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Endomorphisms of Artin groups of type D

FABRICE CASTEL

LUIS PARIS

Abstract In this paper we determine a classification of the endomorphisms of the Artin group of type D_n for $n \geq 6$. In particular we determine its automorphism group and its outer automorphism group. We also determine a classification of the homomorphisms from the Artin group of type D_n to the Artin group of type A_{n-1} and a classification of the homomorphisms from the Artin group of type A_{n-1} to the Artin group of type D_n for $n \geq 6$. The results are algebraic in nature but the proofs are based on topological arguments (curves on surfaces and mapping class groups).

AMS Subject Classification Primary: 20F36. Secondary: 57K20.

Keywords Artin groups of type D , endomorphisms, automorphisms, mapping class groups.

1 Introduction

Let S be a finite set. A *Coxeter matrix* over S is a square matrix $M = (m_{s,t})_{s,t \in S}$ indexed by the elements of S , with coefficients in $\mathbb{N} \cup \{\infty\}$, such that $m_{s,s} = 1$ for all $s \in S$ and $m_{s,t} = m_{t,s} \geq 2$ for all $s, t \in S$, $s \neq t$. Such a matrix is usually represented by a labeled graph Γ , called a *Coxeter graph*, defined as follows. The set of vertices of Γ is S . Two vertices $s, t \in S$ are connected by an edge if $m_{s,t} \geq 3$, and this edge is labeled with $m_{s,t}$ if $m_{s,t} \geq 4$.

If a, b are two letters and m is an integer ≥ 2 , then we denote by $\Pi(a, b, m)$ the word $aba \cdots$ of length m . In other words $\Pi(a, b, m) = (ab)^{\frac{m}{2}}$ if m is even and $\Pi(a, b, m) = (ab)^{\frac{m-1}{2}}a$ if m is odd. Let Γ be a Coxeter graph and let $M = (m_{s,t})_{s,t \in S}$ be its Coxeter matrix. With Γ we associate a group $A[\Gamma]$, called the *Artin group* of Γ , defined by the following presentation.

$$A[\Gamma] = \langle S \mid \Pi(s, t, m_{s,t}) = \Pi(t, s, m_{s,t}) \text{ for } s, t \in S, s \neq t, m_{s,t} \neq \infty \rangle.$$

The *Coxeter group* of Γ , denoted $W[\Gamma]$, is the quotient of $A[\Gamma]$ by the relations $s^2 = 1$, $s \in S$.

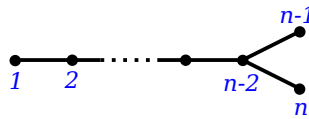
Despite the popularity of Artin groups little is known on their automorphisms and even less on their endomorphisms. The most emblematic cases are the braid groups and the right-angled Artin groups. Recall that the *braid group* on $n + 1$ strands is the Artin group $A[A_n]$ where A_n is the Coxeter graph depicted in Figure 1.1, and an Artin group $A[\Gamma]$ is called a *right-angled Artin group* if $m_{s,t} \in \{2, \infty\}$ for all $s, t \in S$, $s \neq t$. The automorphism group of $A[A_n]$ was determined by Dyer–Grossman [23] and the set of its endomorphisms by Castel [11] for $n \geq 6$ and by Chen–Kordek–Margalit [15] for $n \geq 5$ (see also Bell–Margalit [1]). On the other hand there are many articles studying automorphism groups of right-angled Artin groups (see Charney–Vogtmann [13, 14], Day [20, 21], Laurence [29] and Bregman–Charney–Vogtmann [6] for example), but almost nothing (or too much) is known on endomorphisms of these groups.

Figure 1.1: Coxeter graph A_n

Apart from these two families little is known on automorphisms of Artin groups. The automorphism groups of two generators Artin groups were determined in Gilbert–Howie–Metaftsis–Raptis [26], the automorphism groups of the Artin groups of type B_n , \tilde{A}_n and \tilde{C}_n were determined in Charney–Crisp [12], the automorphisms groups of some 2-dimensional Artin groups were determined in Crisp [18], and the automorphism group of $A[D_4]$ was determined in Soroko [36]. On the other hand, as far as we know the set of endomorphisms of an Artin group is not determined for any Artin group except for those of type A .

Recall that an Artin group $A[\Gamma]$ is of *spherical type* if $W[\Gamma]$ is finite. The study of spherical-type Artin groups began in the early 1970s with works by Brieskorn [7, 8], Brieskorn–Saito [9] and Deligne [22], works that marked in a way the beginning of the theory of Artin groups. This family and that of right-angled Artin groups are the two most studied and best understood families of Artin groups and, obviously, any question on Artin groups first arises for Artin groups of spherical type and for right-angled Artin groups. Here we are interested in Artin groups of spherical type and more particularly in those of type D .

An Artin group $A[\Gamma]$ is called *irreducible* if Γ is connected. If $\Gamma_1, \dots, \Gamma_\ell$ are the connected components of Γ , then $A[\Gamma] = A[\Gamma_1] \times \dots \times A[\Gamma_\ell]$ and $W[\Gamma] = W[\Gamma_1] \times \dots \times W[\Gamma_\ell]$. In particular $A[\Gamma]$ is of spherical type if and only if $A[\Gamma_i]$ is of spherical type for all $i \in \{1, \dots, \ell\}$. So, to classify Artin groups of spherical type it suffices to classify those which are irreducible. Finite irreducible Coxeter groups and hence irreducible Artin groups of spherical type were classified by Coxeter [16, 17]. There are four infinite families, A_n ($n \geq 1$), B_n ($n \geq 2$), D_n ($n \geq 4$) and $I_2(m)$ ($m \geq 5$), and six ‘‘sporadic’’ groups, E_6 , E_7 , E_8 , F_4 , H_3 and H_4 . As mentioned above, the automorphism group of $A[\Gamma]$ for Γ of type A_n ($n \geq 1$), B_n ($n \geq 2$) and $I_2(m)$ ($m \geq 5$) is known. The next step is therefore to understand the automorphism group of $A[D_n]$ for $n \geq 5$ (the case $\Gamma = D_4$ is known by Soroko [36]). The Coxeter graph D_n is illustrated in Figure 1.2.

Figure 1.2: Coxeter graph D_n

In this paper we determine a complete and precise classification of the endomorphisms of $A[D_n]$ for $n \geq 6$ (see Theorem 2.3). In particular we determine the automorphism group and the outer automorphism group of $A[D_n]$ for $n \geq 6$ (see Corollary 2.6). We also determine a complete and precise classification of the homomorphisms from $A[D_n]$ to $A[A_{n-1}]$ (see Theorem 2.1) and a complete and precise classification of the homomorphisms from $A[A_{n-1}]$ to $A[D_n]$ (see Theorem 2.2). Note that all these results were announced but not proved in Castel [11]; actually the proofs turn out to be much more difficult than the first author thought when he announced them. Note also that our techniques cannot be used to treat the cases $n = 4$ and $n = 5$. In particular we do not know how to determine $\text{Aut}(A[D_5])$.

A *geometric representation* of an Artin group is a homomorphism from the group to a mapping class group (see Section 3 for more details). In order to achieve our goals we make a study of a particular geometric representation of $A[D_n]$. In particular we prove that this representation is faithful (see Theorem 3.6). This geometric representation is a variation of a geometric representation previously introduced by Perron–Vannier [35], and its study is interesting by itself independently of its applications to Artin groups of type D . Overall, although the results of the paper are algebraic in nature, the proofs are mostly based on topological arguments (on curves on surfaces and mapping class groups).

The paper is organized as follows. In Section 2 we give the main definitions and precise statements of the main results. Section 3 is dedicated to the study of some geometric representations of Artin groups of type A and type D . In Section 4 we determine the homomorphisms from $A[D_n]$ to $A[A_{n-1}]$, in Section 5 we determine the homomorphisms from $A[A_{n-1}]$ to $A[D_n]$, and in Section 6 we determine the endomorphisms of $A[D_n]$.

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2 Definitions and statements

For $n \geq 4$ we denote by s_1, \dots, s_{n-1} the standard generators of $A[A_{n-1}]$ numbered as in Figure 1.1 and by t_1, \dots, t_n the standard generators of $A[D_n]$ numbered as in Figure 1.2.

Let Γ be a Coxeter graph. For $X \subset S$ we denote by $A_X = A_X[\Gamma]$ the subgroup of $A = A[\Gamma]$ generated by X , by $W_X = W_X[\Gamma]$ the subgroup of $W = W[\Gamma]$ generated by X , and by Γ_X the full subgraph of Γ spanned by X . We know from van der Lek [30] that A_X is the Artin group of Γ_X and from Bourbaki [5] that W_X is the Coxeter group of Γ_X . A subgroup of the form A_X is called a *standard parabolic subgroup* of A and a subgroup of the form W_X is called a *standard parabolic subgroup* of W .

For $w \in W$ we denote by $\text{lg}(w)$ the word length of w with respect to S . A *reduced expression* for w is an expression $w = s_1 s_2 \cdots s_\ell$ of minimal length, that is, such that $\ell = \text{lg}(w)$. Let $\omega : A \rightarrow W$ be the natural epimorphism which sends s to s for all $s \in S$. This epimorphism has a natural set-section $\tau : W \rightarrow A$ defined as follows. Let $w \in W$ and let $w = s_1 s_2 \cdots s_\ell$ be a reduced expression for w . Then $\tau(w) = s_1 s_2 \cdots s_\ell \in A$. We know from Tits [37] that the definition of $\tau(w)$ does not depend on the choice of its reduced expression.

Assume Γ is of spherical type. Then W has a unique element of maximal length, denoted w_S , which satisfies $w_S^2 = 1$ and $w_S w_S = S$. The *Garside element* of A is defined to be $\Delta = \Delta[\Gamma] = \tau(w_S)$. We know that $\Delta S \Delta^{-1} = S$ and, if Γ is connected, then the center $Z(A)$ of A is an infinite cyclic group generated by either Δ or Δ^2 (see Brieskorn–Saito [9]). For $X \subset S$ we denote by w_X the element of maximal length in W_X and by $\Delta_X = \Delta_X[\Gamma] = \tau(w_X)$ the Garside element of A_X .

If $\Gamma = A_{n-1}$, then

$$\Delta = (s_{n-1} \cdots s_1)(s_{n-1} \cdots s_2) \cdots (s_{n-1} s_{n-2}) s_{n-1},$$

$\Delta s_i \Delta^{-1} = s_{n-i}$ for all $1 \leq i \leq n-1$ and $Z(A)$ is generated by Δ^2 . If $\Gamma = D_n$, then

$$\Delta = (t_1 \cdots t_{n-2} t_{n-1} t_n t_{n-2} \cdots t_1)(t_2 \cdots t_{n-2} t_{n-1} t_n t_{n-2} \cdots t_2) \cdots (t_{n-2} t_{n-1} t_n t_{n-2})(t_{n-1} t_n).$$

If n is even, then $\Delta t_i \Delta^{-1} = t_i$ for all $1 \leq i \leq n$ and $Z(A)$ is generated by Δ . If n is odd, then $\Delta t_i \Delta^{-1} = t_i$ for all $1 \leq i \leq n-2$, $\Delta t_{n-1} \Delta^{-1} = t_n$, $\Delta t_n \Delta^{-1} = t_{n-1}$, and $Z(A)$ is generated by Δ^2 .

If G is a group and $g \in G$, then we denote by $\text{ad}_g : G \rightarrow G$, $h \mapsto ghg^{-1}$, the conjugation map by g . We say that two homomorphisms $\varphi_1, \varphi_2 : G \rightarrow H$ are *conjugate* if there exists $h \in H$ such that $\varphi_2 = \text{ad}_h \circ \varphi_1$.

A homomorphism $\varphi : G \rightarrow H$ is called *abelian* if its image is an abelian subgroup of H . A homomorphism $\varphi : G \rightarrow H$ is called *cyclic* if its image is a cyclic subgroup of H . If $G = A[A_{n-1}]$, then $\varphi : A[A_{n-1}] \rightarrow H$ is abelian if and only if it is cyclic, if and only if there exists $h \in H$ such that $\varphi(s_i) = h$ for all $1 \leq i \leq n-1$. Similarly, if $G = A[D_n]$, then $\varphi : A[D_n] \rightarrow H$ is abelian if and only if it is cyclic, if and only if there exists $h \in H$ such that $\varphi(t_i) = h$ for all $1 \leq i \leq n$.

Two automorphisms $\zeta, \chi \in \text{Aut}(A[D_n])$ play a central role in our study. These are defined by

$$\begin{aligned} \zeta(t_i) &= t_i \text{ for } 1 \leq i \leq n-2, \quad \zeta(t_{n-1}) = t_n, \quad \zeta(t_n) = t_{n-1}, \\ \chi(t_i) &= t_i^{-1} \text{ for } 1 \leq i \leq n. \end{aligned}$$

Both are of order 2 and commute, hence they generate a subgroup of $\text{Aut}(A[D_n])$ isomorphic to $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$. If n is odd, then ζ is the conjugation map by $\Delta = \Delta[D_n]$. On the other hand, if n is even, then ζ is not an inner automorphism (see Paris [32]). The automorphism χ is never inner.

