3 (Isotopy)**.** A topological isotopy is a homotopy $F\colon X \times I \to Y$ such that for each $t_0 \in I$, $F(x, t_0)\colon X \to Y$ is a topological embedding (homeomorphism onto some subspace of Y).
Two embeddings $f, g\colon X \to Y$ are said to be isotopic if there exists an isotopy $F\colon X \times I \to Y$ such that $F(x, 0) = f(x)$ and $F(x, 1) = g(x)$.

Definition 8.4 (Orientation)**.** A closed n-manifold M is called orientable if $H_n(M; \mathbb{Z}) = \mathbb{Z}$. The choice of generator $[M]$ in $\mathbb{Z}$ is called an orientation, and the generator is called the fundamental class of M. A manifold together with a choice of orientation is called oriented. A compact n-manifold M with boundary is called orientable if $H_n(M, \partial M; \mathbb{Z}) = \mathbb{Z}$. The choice of generator $[M, \partial M]$ in $\mathbb{Z}$ is called an orientation, and $[M, \partial M]$ is referred to as the fundamental class of M.
A smooth manifold M is orientable if and only if the restriction of its tangent bundle to every smooth curve is trivial.

Remark. This makes sense since T. Radó showed that every surface is triangulable and it is clear then that the 2-cycles form a cyclic group. A choice of generator corresponds to choosing an orientation of each 2-simplex in the triangulation (compatibly).

Definition 8.5 (Inner and outer automorphisms)**.** Let G be any group and $\gamma \in G$. A conjugate automorphism

$$I_\gamma\colon g \mapsto \gamma g \gamma^{-1}$$

is called an *inner automorphism* of G. The group of inner automorphisms is denoted by $\mathrm{Inn}(G)$. It is isomorphic to $G/Z(G)$, and is a normal subgroup of $\mathrm{Aut}(G)$. The quotient

$$\mathrm{Out}(G) := \mathrm{Aut}(G)/\mathrm{Inn}(G)$$

is called the *outer automorphism group* of G.

Remark. A monoidal functor is also sometimes called a strong monoidal functor if one wants to distinguish it from a *lax monoidal functor* which is the definition of a monoidal functor without the requirements that φ_0 and $\varphi_{2,A,B}$ be isomorphisms.

9. Appendix

9.1. **Fiber Bundles.**

9.1.1. *Bredon.*

Definition 9.1. Let X, B and F be Hausdorff spaces and $p\colon X \to B$ a map. Then p is called a bundle projection with fiber F, if each point of B has a neighborhood U such that there is a homeomorphism $\varphi\colon U \times F \to p^{-1}(U)$ such that $p(\varphi\langle b, y\rangle) = b$ for all $b \in U$ and $y \in F$. That is, on $p^{-1}(U)$, p corresponds to projection $U \times F \to U$. Such a map φ is called a *trivialization* of the bundle over U.

Definition 9.2. An action of a group G on a space X is said to be *effective* if

$$(\forall x \in X : gx = x) \implies g = e.$$

Definition 9.3. Let K be a topological group acting effectively on the Hausdorff space F as a group of homeomorphisms. Let X and B be Hausdorff spaces. By a *fiber bundle* over the base space B with total space X, fiber F, and structure group K, we mean a bundle projection $p: X \to B$ together with a collection Φ of trivializations $\varphi: U \times F \to p^{-1}(U)$, of p over U, called *charts* over U, such that

(1) each point of B has a neighborhood over which there is a chart in Φ ;
(2) if $\varphi: U \times F \to p^{-1}(U)$ is in Φ and $V \subset U$ then the restriction of φ to $V \times F$ is in Φ;
(3) if $\varphi, \psi \in \Phi$ are charts over U, then there is a map $\theta: U \to K$ such that $\psi \langle u, y \rangle = \varphi \langle u, \theta(u)(y) \rangle$;
(4) the set Φ is maximal among collections satisfying (1), (2) and (3).

The bundle is called *smooth* if all these spaces are manifolds and all maps involved are smooth.