Two other homomorphisms play an important role in our study. The first, $\pi : A[D_n] \rightarrow A[A_{n-1}]$, is defined by

$$\pi(t_i) = s_i \text{ for } 1 \leq i \leq n-2, \quad \pi(t_{n-1}) = \pi(t_n) = s_{n-1}.$$

The second, $\iota : A[A_{n-1}] \rightarrow A[D_n]$, is defined by

$$\iota(s_i) = t_i \text{ for } 1 \leq i \leq n-1.$$

Observe that $\pi \circ \iota = \text{id}_{A[A_{n-1}]}$, hence π is surjective, ι is injective, and $A[D_n] \simeq \text{Ker}(\pi) \rtimes A[A_{n-1}]$. We refer to Crisp–Paris [19] for a detailed study on this decomposition of $A[D_n]$ as a semi-direct product.

Let $n \geq 4$. For $p \in \mathbb{Z}$ we define a homomorphism $\alpha_p : A[D_n] \rightarrow A[A_{n-1}]$ by

$$\alpha_p(t_i) = s_i \Delta^{2p} \text{ for } 1 \leq i \leq n-2, \quad \alpha_p(t_{n-1}) = \alpha_p(t_n) = s_{n-1} \Delta^{2p},$$

where $\Delta = \Delta[A_{n-1}]$ is the Garside element of $A[A_{n-1}]$. Note that $\alpha_0 = \pi$. Set $Y = \{t_1, \dots, t_{n-1}\}$. For $p, q \in \mathbb{Z}$ we define a homomorphism $\beta_{p,q} : A[A_{n-1}] \rightarrow A[D_n]$ by

$$\beta_{p,q}(s_i) = t_i \Delta_Y^{2p} \Delta^{\kappa q} \text{ for } 1 \leq i \leq n-1,$$

where $\Delta = \Delta[D_n]$ is the Garside element of $A[D_n]$, $\Delta_Y = \Delta_Y[D_n]$, $\kappa = 2$ if n is odd, and $\kappa = 1$ if n is even. Note that $\beta_{0,0} = \iota$. Note also that, by Paris [32, Theorem 1.1], the centralizer of Y in $A[D_n]$ is the free abelian group of rank 2 generated by Δ_Y^2 and Δ^κ . For $p \in \mathbb{Z}$ we define the homomorphism $\gamma_p : A[D_n] \rightarrow A[D_n]$ by

$$\gamma_p(t_i) = t_i \Delta^{\kappa p} \text{ for } 1 \leq i \leq n,$$

where $\Delta = \Delta[D_n]$ is the Garside element of $A[D_n]$, $\kappa = 2$ if n is odd, and $\kappa = 1$ if n is even. Note that $\gamma_0 = \text{id}$.

The main results of this paper are the following.

Theorem 2.1 Let $n \geq 6$. Let $\varphi : A[D_n] \rightarrow A[A_{n-1}]$ be a homomorphism. Then up to conjugation we have one of the following two possibilities.

- (1) φ is cyclic.
- (2) There exist $\psi \in \langle \chi \rangle$ and $p \in \mathbb{Z}$ such that $\varphi = \alpha_p \circ \psi$.

Theorem 2.2 Let $n \geq 6$. Let $\varphi : A[A_{n-1}] \rightarrow A[D_n]$ be a homomorphism. Then up to conjugation we have one of the following two possibilities.

- (1) φ is cyclic.
- (2) There exist $\psi \in \langle \zeta, \chi \rangle$ and $p, q \in \mathbb{Z}$ such that $\varphi = \psi \circ \beta_{p,q}$.

Theorem 2.3 Let $n \geq 6$. Let $\varphi : A[D_n] \rightarrow A[D_n]$ be a homomorphism. Then up to conjugation we have one of the following three possibilities.

- (1) φ is cyclic.
- (2) There exist $\psi \in \langle \zeta, \chi \rangle$ and $p, q \in \mathbb{Z}$ such that $\varphi = \psi \circ \beta_{p,q} \circ \pi$.
- (3) There exist $\psi \in \langle \zeta, \chi \rangle$ and $p \in \mathbb{Z}$ such that $\varphi = \psi \circ \gamma_p$.

From Theorem 2.3 we deduce a classification of the injective endomorphisms and of the automorphisms of $A[D_n]$ as follows.

Corollary 2.4 Let $n \geq 6$. Let $\varphi : A[D_n] \rightarrow A[D_n]$ be an endomorphism. Then φ is injective if and only if there exist $\psi \in \langle \zeta, \chi \rangle$ and $p \in \mathbb{Z}$ such that φ is conjugate to $\psi \circ \gamma_p$.

Proof Let $\varphi : A[D_n] \rightarrow A[D_n]$ be an endomorphism. By Theorem 2.3 we have one of the following three possibilities up to conjugation.

- (1) φ is cyclic.
- (2) There exist $\psi \in \langle \zeta, \chi \rangle$ and $p, q \in \mathbb{Z}$ such that $\varphi = \psi \circ \beta_{p,q} \circ \pi$.
- (3) There exist $\psi \in \langle \zeta, \chi \rangle$ and $p \in \mathbb{Z}$ such that $\varphi = \psi \circ \gamma_p$.

If φ is cyclic, then $\varphi(t_{n-1}) = \varphi(t_n)$, hence φ is not injective. If there exist $\psi \in \langle \zeta, \chi \rangle$ and $p, q \in \mathbb{Z}$ such that $\varphi = \psi \circ \beta_{p,q} \circ \pi$, then, again, $\varphi(t_{n-1}) = \varphi(t_n)$, hence φ is not injective. So, if φ is injective, then there exist $\psi \in \langle \zeta, \chi \rangle$ and $p \in \mathbb{Z}$ such that φ is conjugate to $\psi \circ \gamma_p$.

It remains to show that, if $\psi \in \langle \zeta, \chi \rangle$ and $p \in \mathbb{Z}$, then $\psi \circ \gamma_p$ is injective. Since the elements of $\langle \zeta, \chi \rangle$ are automorphisms, it suffices to show that γ_p is injective. We denote by $z : A[D_n] \rightarrow \mathbb{Z}$ the homomorphism which sends t_i to 1 for all $1 \leq i \leq n$. It is easily seen that $\gamma_p(u) = u \Delta^{\kappa p z(u)}$ for all $u \in A[D_n]$. Let $u \in \text{Ker}(\gamma_p)$. Then $1 = \gamma_p(u) = u \Delta^{\kappa p z(u)}$, hence $u = \Delta^q$ where $q = -\kappa p z(u)$. We have $z(\Delta) = n(n-1)$, hence $z(u) = qn(n-1)$, thus

$$1 = \gamma_p(u) = \Delta^q \Delta^{\kappa p q n(n-1)} = \Delta^{q(1 + \kappa p n(n-1))}.$$

Since $1 + \kappa p n(n-1) \neq 0$, this equality implies that $q = 0$, hence $u = 1$. So, γ_p is injective. \square

Corollary 2.5 *Let $n \geq 6$. Let $\varphi : A[D_n] \rightarrow A[D_n]$ be an endomorphism. Then φ is an automorphism if and only if it is conjugate to an element of $\langle \zeta, \chi \rangle$.*

Proof Clearly, if φ is conjugate to an element of $\langle \zeta, \chi \rangle$, then φ is an automorphism. Conversely, suppose that φ is an automorphism. We know from Corollary 2.4 that there exist $\psi \in \langle \zeta, \chi \rangle$ and $p \in \mathbb{Z}$ such that φ is conjugate to $\psi \circ \gamma_p$. Thus, up to conjugation and up to composing on the left by ψ^{-1} , we can assume that $\varphi = \gamma_p$. It remains to show that $p = 0$.

Let again $z : A[D_n] \rightarrow \mathbb{Z}$ be the homomorphism which sends t_i to 1 for all $1 \leq i \leq n$. Recall that $\gamma_p(u) = u\Delta^{\kappa p z(u)}$ for all $u \in A[D_n]$. For $u \in A[D_n]$, we have

$$(z \circ \gamma_p)(u) = (1 + n(n-1)\kappa p)z(u) \in (1 + n(n-1)\kappa p)\mathbb{Z}.$$

Since γ_p is an automorphism, $z \circ \gamma_p$ is surjective, hence $\mathbb{Z} = \text{Im}(z \circ \gamma_p) \subset (1 + n(n-1)\kappa p)\mathbb{Z}$. It follows that $(1 + n(n-1)\kappa p) \in \{\pm 1\}$, hence $p = 0$. \square

By combining Corollary 2.5 with Crisp–Paris [19, Theorem 4.9] we immediately obtain the following.

Corollary 2.6 *Let $n \geq 6$.*

(1) *If n is even, then*

$$\text{Aut}(A[D_n]) = \text{Inn}(A[D_n]) \rtimes \langle \zeta, \chi \rangle \simeq (A[D_n]/Z(A[D_n])) \rtimes (\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}),$$

and $\text{Out}(A[D_n]) \simeq \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$, where $Z(A[D_n])$ denotes the center of $A[D_n]$.

(2) *If n is odd, then*

$$\text{Aut}(A[D_n]) = \text{Inn}(A[D_n]) \rtimes \langle \chi \rangle \simeq (A[D_n]/Z(A[D_n])) \rtimes (\mathbb{Z}/2\mathbb{Z}),$$

and $\text{Out}(A[D_n]) \simeq \mathbb{Z}/2\mathbb{Z}$.

3 Geometric representations

Let Σ be an oriented compact surface possibly with boundary, and let \mathcal{P} be a finite set of punctures in the interior of Σ . We denote by $\text{Homeo}^+(\Sigma, \mathcal{P})$ the group of homeomorphisms of Σ that preserve the orientation, that are the identity on a neighborhood of the boundary of Σ , and that setwise leave invariant \mathcal{P} . The *mapping class group* of the pair (Σ, \mathcal{P}) , denoted $\mathcal{M}(\Sigma, \mathcal{P})$, is the group of isotopy classes of elements of $\text{Homeo}^+(\Sigma, \mathcal{P})$. If $\mathcal{P} = \emptyset$, then we write $\mathcal{M}(\Sigma, \emptyset) = \mathcal{M}(\Sigma)$, and if $\mathcal{P} = \{x\}$ is a singleton, then we write $\mathcal{M}(\Sigma, \mathcal{P}) = \mathcal{M}(\Sigma, x)$. We only give definitions and results on mapping class groups that we need for our proofs and we refer to Farb–Margalit [25] for a complete account on the subject.

Recall that a *geometric representation* of an Artin group A is a homomorphism from A to a mapping class group. Their study is the main ingredient of our proofs. Important tools for constructing and understanding them are Dehn twists and essential reduction systems. So, we start by recalling their definitions and their main properties.

A *circle* of (Σ, \mathcal{P}) is an embedding $a : \mathbb{S}^1 \hookrightarrow \Sigma \setminus (\partial\Sigma \cup \mathcal{P})$. It is called *generic* if it does not bound any disk containing 0 or 1 puncture and if it is not parallel to any boundary component. The isotopy class of a circle a is denoted by $[a]$. We denote by $\mathcal{C}(\Sigma, \mathcal{P})$ the set of isotopy classes of generic circles of (Σ, \mathcal{P}) . The *intersection number* of two classes $[a], [b] \in \mathcal{C}(\Sigma, \mathcal{P})$ is $i([a], [b]) = \min\{|a' \cap b'| \mid a' \in [a] \text{ and } b' \in [b]\}$. The set $\mathcal{C}(\Sigma, \mathcal{P})$ is endowed with a simplicial complex structure, where a finite set \mathcal{A} is a simplex if $i([a], [b]) = 0$ for all $[a], [b] \in \mathcal{A}$. This complex is called the *curve complex* of (Σ, \mathcal{P}) .

In this paper the Dehn twist along a circle a of (Σ, \mathcal{P}) will be denoted by T_a . The following is an important tool for constructing and understanding geometric representations of Artin groups. Its proof can be found in Farb–Margalit [25, Section 3.5].

Proposition 3.1 *Let Σ be a compact oriented surface and let \mathcal{P} be a finite collection of punctures in the interior of Σ . Let a, b be two generic circles of (Σ, \mathcal{P}) .*

- (1) *We have $T_a T_b = T_b T_a$ if and only if $i([a], [b]) = 0$.*
- (2) *We have $T_a T_b T_a = T_b T_a T_b$ if and only if $i([a], [b]) = 1$.*

Let $f \in \mathcal{M}(\Sigma, \mathcal{P})$. A simplex \mathcal{A} of $\mathcal{C}(\Sigma, \mathcal{P})$ is called a *reduction system* for f if $f(\mathcal{A}) = \mathcal{A}$. In that case any element of \mathcal{A} is called a *reduction class* for f . A reduction class $[a]$ is an *essential reduction class* if, for all $[b] \in \mathcal{C}(\Sigma, \mathcal{P})$ such that $i([a], [b]) \neq 0$ and for all $m \in \mathbb{Z} \setminus \{0\}$, we have $f^m([b]) \neq [b]$. In particular, if $[a]$ is an essential reduction class and $[b]$ is any reduction class, then $i([a], [b]) = 0$. We denote by $\mathcal{S}(f)$ the set of reduction classes for f . The following gathers some key results on $\mathcal{S}(f)$ that will be useful later.

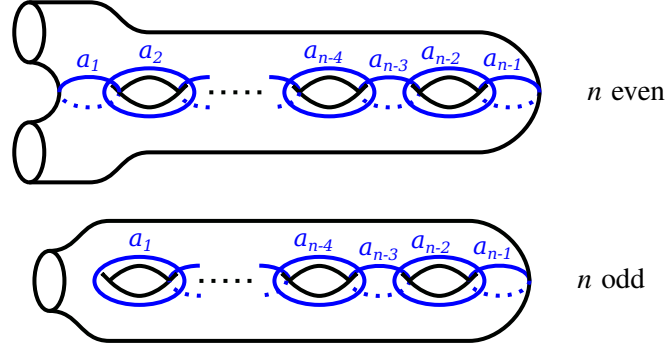
Theorem 3.2 (Birman–Lubotzky–McCarthy [3]) *Let Σ be a compact oriented surface and let \mathcal{P} be a finite set of punctures in the interior of Σ . Let $f \in \mathcal{M}(\Sigma, \mathcal{P})$.*

- (1) *If $\mathcal{S}(f) \neq \emptyset$, then $\mathcal{S}(f)$ is a reduction system for f . In particular, if $\mathcal{S}(f) \neq \emptyset$, then $\mathcal{S}(f)$ is a simplex of $\mathcal{C}(\Sigma, \mathcal{P})$.*
- (2) *We have $\mathcal{S}(f^n) = \mathcal{S}(f)$ for all $n \in \mathbb{Z} \setminus \{0\}$.*
- (3) *We have $\mathcal{S}(gfg^{-1}) = g(\mathcal{S}(f))$ for all $g \in \mathcal{M}(\Sigma, \mathcal{P})$.*

The following is well-known and it is a direct consequence of Birman–Lubotzky–McCarthy [3]. It will be often used in our proofs.

Proposition 3.3 *Let Σ be an oriented compact surface of genus ≥ 2 and let \mathcal{P} a finite set of punctures in the interior of Σ . Let $f_0 \in Z(\mathcal{M}(\Sigma, \mathcal{P}))$ be a central element of $\mathcal{M}(\Sigma, \mathcal{P})$, let $\mathcal{A} = \{[a_1], \dots, [a_p]\}$ be a simplex of $\mathcal{C}(\Sigma, \mathcal{P})$, and let k_1, \dots, k_p be nonzero integers. Let $g = T_{a_1}^{k_1} T_{a_2}^{k_2} \dots T_{a_p}^{k_p} f_0$. Then $\mathcal{S}(g) = \mathcal{A}$.*

Let $n \geq 4$. If n is even, then Σ_n denotes the surface of genus $\frac{n-2}{2}$ with two boundary components, and if n is odd, then Σ_n denotes the surface of genus $\frac{n-1}{2}$ with one boundary component. Consider the circles a_1, \dots, a_{n-1} drawn in Figure 3.1. Then by Proposition 3.1 we have a geometric representation $\rho_A : A[A_{n-1}] \rightarrow \mathcal{M}(\Sigma_n)$ which sends s_i to T_{a_i} for all $1 \leq i \leq n-1$. The following is well-known, it is a direct consequence of Birman–Hilden [4], and its proof is explicitly given in Perron–Vannier [35].

Figure 3.1: Geometric representation of $A[A_{n-1}]$

Theorem 3.4 (Birman–Hilden [4]) *Let $n \geq 4$. Then $\rho_A : A[A_{n-1}] \rightarrow \mathcal{M}(\Sigma_n)$ is injective.*

We denote by $\bar{\chi} : A[A_{n-1}] \rightarrow A[A_{n-1}]$ the automorphism defined by

$$\bar{\chi}(s_i) = s_i^{-1} \text{ for } 1 \leq i \leq n-1.$$

On the other hand, for $p \in \mathbb{Z}$ we denote by $\bar{\gamma}_p : A[A_{n-1}] \rightarrow A[A_{n-1}]$ the homomorphism defined by

$$\bar{\gamma}_p(s_i) = s_i \Delta^{2p} \text{ for } 1 \leq i \leq n-1,$$

where Δ is the Garside element of $A[A_{n-1}]$. The following is proved in Castel [10] for $n \geq 6$ using the geometric representation ρ_A defined above. It is proved in Chen–Kordek–Margalit [15] for $n \geq 5$ with a different method.

Theorem 3.5 (Castel [10], Chen–Kordek–Margalit [15]) *Let $n \geq 5$. Let $\varphi : A[A_{n-1}] \rightarrow A[A_{n-1}]$ be a homomorphism. Then up to conjugation we have one of the following two possibilities.*

- (1) φ is cyclic.
- (2) There exist $\psi \in \langle \bar{\chi} \rangle$ and $p \in \mathbb{Z}$ such that $\varphi = \psi \circ \bar{\gamma}_p$.

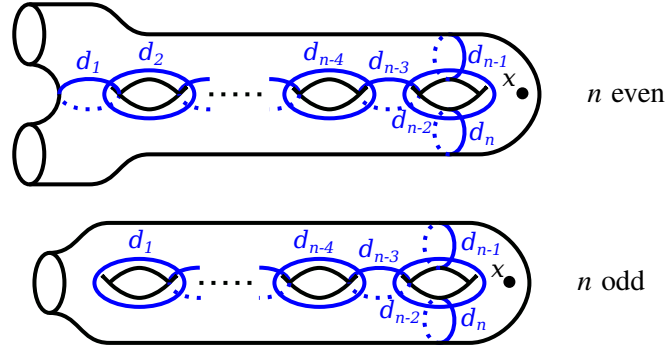
Let $n \geq 6$. Pick a puncture x in the interior of Σ_n and consider the circles d_1, \dots, d_n drawn in Figure 3.2. Then by Proposition 3.1 we have a geometric representation $\rho_D : A[D_n] \rightarrow \mathcal{M}(\Sigma_n, x)$ which sends t_i to T_{d_i} for all $1 \leq i \leq n$. On the other hand, the embedding of $\text{Homeo}^+(\Sigma_n, x)$ into $\text{Homeo}^+(\Sigma_n)$ induces a surjective homomorphism $\theta : \mathcal{M}(\Sigma_n, x) \rightarrow \mathcal{M}(\Sigma_n)$ whose kernel is naturally isomorphic to $\pi_1(\Sigma_n, x)$ (see Birman [2]). It is easily seen that

$$\theta(T_{d_i}) = T_{a_i} \text{ for } 1 \leq i \leq n-2, \theta(T_{d_{n-1}}) = \theta(T_{d_n}) = T_{a_{n-1}},$$

hence we have the following commutative diagram:

$$(3-1) \quad \begin{array}{ccccccc} 1 & \longrightarrow & \text{Ker}(\pi) & \longrightarrow & A[D_n] & \xrightarrow{\pi} & A[A_{n-1}] \longrightarrow 1 \\ & & \downarrow & & \downarrow \rho_D & & \downarrow \rho_A \\ 1 & \longrightarrow & \text{Ker}(\theta) & \longrightarrow & \mathcal{M}(\Sigma_n, x) & \xrightarrow{\theta} & \mathcal{M}(\Sigma_n) \longrightarrow 1 \end{array}$$

We denote by $\bar{\rho} : \text{Ker}(\pi) \rightarrow \text{Ker}(\theta)$ the restriction of ρ_D to $\text{Ker}(\pi)$. The following is implicitly proved in Perron–Vannier [35, Theorem 1].

Figure 3.2: Geometric representation of $A[D_n]$

Theorem 3.6 Let $n \geq 4$.

- (1) The homomorphism $\bar{\rho} : \text{Ker}(\pi) \rightarrow \text{Ker}(\theta)$ is an isomorphism.
- (2) The geometric representation $\rho_D : A[D_n] \rightarrow \mathcal{M}(\Sigma_n, x)$ is injective.

Proof Part (2) is a consequence of Part (1) because of the following. Suppose $\bar{\rho}$ is an isomorphism. Then, since ρ_A is injective, ρ_D is injective by the five lemma applied to the diagram of Equation (3–1).

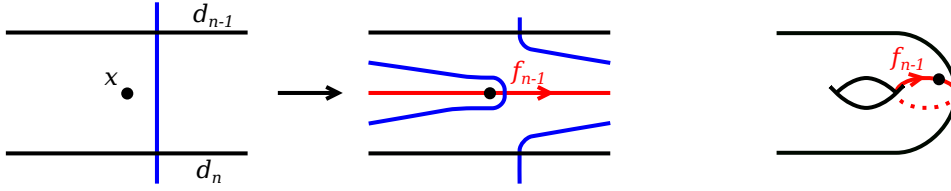
Now, we prove Part (1). We know from Crisp–Paris [19, Proposition 2.3] that $\text{Ker}(\pi)$ is a free group of rank $n - 1$. We also know from Birman [2] that $\text{Ker}(\theta) = \pi_1(\Sigma_n, x)$, which is also a free group of rank $n - 1$. Recall that a group G is Hopfian if every surjective endomorphism $G \rightarrow G$ is an isomorphism. It is well-known that free groups of finite rank are Hopfian (see de la Harpe [27, Chapter III, Section 19]), hence in order to show that $\bar{\rho}$ is an isomorphism it suffices to show that $\bar{\rho}$ is surjective.

Set $f_{n-1} = T_{d_{n-1}}^{-1} T_{d_n}$. Note that $t_{n-1}^{-1} t_n \in \text{Ker}(\pi)$ and $f_{n-1} = \bar{\rho}(t_{n-1}^{-1} t_n)$. In particular $f_{n-1} \in \text{Im}(\bar{\rho}) \subset \text{Ker}(\theta) = \pi_1(\Sigma_n, x)$. This element, seen as an element of $\pi_1(\Sigma_n, x)$, is represented by the loop drawn in Figure 3.3. For $2 \leq i \leq n - 1$ we define $f_{n-i} \in \pi_1(\Sigma_n, x) \subset \mathcal{M}(\Sigma_n, x)$ by induction on i by setting $f_{n-i} = T_{d_{n-i}} f_{n-i+1} T_{d_{n-i}}^{-1} f_{n-i+1}^{-1}$. The element f_{n-i} , viewed as an element of $\pi_1(\Sigma_n, x)$, is represented by the loop drawn in the left-hand side of Figure 3.4 if $i = 2j$ is even, and by the loop drawn in the right-hand side of Figure 3.4 if $i = 2j + 1$ is odd, where we compose paths from right to left. Observe that f_1, \dots, f_{n-1} generate $\pi_1(\Sigma_n, x)$. So, in order to show that $\bar{\rho}$ is surjective, it suffices to show that $f_{n-i} \in \text{Im}(\bar{\rho})$ for all $i \in \{1, \dots, n - 1\}$. We argue by induction on i . We already know that $f_{n-1} = \bar{\rho}(t_{n-1}^{-1} t_n) \in \text{Im}(\bar{\rho})$. Suppose $i \geq 2$ and $f_{n-i+1} \in \text{Im}(\bar{\rho})$. Let $u \in \text{Ker}(\pi)$ such that $f_{n-i+1} = \bar{\rho}(u)$. Since $\text{Ker}(\pi)$ is a normal subgroup of $A[D_n]$, we have $t_{n-i} u t_{n-i}^{-1} \in \text{Ker}(\pi)$, hence $t_{n-i} u t_{n-i}^{-1} u^{-1} \in \text{Ker}(\pi)$, and therefore

$$f_{n-i} = T_{d_{n-i}} f_{n-i+1} T_{d_{n-i}}^{-1} f_{n-i+1}^{-1} = \bar{\rho}(t_{n-i} u t_{n-i}^{-1} u^{-1}) \in \text{Im}(\bar{\rho}). \quad \square$$

Our last preliminary on geometric representations is a particular case of Theorems 0.2.1 and 0.2.2 of Castel [11], and it is where we need the hypothesis $n \geq 6$.