Definition 9.4. A *vector bundle* is a fiber bundle in which the fiber is a Euclidean space and the structure group is the general linear group if this Euclidean space or some subgroup of that group.

9.1.2. *Hatcher.*

Definition 9.5 (Homotopy lifting property)**.** A map $p: E \to B$ is said to have the homotopy lifting property with respect to a space X if, given a homotopy $g: X \times I \to B$ and a map $\tilde{g}_0: X \times \{0\} \to E$ lifting $g(x, 0)$, so $p\tilde{g}_0(t, 0) = g(t, 0)$, then there exists a homotopy $\tilde{g}: X \times I \to E$ lifting g_t.

$$\begin{tikzcd}
X \times \{0\} \arrow[r, "\tilde{g}_0"] \arrow[d, hook] & E \arrow[d, "p"] \\
X \times I \arrow[r, "g"'] \arrow[ur, dashed, "\tilde{g}"] & B
\end{tikzcd}$$

This is a special case of the *lift extension property for a pair* (Z, A) (See [6])

Definition 9.6 (Fibration)**.** A fibration is a map $p: E \to B$ having the homotopy lifting property with respect to all spaces X. For example, a projection $B \times F \to B$ is a fibration since we can choose lifts of the form $\tilde{g}(x, t) = (g(x, t), h(x))$ where $\tilde{g}(x, 0) = (g(x, 0), h(x))$.

Definition 9.7 (Homotopy lifting property for a pair (X, A))**.** The map $p: E \to B$ is said to have the *homotopy lifting property for a pair* (X, A) if each homotopy $f: X \times I \to B$ lifts to a homotopy $\tilde{g}: X \times I \to E$ starting with a given lift $\tilde{g}_0: X \times \{0\} \to E$ and extending a given lift $\tilde{g}: A \times I \to E$.

Theorem 9.8. *Suppose $p: E \to B$ has the homotopy lifting property with respect to disks D^k for all $k \geqslant 0$. Choose basepoints $b_0 \in B$ and $x_0 \in F = p^{-1}(b_0)$. Then the map $p_*: \pi_n(E, F, x_0) \to \pi_n(B, b_0)$ is an isomorphism for all $n \geqslant 1$. Hence if B is path-connected, there is a long exact sequence*

$$\ldots \to \pi_n(F, x_0) \to \pi_n(E, x_0) \xrightarrow{p_*} \pi_n(B, b_0) \to \pi_{n-1}(F, x_0) \to \ldots \to \pi_0(E, x_0) \to 0$$

Definition 9.9 (Fiber bundle)**.** A fiber bundle structure on a space E, with fiber F, consists of a projection map $p\colon E \to B$ such that each point of B has a neighborhood U for which there is a homeomorphism $h\colon p^{-1}(U) \to U \times F$ making the following diagram commute

$$\begin{tikzcd} p^{-1}(U) \arrow[rr, "h"] \arrow[dr, "p"'] & & U \times F \arrow[dl, "proj"] \\ & U & \end{tikzcd}$$

Thus $h\left(p^{-1}(b)\right) = \{b\} \times F$ by the projection map $p\colon E \to B$, but to indicate what the fiber is we sometimes write a fiber bundle as $F \to E \to B$, a "short exact sequence of spaces". The space B is called the *base space* of the bundle, and E is the *total space*.

Remark. This is just the definition of a covering map without the restriction of F having the discrete topology.

9.2. **A couple of results on hyperelliptic involutions.**

Lemma 9.10. *If S is a Riemann surface of genus $g \geqslant 2$ admitting an involution J such that $S/\langle J\rangle$ has genus 0, then S is a hyperelliptic Riemann surface with equation of the form $y^2 = (x-a_1)\cdots(x-a_{2g+1})$*

Proposition 9.11. *The hyperelliptic involution J of a hyperelliptic Riemann surface S is the only automorphism of order 2 such that $S/\langle J\rangle \approx \mathbb{P}^1$.*

Corollary 9.12. *The hyperelliptic involution J of a hyperelliptic Riemann surface lies in the center of* $\mathrm{Aut}(S)$.

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