Theorem 3.7 (Castel [11]) Let $n \geq 6$. Let $\varphi : A[A_{n-1}] \rightarrow \mathcal{M}(\Sigma_n, x)$ be a non-cyclic homomorphism. Then there exist generic circles c_1, \dots, c_{n-1} in $\Sigma_n \setminus \{x\}$, $\varepsilon \in \{\pm 1\}$ and $g \in \mathcal{M}(\Sigma_n, x)$ such that

Figure 3.3: The loop $f_{n-1} \in \pi_1(\Sigma_n, x)$ Figure 3.4: The loop $f_{n-i} \in \pi_1(\Sigma_n, x)$

- (a) $|c_i \cap c_j| = 1$ if $|i - j| = 1$ and $|c_i \cap c_j| = 0$ if $|i - j| \geq 2$, for all $1 \leq i, j \leq n - 1$,
- (b) g commutes with T_{c_i} for all $1 \leq i \leq n - 1$,
- (c) $\varphi(s_i) = T_{c_i}^{\varepsilon} g$ for all $1 \leq i \leq n - 1$.

4 Homomorphisms from $A[D_n]$ to $A[A_{n-1}]$

Proof of Theorem 2.1 Let $n \geq 6$. Let $\varphi : A[D_n] \rightarrow A[A_{n-1}]$ be a homomorphism. By Theorem 3.5 we know that one of the following two possibilities holds.

- $\varphi \circ \iota$ is cyclic.
- There exist $\psi \in \langle \bar{\chi} \rangle$ and $p \in \mathbb{Z}$ such that $\varphi \circ \iota$ is conjugate to $\psi \circ \bar{\gamma}_p$.

Suppose $\varphi \circ \iota$ is cyclic. Then there exists $u \in A[A_{n-1}]$ such that $(\varphi \circ \iota)(s_i) = \varphi(t_i) = u$ for all $1 \leq i \leq n - 1$. Moreover,

$$\varphi(t_n) = \varphi(t_{n-2}t_n) \varphi(t_{n-2}) \varphi(t_n^{-1}t_{n-2}^{-1}) = \varphi(t_{n-2}t_n) \varphi(t_1) \varphi(t_n^{-1}t_{n-2}^{-1}) = \varphi(t_1) = u,$$

hence φ is cyclic.

So, up to conjugating and replacing φ by $\varphi \circ \chi$ if necessary, we can assume that there exists $p \in \mathbb{Z}$ such that $\varphi \circ \iota = \bar{\gamma}_p$. This means that $\varphi(t_i) = (\varphi \circ \iota)(s_i) = s_i \Delta^{2p}$ for all $1 \leq i \leq n - 1$, where Δ is the Garside element of $A[A_{n-1}]$. Now we turn to show that $\varphi = \alpha_p$.

Set $Y = \{s_1, \dots, s_{n-3}\}$. By Paris [31, Theorem 5.1] the centralizer of $\langle s_1, \dots, s_{n-3}, s_{n-1} \rangle$ in $A[A_{n-1}]$ is generated by Δ^2 , Δ_Y^2 and s_{n-1} , where $\Delta_Y = \Delta_Y[A_{n-1}]$. These three elements pairwise commute and generate a copy of \mathbb{Z}^3 . Set $u = \varphi(t_n)$. Since u commutes with $\varphi(t_i) = s_i \Delta^{2p}$ for all $i \in \{1, \dots, n-3, n-1\}$ and Δ^2 in central in $A[A_{n-1}]$, u belongs to the centralizer of $\langle s_1, \dots, s_{n-3}, s_{n-1} \rangle$, hence there exist $k_1, k_2, k_3 \in \mathbb{Z}$ such that $u = s_{n-1}^{k_1} \Delta_Y^{2k_2} \Delta^{2k_3}$.

It is well-known that $A[A_{n-1}]$ is naturally isomorphic to the mapping class group $\mathcal{M}(\mathbb{D}, \mathcal{P})$, where \mathbb{D} denotes the disk and $\mathcal{P} = \{x_1, \dots, x_n\}$ is a set of n punctures in the interior of \mathbb{D} . In this identification

s_{n-1}^2 corresponds to the Dehn twist along the circle c_1 depicted in Figure 4.1, Δ_Y^2 corresponds to the Dehn twist along the circle c_2 depicted in the same figure, and Δ^2 corresponds to the Dehn twist along a circle parallel to $\partial\mathbb{D}$. By Proposition 3.3 we have $\mathcal{S}(u^2) \subseteq \{c_1, c_2\}$, where $c_1 \in \mathcal{S}(u^2)$ if and only if $k_1 \neq 0$ and $c_2 \in \mathcal{S}(u^2)$ if and only if $k_2 \neq 0$. We know that $\varphi(t_1^2) = s_1^2 \Delta^{4p}$, hence $\mathcal{S}(\varphi(t_1^2))$ is formed by a single circle containing two marked points in its interior. Since t_1^2 and t_n^2 are conjugate, $\varphi(t_1^2)$ and $\varphi(t_n^2) = u^2$ are conjugate, hence, by Theorem 3.2, $\mathcal{S}(u^2)$ is also formed by a single circle containing two marked points in its interior. It follows that $\mathcal{S}(u^2) = \{c_1\}$, hence $k_1 \neq 0$ and $k_2 = 0$. It remains to show that $k_1 = 1$ and $k_3 = p$.

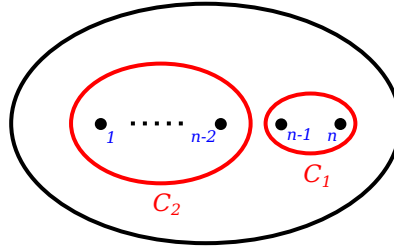


Figure 4.1: Circles in the punctured disk

From the equality $t_{n-2}t_n t_{n-2} = t_n t_{n-2} t_n$ it follows that $s_{n-2} s_{n-1}^{k_1} s_{n-2} \Delta^{4p+2k_3} = s_{n-1}^{k_1} s_{n-2} s_{n-1}^{k_1} \Delta^{2p+4k_3}$, hence $(s_{n-2} s_{n-1}^{k_1} s_{n-2})(s_{n-1}^{k_1} s_{n-2} s_{n-1}^{k_1})^{-1} = \Delta^{2k_3-2p}$. We know from Paris [33, Corollary 2.6] that $A_{\{s_{n-2}, s_{n-1}\}}[A_{n-1}] \cap \langle \Delta \rangle = \{1\}$, hence $(s_{n-2} s_{n-1}^{k_1} s_{n-2})(s_{n-1}^{k_1} s_{n-2} s_{n-1}^{k_1})^{-1} = \Delta^{2k_3-2p} = 1$. Let $z : A[A_{n-1}] \rightarrow \mathbb{Z}$ be the homomorphism which sends s_i to 1 for all $1 \leq i \leq n-1$. We have

$$0 = z(1) = z((s_{n-2} s_{n-1}^{k_1} s_{n-2})(s_{n-1}^{k_1} s_{n-2} s_{n-1}^{k_1})^{-1}) = 1 - k_1,$$

hence $k_1 = 1$. Moreover, $\Delta^{2k_3-2p} = 1$ and Δ is of infinite order, thus $k_3 = p$. \square

5 Homomorphisms from $A[A_{n-1}]$ to $A[D_n]$

Lemmas 5.1 to 5.7 are preliminaries to the proof of Theorem 2.2.

Lemma 5.1 *Let $n \geq 6$. Let $\varphi : A[A_{n-1}] \rightarrow A[D_n]$ be a homomorphism. If $\pi \circ \varphi : A[A_{n-1}] \rightarrow A[A_{n-1}]$ is cyclic, then φ is cyclic.*

Proof Assume $\pi \circ \varphi$ is cyclic. Then there exists $u \in A[A_{n-1}]$ such that $(\pi \circ \varphi)(s_i) = u$ for all $1 \leq i \leq n-1$. For $3 \leq i \leq n-1$ we set $v_i = \varphi(s_i s_1^{-1})$. We have $\pi(v_i) = u u^{-1} = 1$, hence $v_i \in \text{Ker}(\pi)$. We have

$$(s_3 s_1^{-1})(s_4 s_1^{-1})(s_3 s_1^{-1}) = s_3 s_4 s_3 s_1^{-3} = s_4 s_3 s_4 s_1^{-3} = (s_4 s_1^{-1})(s_3 s_1^{-1})(s_4 s_1^{-1}),$$

hence $v_3 v_4 v_3 = v_4 v_3 v_4$. Since $\text{Ker}(\pi)$ is a free group (see Crisp–Paris [19, Proposition 2.3]) and two elements in a free group either freely generate a free group or commute, the existence of such equality implies that $v_3 v_4 = v_4 v_3$. It follows that $v_3 v_4 v_3 = v_3 v_4^2$, hence $v_3 = v_4$, and therefore

$$\varphi(s_3) \varphi(s_1)^{-1} = v_3 = v_4 = \varphi(s_4) \varphi(s_1)^{-1}.$$

So, $\varphi(s_3) = \varphi(s_4)$. We conclude by Castel [11, Lemma 3.1.1] that φ is cyclic. \square

Let $n \geq 6$. If n is odd, then Σ_n has one boundary component that we denote by ∂ , and we denote by T_∂ the Dehn twist along ∂ . If n is even, then Σ_n has two boundary components that we denote by ∂_1 and ∂_2 , and we denote by T_{∂_1} and T_{∂_2} the Dehn twists along ∂_1 and ∂_2 , respectively. It is known that the center of $\mathcal{M}(\Sigma_n)$, denoted $Z(\mathcal{M}(\Sigma_n))$, is the cyclic group generated by T_∂ if n is odd, and it is a free abelian group of rank two generated by T_{∂_1} and T_{∂_2} if n is even (see Paris–Rolfsen [34, Theorem 5.6] for example).

Lemma 5.2 *Let $n \geq 6$. Let $f \in \mathcal{M}(\Sigma_n)$ such that $fT_{a_i}^2 = T_{a_i}^2f$ for all $1 \leq i \leq n-1$. Then $f^2 \in Z(\mathcal{M}(\Sigma_n))$.*

Proof Assume n is odd. The case where n is even can be proved in the same way. Let $f \in \mathcal{M}(\Sigma_n)$ such that $fT_{a_i}^2 = T_{a_i}^2f$ for all $1 \leq i \leq n-1$. Since $fT_{a_i}^2f^{-1} = T_{a_i}^2$ we have $f([a_i]) = [a_i]$ (see Farb–Margalit [25, Section 3.3]). The mapping class f may reverse the orientation of each a_i up to isotopy, but f^2 preserves the orientation of all a_i up to isotopy, hence f^2 can be represented by an element of $\text{Homeo}^+(\Sigma_n)$ which is the identity on a (closed) regular neighborhood Σ' of $\bigcup_{i=1}^{n-1} a_i$. We observe that Σ' is a surface of genus $\frac{n-1}{2}$ with one boundary component, ∂' , and that $\partial \cup \partial'$ bounds a cylinder C . This implies that $f^2 \in \mathcal{M}(C) \subset \mathcal{M}(\Sigma_n)$. Since $\mathcal{M}(C) = \langle T_\partial \rangle = Z(\mathcal{M}(\Sigma_n))$, we conclude that $f^2 \in Z(\mathcal{M}(\Sigma_n))$. \square

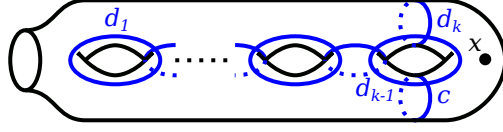
Lemma 5.3 *Let $n \geq 6$. We set $m = n-1$ if n is odd and $m = n-2$ if n is even. Let $1 \leq k \leq m$. Let c be a generic circle of $\Sigma_n \setminus \{x\}$ such that $c \cap d_i = \emptyset$ for $1 \leq i \leq k-2$, $|c \cap d_{k-1}| = 1$ if $k \geq 2$, $c \cap d_k = \emptyset$, and c is isotopic to d_k in Σ_n . Then there exists $g \in \text{Ker}(\theta)$ such that $g([d_i]) = [d_i]$ for all $1 \leq i \leq k-1$ and $g([c]) = [d_k]$.*

Proof We identify D_3 with A_3 in this proof to treat the cases $k=2$ and $k=1$. We first assume that k is even. If c is isotopic in $\Sigma_n \setminus \{x\}$ to d_k , then it suffices to take $g = \text{id}$. So, we can assume that c and d_k are not isotopic in $\Sigma_n \setminus \{x\}$. Since c and d_k are isotopic in Σ_n , by Epstein [24] there exists a cylinder C in Σ_n whose boundary components are d_k and c . Since c and d_k are not isotopic in $\Sigma_n \setminus \{x\}$, this cylinder must contain the puncture x . Let Σ' be a regular neighborhood of $(\bigcup_{i=1}^{k-1} d_i) \cup C$. Then Σ' is a surface of genus $\frac{k}{2}$ with one boundary component where the circles $d_1, \dots, d_{k-1}, d_k, c$ are arranged as shown in Figure 5.1. By Proposition 3.1 there are homomorphisms $\psi_1 : A[D_{k+1}] \rightarrow \mathcal{M}(\Sigma_n, x)$ and $\psi_2 : A[A_k] \rightarrow \mathcal{M}(\Sigma_n, x)$ defined by

$$\begin{aligned} \psi_1(t_i) &= T_{d_i} \text{ for } 1 \leq i \leq k, \quad \psi_1(t_{k+1}) = T_c, \\ \psi_2(s_i) &= T_{d_i} \text{ for } 1 \leq i \leq k-1, \quad \psi_2(s_k) = T_c. \end{aligned}$$

We denote by $\Delta_{D,k}$ the Garside element of $A[D_{k+1}]$ and by $\Delta_{A,k}$ the Garside element of $A[A_k]$, and we set $g = \psi_1(\Delta_{D,k})\psi_2(\Delta_{A,k}^{-2})$. We have $\Delta_{D,k}t_i\Delta_{D,k}^{-1} = t_i$ for all $1 \leq i \leq k-1$, $\Delta_{D,k}t_{k+1}\Delta_{D,k}^{-1} = t_k$ and $\Delta_{A,k}^2s_i\Delta_{A,k}^{-2} = s_i$ for all $1 \leq i \leq k$, hence $gT_{d_i}g^{-1} = T_{g(d_i)} = T_{d_i}$ for all $1 \leq i \leq k-1$ and $gT_cg^{-1} = T_{g(c)} = T_{d_k}$. It follows that $g([d_i]) = [d_i]$ for all $1 \leq i \leq k-1$ and $g([c]) = [d_k]$ (see Farb–Margalit [25, Fact 3.6]). Moreover,

$$\begin{aligned} \Delta_{D,k} &= (t_1 \cdots t_{k-1} t_k t_{k+1} t_{k-1} \cdots t_1) \cdots (t_{k-1} t_k t_{k+1} t_{k-1}) (t_k t_{k+1}), \\ \Delta_{A,k}^2 &= (s_1 \cdots s_{k-1} s_k^2 s_{k-1} \cdots s_1) \cdots (s_{k-1} s_k^2 s_{k-1}) s_k^2, \end{aligned}$$

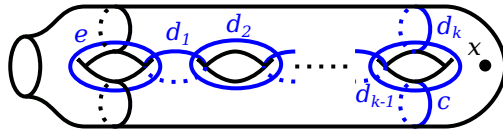
Figure 5.1: Regular neighborhood of $(\bigcup_{i=1}^{k-1} d_i) \cup C$, case where k is even

hence $\theta(g) = 1$, that is, $g \in \text{Ker}(\theta)$.

Now, assume k is odd. If c is isotopic in $\Sigma_n \setminus \{x\}$ to d_k , then we can take $g = \text{id}$. So, we can assume that c and d_k are not isotopic in $\Sigma_n \setminus \{x\}$. Since c and d_k are isotopic in Σ_n , there exists a cylinder C in Σ_n whose boundary components are d_k and c . Since c and d_k are not isotopic in $\Sigma_n \setminus \{x\}$, this cylinder must contain the puncture x . Let Σ' be a closed regular neighborhood of $(\bigcup_{i=1}^{k-1} d_i) \cup C$. Then Σ' is a surface of genus $\frac{k-1}{2}$ with two boundary components and the circles $d_1, \dots, d_{k-1}, d_k, c$ are arranged as shown in Figure 5.2. Since $k \leq m$ and k is odd, $\frac{k-1}{2}$ is strictly less than the genus of Σ_n , hence we can choose a sub-surface Σ'' of Σ_n of genus $\frac{k+1}{2}$, with one boundary component, and containing Σ' . We can also choose a generic circle e in $\Sigma'' \setminus \{x\}$ such that $|e \cap d_1| = 1$, $|e \cap c| = 1$ if $k = 1$, $e \cap d_i = \emptyset$ for all $2 \leq i \leq k$ and $e \cap c = \emptyset$ if $k \geq 2$ (see Figure 5.2). By Proposition 3.1 there are homomorphisms $\psi_1 : A[D_{k+2}] \rightarrow \mathcal{M}(\Sigma_n, x)$ and $\psi_2 : A[A_{k+1}] \rightarrow \mathcal{M}(\Sigma_n, x)$ defined by

$$\begin{aligned} \psi_1(t_1) &= T_e, \quad \psi_1(t_i) = T_{d_{i-1}} \text{ for } 2 \leq i \leq k+1, \quad \psi_1(t_{k+2}) = T_c, \\ \psi_2(s_1) &= T_e, \quad \psi_2(s_i) = T_{d_{i-1}} \text{ for } 2 \leq i \leq k, \quad \psi_2(s_{k+1}) = T_c. \end{aligned}$$

We denote by $\Delta_{D,k+1}$ the Garside element of $A[D_{k+2}]$ and by $\Delta_{A,k+1}$ the Garside element of $A[A_{k+1}]$, and we set $g = \psi_1(\Delta_{D,k+1})\psi_2(\Delta_{A,k+1}^{-2})$. Then, as in the case where k is even, we have $g([d_i]) = [d_i]$ for all $1 \leq i \leq k-1$, $g([c]) = [d_k]$, and $g \in \text{Ker}(\theta)$. \square

Figure 5.2: Regular neighborhood of $(\bigcup_{i=1}^{k-1} d_i) \cup C$, case where k is odd

Lemma 5.4 *Let $n \geq 6$. Set $m = n - 1$ if n is odd and $m = n - 2$ if n is even. Let $1 \leq k \leq m$. Let c be a generic circle of $\Sigma_n \setminus \{x\}$ such that $c \cap d_i = \emptyset$ for $1 \leq i \leq k - 2$, $|c \cap d_{k-1}| = 1$ if $k \geq 2$, and c is isotopic to d_k in Σ_n . Then there exists $g \in \text{Ker}(\theta)$ such that $g([d_i]) = [d_i]$ for all $1 \leq i \leq k - 1$ and $g([c]) = [d_k]$.*

Proof We argue by induction on $i([c], [d_k])$. The case $i([c], [d_k]) = 0$ is proved in Lemma 5.3, hence we can assume that $i([c], [d_k]) \geq 1$ and that the induction hypothesis holds. Note that now c and d_k cannot be isotopic in $\Sigma_n \setminus \{x\}$ since $i([c], [d_k]) \neq 0$. We can assume without loss of generality that $i([c], [d_k]) = |c \cap d_k|$. Since c and d_k are isotopic in Σ_n , there exists a bigon D in Σ_n cobounded by an arc of d_k and an arc of c as shown in Figure 5.3. We can choose this bigon to be minimal in the sense

that its interior intersects neither c nor d_k . The bigon D cannot intersect d_i for $1 \leq i \leq k-2$ and one can easily modify c so that D does not intersect d_{k-1} either. Since c and d_k are not isotopic in $\Sigma_n \setminus \{x\}$, D necessarily contains the puncture x in its interior. We choose a circle c' parallel to c except in the bigon D where it follows the arc of d_k which borders D as illustrated in Figure 5.3. By construction $c' \cap d_i = \emptyset$ for $1 \leq i \leq k-2$, $|c' \cap d_{k-1}| = 1$ if $k \geq 2$, and c' is isotopic to d_k in Σ_n . Moreover $i([c'], [d_k]) \leq |c' \cap d_k| < |c \cap d_k| = i([c], [d_k])$. By the induction hypothesis there exists $g_1 \in \text{Ker}(\theta)$ such that $g_1([d_i]) = [d_i]$ for all $1 \leq i \leq k-1$ and $g_1([c']) = [d_k]$. We choose $G_1 \in \text{Homeo}^+(\Sigma_n, x)$ which represents g_1 such that $G_1(d_i) = d_i$ for all $1 \leq i \leq k-1$ and $G_1(c') = d_k$. We set $c'' = G_1(c)$. Then $c'' \cap d_i = \emptyset$ for $1 \leq i \leq k-2$, $|c'' \cap d_{k-1}| = 1$ if $k \geq 2$, $c'' \cap d_k = \emptyset$, and c'' is isotopic to d_k in Σ_n . By Lemma 5.3 there exists $g_2 \in \text{Ker}(\theta)$ such that $g_2([d_i]) = [d_i]$ for all $1 \leq i \leq k-1$ and $g_2([c'']) = [d_k]$. We set $g = g_2 \circ g_1$. Then $g \in \text{Ker}(\theta)$, $g([d_i]) = [d_i]$ for all $1 \leq i \leq k-1$ and $g([c]) = [d_k]$. \square

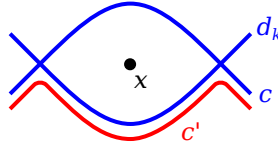


Figure 5.3: Bigon cobounded by c and d_k

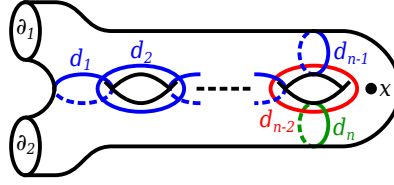
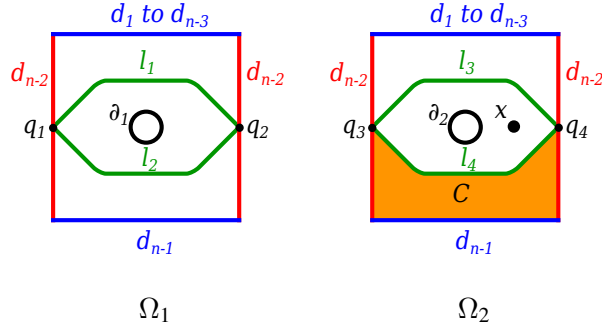
Lemma 5.5 *Let n be an even number, $n \geq 6$. Let c be a generic circle of $\Sigma_n \setminus \{x\}$ such that $c \cap d_i = \emptyset$ for all $1 \leq i \leq n-3$, $|c \cap d_{n-2}| = 1$, $c \cap d_{n-1} = \emptyset$, and c is isotopic to d_{n-1} in Σ_n . Then we have one of the following two possibilities.*

- (1) c is isotopic to d_{n-1} in $\Sigma_n \setminus \{x\}$.
- (2) There exists $g \in \text{Ker}(\theta)$ such that $g([d_i]) = [d_i]$ for all $1 \leq i \leq n-1$ and $g([c]) = [d_n]$.

Proof The surface Σ_n is a surface of genus $\frac{n-2}{2}$ with two boundary components ∂_1 and ∂_2 . We assume that the circles d_1, \dots, d_{n-1}, d_n are arranged as in Figure 5.4. Let Ω be the surface obtained by cutting Σ_n along $\bigcup_{i=1}^{n-1} d_i$. Then Ω has two connected components Ω_1 and Ω_2 . Each of these components is a cylinder that we represent by a square with a hole in the middle as shown in Figure 5.5. Two opposite sides of each square represent arcs of d_{n-2} , one side represents an arc of d_{n-1} , and the last side represents a union of arcs of d_1, \dots, d_{n-3} . The boundary of the hole represents ∂_1 for Ω_1 and ∂_2 for Ω_2 . The puncture x sits inside Ω_2 . The trace of the circle c in Ω is a simple arc ℓ , either in Ω_1 or in Ω_2 .

Suppose ℓ is in Ω_1 . Let q be the intersection point of c with d_{n-2} . Then q is represented in Ω_1 by two points q_1 and q_2 on two opposite sides of Ω_1 as shown in Figure 5.5, and ℓ is a simple arc connecting q_1 with q_2 . Up to isotopy pointwise fixing the boundary of Ω_1 , there exist exactly two simple arcs in Ω_1 connecting q_1 to q_2 that are represented by the arcs ℓ_1 and ℓ_2 depicted in Figure 5.5. The arc ℓ cannot be isotopic to ℓ_1 , otherwise c would not be isotopic to d_{n-1} in Σ_n . So, ℓ is isotopic to ℓ_2 in Ω_1 which implies that c is isotopic to d_{n-1} in $\Sigma_n \setminus \{x\}$.

Now suppose ℓ is in Ω_2 . Let q be the intersection point of c with d_{n-2} . Then q is represented in Ω_2 by two points q_3 and q_4 on two opposite sides of Ω_2 as shown in Figure 5.5, and ℓ is a simple arc

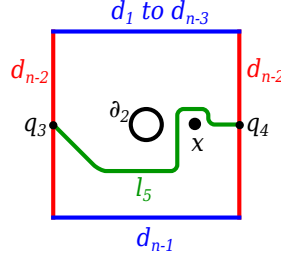

 Figure 5.4: Circles d_1, \dots, d_n

 Figure 5.5: The surface Ω

connecting q_3 with q_4 . Up to isotopy (in Ω_2 and not in $\Omega_2 \setminus \{x\}$) pointwise fixing the boundary of Ω_2 , there exist exactly two simple arcs in Ω_2 connecting q_3 to q_4 that are represented by the arcs ℓ_3 and ℓ_4 depicted in Figure 5.5. The arc ℓ cannot be isotopic to ℓ_3 in Ω_2 , otherwise c would not be isotopic to d_{n-1} in Σ_n . So, ℓ is isotopic to ℓ_4 in Ω_2 . Let $\{F_t : \Omega_2 \rightarrow \Omega_2\}_{t \in [0,1]}$ be an isotopy such that $F_0 = \text{id}$, $F_1(\ell) = \ell_4$ and F_t is the identity on the boundary of Ω_2 for all $t \in [0, 1]$. The arc ℓ_4 divides Ω_2 into two parts, the lower one which does not contain the hole bordered by ∂_2 and the puncture x , and the upper one which contains the hole bordered by ∂_2 and the puncture x , as shown in Figure 5.5.

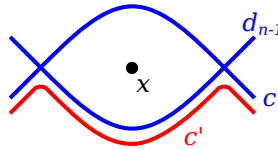
Suppose $F_1(x)$ is in the upper part. Let C be the domain of Ω_2 bounded by ℓ_4 , two arcs of d_{n-2} and an arc of d_{n-1} as shown in Figure 5.5. Let $C' = F_1^{-1}(C)$. Then C' is a domain of Ω_2 bounded by ℓ , two arcs of d_{n-2} and an arc of d_{n-1} and C' does not contain the puncture x . The existence of such a domain implies that c is isotopic to d_{n-1} in $\Sigma_n \setminus \{x\}$.

Now, suppose $F_1(x)$ is in the lower part. We can assume without loss of generality that the trace of d_n on Ω_2 is the simple arc ℓ_5 drawn in Figure 5.6. We can choose an isotopy $\{F'_t : \Omega_2 \rightarrow \Omega_2\}_{t \in [0,1]}$ such that $F'_0 = \text{id}$, $F'_1(\ell_4) = \ell_5$, F'_t is the identity on the boundary of Ω_2 for all $t \in [0, 1]$, and $F'_1(F_1(x)) = x$. Let $\tilde{F} : \Sigma_n \rightarrow \Sigma_n$ be the homeomorphism which is $F'_1 \circ F_1$ on Ω_2 and is the identity outside Ω_2 , and let $g \in \mathcal{M}(\Sigma_n, x)$ be the mapping class represented by \tilde{F} . Then $g \in \text{Ker}(\theta)$, $g([d_i]) = [d_i]$ for all $1 \leq i \leq n-1$, and $g([c]) = [d_n]$. \square

Lemma 5.6 *Let n be an even number, $n \geq 6$. Let c be a generic circle of $\Sigma_n \setminus \{x\}$ such that $c \cap d_i = \emptyset$ for all $1 \leq i \leq n-3$, $|c \cap d_{n-2}| = 1$, and c is isotopic to d_{n-1} in Σ_n . Then there exists $g \in \text{Ker}(\theta)$ such that $g([d_i]) = [d_i]$ for all $1 \leq i \leq n-2$, and either $g([c]) = [d_{n-1}]$ or $g([c]) = [d_n]$.*

Figure 5.6: The arc ℓ_5

Proof We can assume that $|c \cap d_{n-1}| = i([c], [d_{n-1}])$ and $|c \cap d_n| = i([c], [d_n])$. We argue by induction on $|c \cap d_{n-1}| + |c \cap d_n| = i([c], [d_{n-1}]) + i([c], [d_n])$. The case $|c \cap d_{n-1}| = 0$ follows directly from Lemma 5.5, and the case $|c \cap d_n| = 0$ is proved in the same way by replacing d_{n-1} with d_n . So we can assume that $i([c], [d_{n-1}]) = |c \cap d_{n-1}| \geq 1$, $i([c], [d_n]) = |c \cap d_n| \geq 1$, and that the induction hypothesis holds. Note that now c and d_{n-1} cannot be isotopic in $\Sigma_n \setminus \{x\}$. Since c and d_{n-1} are isotopic in Σ_n , there exists a bigon D in Σ_n cobounded by an arc of d_{n-1} and an arc of c (see Figure 5.7). Since c and d_{n-1} are not isotopic in $\Sigma_n \setminus \{x\}$, this bigon necessarily contains the puncture x . We can choose D to be minimal in the sense that its interior does not intersect c and d_{n-1} . Moreover, up to exchanging the roles of d_{n-1} and d_n if necessary, we can also suppose that d_n does not intersect the interior of D . Clearly, D does not intersect d_i for any $1 \leq i \leq n-3$ and, up to replacing c with an isotopic circle, we can assume that D does not intersect d_{n-2} either. Let c' be a circle parallel to c except in the bigon D where it follows the arc of d_{n-1} which borders D as illustrated in Figure 5.7. We have $c' \cap d_i = \emptyset$ for all $1 \leq i \leq n-3$, $|c' \cap d_{n-2}| = 1$ and c' is isotopic to d_{n-1} in Σ_n . We also have $i([c'], [d_{n-1}]) < i([c], [d_{n-1}])$ and $i([c'], [d_n]) \leq i([c], [d_n])$, hence by the induction hypothesis there exists $g_1 \in \text{Ker}(\theta)$ such that $g_1([d_i]) = [d_i]$ for all $1 \leq i \leq n-2$, and either $g_1([c']) = [d_{n-1}]$ or $g_1([c']) = [d_n]$. Without loss of generality we can assume that $g_1([c']) = [d_{n-1}]$. We choose $G_1 \in \text{Homeo}^+(\Sigma_n, x)$ which represents g_1 such that $G_1(d_i) = d_i$ for all $1 \leq i \leq n-2$ and $G_1(c') = d_{n-1}$. We set $c'' = G_1(c)$. Then $c'' \cap d_i = \emptyset$ for all $1 \leq i \leq n-3$, $|c'' \cap d_{n-2}| = 1$, $c'' \cap d_{n-1} = \emptyset$, and c'' is isotopic to d_{n-1} in Σ_n . By Lemma 5.5 there exists $g_2 \in \text{Ker}(\theta)$ such that $g_2([d_i]) = [d_i]$ for all $1 \leq i \leq n-2$, and either $g_2([c'']) = [d_{n-1}]$ or $g_2([c'']) = [d_n]$. We set $g = g_2 \circ g_1$. Then $g \in \text{Ker}(\theta)$, $g([d_i]) = [d_i]$ for all $1 \leq i \leq n-2$, and either $g([c]) = [d_{n-1}]$ or $g([c]) = [d_n]$. \square

Figure 5.7: Bigon cobounded by c and d_{n-1}

Lemma 5.7 Let $n \geq 6$. Let c_1, \dots, c_{n-1} be generic circles in $\Sigma_n \setminus \{x\}$ such that

- (a) $|c_i \cap c_j| = 1$ if $|i - j| = 1$ and $|c_i \cap c_j| = 0$ if $|i - j| \geq 2$, for all $1 \leq i, j \leq n-1$,

(b) c_i is isotopic to d_i in Σ_n for all $1 \leq i \leq n-1$.

Then:

- (1) If n is odd, then there exists $g \in \text{Ker}(\theta)$ such that $g([c_i]) = [d_i]$ for all $1 \leq i \leq n-1$.
- (2) If n is even, then there exists $g \in \text{Ker}(\theta)$ such that $g([c_i]) = [d_i]$ for all $1 \leq i \leq n-2$, and either $g([c_{n-1}]) = [d_{n-1}]$ or $g([c_{n-1}]) = [d_n]$.

Proof We prove Part (2). Part (1) can be proved in the same way. For $1 \leq k \leq n-2$ we construct by induction on k an element $g_k \in \text{Ker}(\theta)$ such that $g_k([c_i]) = [d_i]$ for all $1 \leq i \leq k$. Assume $k = 1$. Then, by Lemma 5.4 applied to $k = 1$, there exists $g_1 \in \text{Ker}(\theta)$ such that $g_1([c_1]) = [d_1]$. Suppose $2 \leq k \leq n-1$ and g_{k-1} is constructed. We choose $G_{k-1} \in \text{Homeo}^+(\Sigma_n, x)$ which represents g_{k-1} and such that $G_{k-1}(c_i) = d_i$ for all $1 \leq i \leq k-1$, and we set $c'_k = G_{k-1}(c_k)$. Note that, since $g_{k-1} \in \text{Ker}(\theta)$, the circle c'_k is isotopic to c_k in Σ_n . Then, by Lemma 5.4, there exists $h_k \in \text{Ker}(\theta)$ such that $h_k([d_i]) = [d_i]$ for all $1 \leq i \leq k-1$ and $h_k([c'_k]) = [d_k]$. We set $g_k = h_k \circ g_{k-1}$. Then $g_k([c_i]) = [d_i]$ for all $1 \leq i \leq k$. Note that when n is odd we can extend the induction to $k = n-1$ and conclude the proof here by setting $g = g_{n-1}$. The case where n is even requires an extra argument.

We choose $G_{n-2} \in \text{Homeo}^+(\Sigma_n, x)$ which represents g_{n-2} and such that $G_{n-2}(c_i) = d_i$ for all $1 \leq i \leq n-2$, and we set $c'_{n-1} = G_{n-2}(c_{n-1})$. Again, since $g_{n-2} \in \text{Ker}(\theta)$, the circle c'_{n-1} is isotopic to c_{n-1} in Σ_n . By Lemma 5.6 there exists $h_{n-1} \in \text{Ker}(\theta)$ such that $h_{n-1}([d_i]) = [d_i]$ for all $1 \leq i \leq n-2$, and either $h_{n-1}([c'_{n-1}]) = [d_{n-1}]$ or $h_{n-1}([c'_{n-1}]) = [d_n]$. We set $g = h_{n-1} \circ g_{n-2}$. Then $g([c_i]) = [d_i]$ for all $1 \leq i \leq n-2$, and either $g([c_{n-1}]) = [d_{n-1}]$ or $g([c_{n-1}]) = [d_n]$. \square

Proof of Theorem 2.2 Let $\varphi : A[A_{n-1}] \rightarrow A[D_n]$ be a homomorphism. We know by Theorem 3.5 that we have one of the following possibilities.

- $\pi \circ \varphi$ is cyclic.
- There exist $\psi \in \langle \bar{\chi} \rangle$ and $p \in \mathbb{Z}$ such that $\pi \circ \varphi$ is conjugate to $\psi \circ \bar{\gamma}_p$.

By Lemma 5.1, if $\pi \circ \varphi$ is cyclic, then φ is cyclic. So, we can assume that there exists $\psi \in \langle \bar{\chi} \rangle$ and $p \in \mathbb{Z}$ such that $\pi \circ \varphi$ is conjugate to $\psi \circ \bar{\gamma}_p$. Up to conjugating and composing φ on the left by χ if necessary, we can assume that $\pi \circ \varphi = \bar{\gamma}_p$, that is, $(\pi \circ \varphi)(s_i) = s_i \Delta_A^{2p}$, where Δ_A denotes the Garside element of $A[A_{n-1}]$.

Set $U = \rho_A(\Delta_A^2)$. If n is odd, then $U^2 = T_\partial$, where ∂ is the boundary component of Σ_n , and if n is even, then $U = T_{\partial_1} T_{\partial_2}$, where ∂_1 and ∂_2 are the two boundary components of Σ_n (see Labruère–Paris [28, Proposition 2.12]). In particular $U^2 \in Z(\mathcal{M}(\Sigma_n))$ in both cases.

By Theorem 3.7 we know that there exist generic circles c_1, \dots, c_{n-1} in $\Sigma_n \setminus \{x\}$, $\varepsilon \in \{\pm 1\}$ and $f_0 \in \mathcal{M}(\Sigma_n, x)$ such that

- (a) $|c_i \cap c_j| = 1$ if $|i - j| = 1$ and $|c_i \cap c_j| = 0$ if $|i - j| \geq 2$, for all $1 \leq i, j \leq n-1$,
- (b) f_0 commutes with T_{c_i} for all $1 \leq i \leq n-1$,
- (c) $(\rho_D \circ \varphi)(s_i) = T_{c_i}^\varepsilon f_0$ for all $1 \leq i \leq n-1$.

For $1 \leq i \leq n-1$ we denote by b_i the circle in Σ_n obtained by composing $c_i : \mathbb{S}^1 \rightarrow \Sigma_n \setminus \{x\}$ with the embedding $\Sigma_n \setminus \{x\} \hookrightarrow \Sigma_n$. In addition we set $g_0 = \theta(f_0)$. Then $(\theta \circ \rho_D \circ \varphi)(s_i) = T_{b_i}^\varepsilon g_0$ for all $1 \leq i \leq n-1$. Note that, since $\theta \circ \rho_D = \rho_A \circ \pi$, we also have $(\theta \circ \rho_D \circ \varphi)(s_i) = T_{a_i} U^p$ for all $1 \leq i \leq n-1$.

Claim 1. We have $\varepsilon = 1$, $g_0 = U^p$ and b_i is isotopic to a_i in Σ_n for all $1 \leq i \leq n-1$.

Proof of Claim 1. Since g_0^2 commutes with $T_{b_i}^{2\varepsilon} g_0^2 = T_{a_i}^2 U^{2p}$ and $U^2 \in Z(\mathcal{M}(\Sigma_n))$, g_0^2 commutes with $T_{a_i}^2$ for all $1 \leq i \leq n-1$. By lemma 5.2 it follows that $g_0^4 \in Z(\mathcal{M}(\Sigma_n))$. By Proposition 3.3 we deduce that $\mathcal{S}(T_{a_i}^4 U^{4p}) = \mathcal{S}(T_{b_i}^{4\varepsilon} g_0^4) = \{[a_i]\} = \{[b_i]\}$, hence $[a_i] = [b_i]$ for all $1 \leq i \leq n-1$. Then $T_{a_i}^{4-4\varepsilon} = U^{-4p} g_0^4$, hence, by Proposition 3.3, $4-4\varepsilon = 0$, and therefore $\varepsilon = 1$. Finally, from the equality $T_{a_i} U^p = T_{a_i} g_0$ it follows that $g_0 = U^p$. This finishes the proof of Claim 1.

From Claim 1 it follows that c_i is isotopic to d_i in Σ_n hence, by Lemma 5.7, there exists $g \in \text{Ker}(\theta)$ such that $g([c_i]) = [d_i]$ for all $1 \leq i \leq n-2$, $g([c_{n-1}]) = [d_{n-1}]$ if n is odd, and either $g([c_{n-1}]) = [d_{n-1}]$ or $g([c_{n-1}]) = [d_n]$ if n is even. These equalities imply that $gT_{c_i} g^{-1} = T_{d_i}$ for $1 \leq i \leq n-2$, $gT_{c_{n-1}} g^{-1} = T_{d_{n-1}}$ if n is odd, and either $gT_{c_{n-1}} g^{-1} = T_{d_{n-1}}$ or $gT_{c_{n-1}} g^{-1} = T_{d_n}$ if n is even. By Theorem 3.6(1) there exists $v \in \text{Ker}(\pi)$ such that $\rho_D(v) = g$. So, up to composing φ on the left by ad_v first, and composing on the left by ζ if necessary after, we can assume that $(\rho_D \circ \varphi)(s_i) = T_{d_i} f_0$ for all $1 \leq i \leq n-1$, where f_0 commutes with T_{d_i} for all $1 \leq i \leq n-1$. Since $T_{d_1} = \rho_D(t_1) \in \text{Im}(\rho_D)$, we have $f_0 \in \text{Im}(\rho_D)$, hence there exists $u_0 \in A[D_n]$ such that $\rho_D(u_0) = f_0$. Since ρ_D is injective (see Theorem 3.6), we deduce that $\varphi(s_i) = t_i u_0$ for all $1 \leq i \leq n-1$ and u_0 commutes with t_i for all $1 \leq i \leq n-1$. We set $Y = \{t_1, \dots, t_{n-1}\}$, $\Delta_Y = \Delta_Y[D_n]$, $\Delta_D = \Delta[D_n]$, $\kappa = 2$ if n is odd, and $\kappa = 1$ if n is even. By Paris [32, Theorem 1.1] the centralizer of Y in $A[D_n]$ is generated by Δ_Y^2 and Δ_D^κ , hence there exists $q, r \in \mathbb{Z}$ such that $u_0 = \Delta_Y^{2q} \Delta_D^{\kappa r}$. We conclude that $\varphi = \beta_{q,r}$. \square

6 Endomorphisms of $A[D_n]$

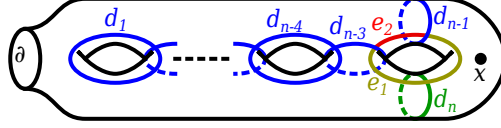
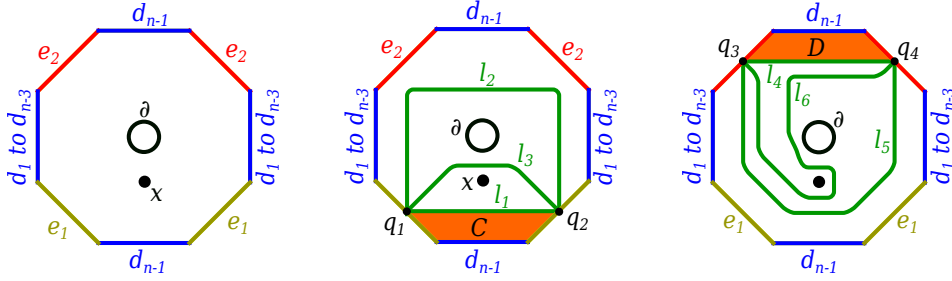
The following is a preliminary to the proof of Theorem 2.3.

Lemma 6.1 *Let n be an odd number, $n \geq 7$. Let c be a generic circle of $\Sigma_n \setminus \{x\}$ such that $c \cap d_i = \emptyset$ for $1 \leq i \leq n-3$, $|c \cap d_{n-2}| = 1$, $c \cap d_{n-1} = \emptyset$, and c is isotopic to d_{n-1} in Σ_n . Then we have one of the following three possibilities.*

- (1) c is isotopic to d_{n-1} in $\Sigma_n \setminus \{x\}$.
- (2) There exists $g \in \text{Ker}(\theta)$ such that $g([d_i]) = [d_i]$ for all $1 \leq i \leq n-1$ and $g([c]) = [d_n]$.
- (3) There exists $g \in \text{Ker}(\theta)$ such that $g([d_i]) = [d_i]$ for all $1 \leq i \leq n-2$, $g([d_{n-1}]) = [d_n]$ and $g([c]) = [d_{n-1}]$.

Proof The surface Σ_n is a surface of genus $\frac{n-1}{2}$ with one boundary component, ∂ . We assume that the circles d_1, \dots, d_{n-1}, d_n are arranged as shown in Figure 6.1. The circles d_{n-3} and d_{n-1} divide d_{n-2} into two arcs, e_1 and e_2 , where the arc e_1 intersects d_n and the arc e_2 does not intersect d_n (see Figure 6.1). Let Ω be the surface obtained by cutting Σ_n along $\bigcup_{i=1}^{n-1} d_i$. Then Ω is a cylinder represented by

an octagon with a hole in the middle (see Figure 6.2). Two opposite sides of this octagon represent arcs of d_{n-1} and two opposite sides represent arcs of d_1, \dots, d_{n-3} , as shown in the figure. Two other sides represent arcs of e_1 and the last two sides represent arcs of e_2 , arranged as shown in Figure 6.2. The boundary of the hole represents ∂ .


 Figure 6.1: The circles d_1, \dots, d_n

 Figure 6.2: The surface Ω

The circle c intersects d_{n-2} in a point q , and q is either on the arc e_1 or on the arc e_2 . Suppose first that q is on the arc e_1 . Then q is represented on Ω by two points q_1 and q_2 lying on two different sides of Ω that represent e_1 , and the trace of c in Ω is a simple arc ℓ connecting q_1 to q_2 . Up to isotopy (in Ω and not in $\Omega \setminus \{x\}$) pointwise fixing the boundary of Ω , there are exactly two simple arcs in Ω connecting q_1 to q_2 represented by the arcs ℓ_1 and ℓ_2 depicted in Figure 6.2. The arc ℓ cannot be isotopic to ℓ_2 , otherwise c would not be isotopic to d_{n-1} in Σ_n . So, ℓ is isotopic to ℓ_1 in Ω . Let $\{F_t : \Omega \rightarrow \Omega\}_{t \in [0,1]}$ be an isotopy such that $F_0 = \text{id}$, $F_1(\ell) = \ell_1$ and F_t is the identity on the boundary of Ω for all $t \in [0, 1]$. The arc ℓ_1 divides Ω into two parts, the lower one which does not contain the hole bounded by ∂ and the puncture x , and the upper one which contains the hole bounded by ∂ and the puncture x , as shown in Figure 6.2.

Suppose $F_1(x)$ is in the upper part. Let C be the domain of Ω bounded by ℓ_1 , two arcs of e_1 and an arc of d_{n-1} as shown in Figure 6.2. Let $C' = F_1^{-1}(C)$. Then C' is a domain of Ω bounded by ℓ , two arcs of e_1 and an arc of d_{n-1} which does not contain the puncture x . The existence of such a domain implies that c is isotopic to d_{n-1} in $\Sigma_n \setminus \{x\}$.

Suppose $F_1(x)$ is in the lower part. We can suppose that the trace of d_n on Ω is the arc ℓ_3 depicted in Figure 6.2. We can choose an isotopy $\{F'_t : \Omega \rightarrow \Omega\}_{t \in [0,1]}$ such that $F'_0 = \text{id}$, $F'_1(\ell_1) = \ell_3$, F'_t is the identity on the boundary of Ω for all $t \in [0, 1]$, and $F'_1(F_1(x)) = x$. Let $\tilde{F} : \Sigma_n \rightarrow \Sigma_n$ be the homeomorphism which is $F'_1 \circ F_1$ on Ω and is the identity outside Ω , and let $g \in \mathcal{M}(\Sigma_n, x)$ be the mapping class represented by \tilde{F} . Then $g \in \text{Ker}(\theta)$, $g([d_i]) = [d_i]$ for all $1 \leq i \leq n-1$, and $g([c]) = [d_n]$.

Suppose now that q is on the arc e_2 . Then q is represented on Ω by two points q_3 and q_4 lying on two different sides of Ω which represent e_2 , and the trace of c in Ω is a simple arc ℓ connecting q_3 to q_4 . Up to isotopy (in Ω and not in $\Omega \setminus \{x\}$) pointwise fixing the boundary of Ω , there are exactly two simple arcs in Ω connecting q_3 to q_4 represented by the arcs ℓ_4 and ℓ_5 depicted in Figure 6.2. The arc ℓ cannot be isotopic to ℓ_5 , otherwise c would not be isotopic to d_{n-1} in Σ_n . So, ℓ is isotopic to ℓ_4 in Ω . Let $\{F_t : \Omega \rightarrow \Omega\}_{t \in [0,1]}$ be an isotopy such that $F_0 = \text{id}$, $F_1(\ell) = \ell_4$ and F_t is the identity on the boundary of Ω for all $t \in [0, 1]$. The arc ℓ_4 divides Ω into two parts, the upper one which does not contain the hole bounded by ∂ and the puncture x , and the lower one which contains the hole bounded by ∂ and the puncture x , as shown in Figure 6.2.

Suppose $F_1(x)$ is in the lower part. Let D be the domain of Ω bounded by ℓ_4 , two arcs of e_2 and an arc of d_{n-1} as shown in Figure 6.2. Let $D' = F_1^{-1}(D)$. Then D' is a domain of Ω bounded by ℓ , two arcs of e_2 and an arc of d_{n-1} which does not contain the puncture x . The existence of such a domain implies that c is isotopic to d_{n-1} in $\Sigma_n \setminus \{x\}$.

Suppose $F_1(x)$ is in the upper part. Let c' be the circle drawn in Figure 6.3. We can assume that the trace of c' on Ω is the arc ℓ_6 drawn in Figure 6.2. We can choose an isotopy $\{F'_t : \Omega \rightarrow \Omega\}_{t \in [0,1]}$ such that $F'_0 = \text{id}$, $F'_1(\ell_4) = \ell_6$, F'_t is the identity on the boundary of Ω for all $t \in [0, 1]$, and $F'_1(F_1(x)) = x$. Let $\tilde{F} : \Sigma_n \rightarrow \Sigma_n$ be the homeomorphism which is $F'_1 \circ F_1$ on Ω and is the identity outside Ω , and let $g_1 \in \mathcal{M}(\Sigma_n, x)$ be the mapping class represented by \tilde{F} . Then $g_1 \in \text{Ker}(\theta)$, $g_1([d_i]) = [d_i]$ for all $1 \leq i \leq n-1$, and $g_1([c]) = [c']$.

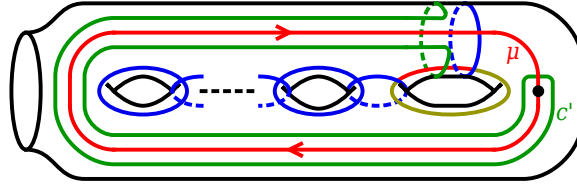


Figure 6.3: The circle c' and the loop μ

Let $g_2 \in \pi_1(\Sigma_n, x) = \text{Ker}(\theta)$ be the element represented by the loop μ drawn in Figure 6.3. We have $g_2([d_i]) = [d_i]$ for all $1 \leq i \leq n-2$, $g_2([d_{n-1}]) = [d_n]$ and $g_2([c']) = [d_{n-1}]$. Set $g = g_2 \circ g_1$. Then $g \in \text{Ker}(\theta)$, $g([d_i]) = [d_i]$ for all $1 \leq i \leq n-2$, $g([d_{n-1}]) = [d_n]$ and $g([c]) = [d_{n-1}]$. \square

Proof of Theorem 2.3 Let $n \geq 6$. Let $\varphi : A[D_n] \rightarrow A[D_n]$ be an endomorphism. We know from Theorem 2.2 that we have one of the following two possibilities up to conjugation.

- (1) $\varphi \circ \iota$ is cyclic.
- (2) There exist $\psi \in \langle \zeta, \chi \rangle$ and $p, q \in \mathbb{Z}$ such that $\varphi \circ \iota = \psi \circ \beta_{p,q}$.

Suppose $\varphi \circ \iota$ is cyclic. Then there exists $u \in A[D_n]$ such that $\varphi(t_i) = (\varphi \circ \iota)(s_i) = u$ for all $1 \leq i \leq n-1$. We also have

$$\begin{aligned} \varphi(t_n) &= \varphi(t_{n-2}t_n t_{n-2}^{-1} t_{n-2}^{-1}) = \varphi(t_{n-2}t_n) \varphi(t_{n-2}) \varphi(t_n^{-1} t_{n-2}^{-1}) = \\ &= \varphi(t_{n-2}t_n) \varphi(t_1) \varphi(t_n^{-1} t_{n-2}^{-1}) = \varphi(t_1) = u, \end{aligned}$$

hence φ is cyclic.

So, we can assume that there exist $\psi \in \langle \zeta, \chi \rangle$ and $p, q \in \mathbb{Z}$ such that $\varphi \circ \iota$ is conjugate to $\psi \circ \beta_{p,q}$. We set $Y = \{t_1, \dots, t_{n-2}, t_{n-1}\}$, $\Delta_Y = \Delta_Y[D_n]$, $\Delta_D = \Delta[D_n]$, $\kappa = 2$ if n is odd, and $\kappa = 1$ if n is even. Up to conjugating and composing φ on the left by ζ if necessary, we can assume that there exist $\varepsilon \in \{\pm 1\}$ and $p, q \in \mathbb{Z}$ such that $\varphi(t_i) = (\varphi \circ \iota)(s_i) = t_i^\varepsilon \Delta_Y^{2p} \Delta_D^{\kappa q}$ for all $1 \leq i \leq n-1$. The remainder of the proof is divided into four cases depending on whether p is zero or not and whether n is even or odd.

Case 1: n is even and $p \neq 0$. Then Σ_n is a surface of genus $\frac{n-2}{2}$ with two boundary components, ∂_1 and ∂_2 , and $\kappa = 1$. We have $\rho_D(t_i) = T_{d_i}$ for $1 \leq i \leq n-1$ and, by Labruère–Paris [28, Proposition 2.12], $\rho_D(\Delta_Y^2) = T_e T_{\partial_1}$ and $\rho_D(\Delta_D) = T_{\partial_1} T_{\partial_2}$, where e is the circle drawn in Figure 6.4. Set $f_i = (\rho_D \circ \varphi)(t_i)$ for all $1 \leq i \leq n$. Then, by the above,

$$f_i = T_{d_i}^\varepsilon T_e^p T_{\partial_1}^{p+q} T_{\partial_2}^q \quad \text{for all } 1 \leq i \leq n-1.$$

In particular, $\mathcal{S}(f_i) = \{[d_i], [e]\}$ for all $1 \leq i \leq n-1$. Since t_n is conjugate in $A[D_n]$ to t_1 , f_n is conjugate to f_1 in $\mathcal{M}(\Sigma_n, x)$, hence f_n is of the form $f_n = T_{d'}^\varepsilon T_{e'}^p T_{\partial_1}^{p+q} T_{\partial_2}^q$, where d' is a non-separating circle and e' is a circle that separates Σ_n into two components, one being a cylinder containing x and the other being a surface of genus $\frac{n-2}{2}$ with two boundary components, ∂_1 and e' , which does not contain x . Moreover, by Theorem 2.1, $(\pi \circ \varphi)(t_{n-1}) = (\pi \circ \varphi)(t_n)$, hence $\theta(f_{n-1}) = \theta(f_n)$. This implies that d' is isotopic to d_{n-1} in Σ_n . We have $f_i f_n = f_n f_i$, hence, by Proposition 3.3 (3) we have $f_n(\mathcal{S}(f_i)) = \mathcal{S}(f_i)$, thus $[e]$ is a reduction class for f_n , and therefore $i([e], [e']) = 0$, because $[e']$ is an essential reduction class for f_n . This combined with the fact that e' and ∂_1 cobound a subsurface of genus $\frac{n-2}{2}$ with two boundary components which does not contain x implies that $[e] = [e']$. So, we can assume that $e = e'$. Then the fact that d' does not intersect $e = e'$ and d' is isotopic to d_{n-1} in Σ_n implies that d' is isotopic to d_{n-1} in $\Sigma_n \setminus \{x\}$, hence we can also assume that $d' = d_{n-1}$. In conclusion we have $(\rho_D \circ \varphi)(t_{n-1}) = (\rho_D \circ \varphi)(t_n) = T_{d_{n-1}}^\varepsilon T_e^p T_{\partial_1}^{p+q} T_{\partial_2}^q$, hence $\varphi(t_{n-1}) = \varphi(t_n) = t_{n-1}^\varepsilon \Delta_Y^{2p} \Delta_D^q$. We conclude that $\varphi = \beta_{p,q} \circ \pi$ if $\varepsilon = 1$ and $\varphi = \chi \circ \beta_{-p,-q} \circ \pi$ if $\varepsilon = -1$.

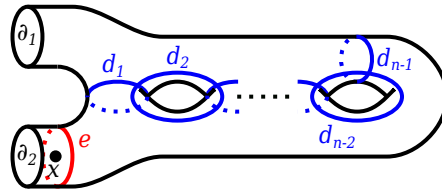


Figure 6.4: Circles in Σ_n , case where n is even and $p \neq 0$

Case 2: n is odd and $p \neq 0$. Then Σ_n is a surface of genus $\frac{n-1}{2}$ with one boundary component, ∂ , and $\kappa = 2$. We have $\rho_D(t_i) = T_{d_i}$ for $1 \leq i \leq n-1$ and, by Labruère–Paris [28, Proposition 2.12], $\rho_D(\Delta_Y^4) = T_e$ and $\rho_D(\Delta_D^2) = T_\partial$, where e is the circle drawn in Figure 6.5. Set $f_i = (\rho_D \circ \varphi)(t_i)$ for all $1 \leq i \leq n$. Then, by the above,

$$f_i^2 = T_{d_i}^{2\varepsilon} T_e^p T_\partial^{2q} \quad \text{for all } 1 \leq i \leq n-1.$$

In particular, $\mathcal{S}(f_i) = \mathcal{S}(f_i^2) = \{[d_i], [e]\}$ for all $1 \leq i \leq n-1$. The element t_n is conjugate to t_1 in $A[D_n]$, hence $\varphi(t_n)$ is conjugate to $\varphi(t_1)$ in $A[D_n]$, and therefore there exists $v \in A[D_n]$ such that

$\varphi(t_n) = v\varphi(t_1)v^{-1} = (vt_1v^{-1})(v\Delta_Y^{2p}v^{-1})\Delta_D^{2q}$. The element $\rho_D(vt_1v^{-1})$ is conjugate to $\rho_D(t_1) = T_{d_1}$, hence $\rho_D(vt_1v^{-1}) = T_{d'}$, where d' is a non-separating circle. The element $\rho_D(v\Delta_Y^{2p}v^{-1})$ is conjugate to $\rho_D(\Delta_Y^{2p}) = T_e$, hence $\rho_D(v\Delta_Y^{2p}v^{-1}) = T_{e'}$, where e' is a circle that separates Σ_n into two components, one being a cylinder containing x and the other being a surface of genus $\frac{n-1}{2}$ with one boundary component, e' , which does not contain x . We also have $f_n^2 = T_{d'}^2 T_{e'}^p T_{\partial}^{2q}$ and $\mathcal{S}(f_n) = \mathcal{S}(f_n^2) = \{[d'], [e']\}$. By Theorem 2.1 $(\pi \circ \varphi)(t_{n-1}) = (\pi \circ \varphi)(t_n)$, hence $\theta(f_{n-1}^2) = \theta(f_n^2)$. This implies that d' is isotopic to d_{n-1} in Σ_n . Since $f_1 f_n = f_n f_1$, by Proposition 3.3 (3) we have $f_n^2(\mathcal{S}(f_1)) = \mathcal{S}(f_1)$, hence $[e]$ is a reduction class for f_n^2 , and therefore $i([e], [e']) = 0$, because $[e']$ is an essential reduction class for f_n^2 . This combined with the fact that e' bounds a subsurface of genus $\frac{n-1}{2}$ with one boundary component which does not contain x implies that $[e] = [e']$. So, we can assume that $e = e'$. In particular, since ρ_D is injective, we have $v\Delta_Y^{2p}v^{-1} = \Delta_Y^{2p}$. Since d' does not intersect $e = e'$ and d' is isotopic to d_{n-1} in Σ_n , d' is isotopic to d_{n-1} in $\Sigma_n \setminus \{x\}$, hence we can also assume that $d' = d_{n-1}$. Since ρ_D is injective, this last equality implies that $vt_1v^{-1} = t_{n-1}$. At this level of the proof we have that $\varphi(t_n) = t_{n-1}^\varepsilon (v\Delta_Y^{2p}v^{-1})\Delta_D^{2q}$ and $(v\Delta_Y^{2p}v^{-1})^2 = v\Delta_Y^{4p}v^{-1} = \Delta_Y^{4p}$. It remains to show that $v\Delta_Y^{2p}v^{-1} = \Delta_Y^{2p}$.

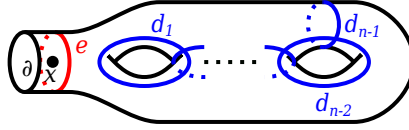


Figure 6.5: Circles in Σ_n , case where n is odd and $p \neq 0$

By Theorem 2.2 there exists $\psi \in \langle \zeta, \chi \rangle$ and $r, s \in \mathbb{Z}$ such that $\varphi \circ \zeta \circ \iota$ is conjugate to $\psi \circ \beta_{r,s}$. The automorphism ζ is inner since n is odd, hence we can assume that $\psi \in \langle \chi \rangle$. So, there exist $w \in A[D_n]$, $\mu \in \{\pm 1\}$ and $r, s \in \mathbb{Z}$ such that $\varphi(t_i) = wt_i^\mu \Delta_Y^{2r} \Delta_D^{2s} w^{-1}$ for all $1 \leq i \leq n-2$ and $\varphi(t_n) = wt_{n-1}^\mu \Delta_Y^{2r} \Delta_D^{2s} w^{-1}$. Set $g = \rho_D(w)$. We have $(\rho_D \circ \varphi)(t_i^2) = T_{d_i}^2 T_e^p T_{\partial}^{2q} = g T_{d_i}^2 T_e^p T_{\partial}^{2q} g^{-1}$ for all $1 \leq i \leq n-2$ and $(\rho_D \circ \varphi)(t_n^2) = T_{d_{n-1}}^2 T_e^p T_{\partial}^{2q} = g T_{d_{n-1}}^2 T_e^p T_{\partial}^{2q} g^{-1}$. So, $g^{-1}(\mathcal{S}(T_{d_i}^2 T_e^p T_{\partial}^{2q})) = \mathcal{S}(T_{d_i}^2 T_e^p T_{\partial}^{2q})$, hence $g^{-1}(\{[d_i], [e]\}) \subset \{[d_i], [e]\}$ for all $1 \leq i \leq n-1$. This implies $g^{-1}([d_i]) = [d_i]$, hence g commutes with T_{d_i} , and therefore w commutes with t_i for all $1 \leq i \leq n-1$. Since Δ_Y is in the subgroup of $A[D_n]$ generated by $Y = \{t_1, \dots, t_{n-1}\}$ and Δ_D^2 is central, it follows that $\varphi(t_i) = t_i^\mu \Delta_Y^{2r} \Delta_D^{2s}$ for all $1 \leq i \leq n-2$ and $\varphi(t_n) = t_{n-1}^\mu \Delta_Y^{2r} \Delta_D^{2s}$. From the equality $\varphi(t_1) = t_1^\varepsilon \Delta_Y^{2p} \Delta_D^{2q} = t_1^\mu \Delta_Y^{2r} \Delta_D^{2s}$ it easily follows that $\mu = \varepsilon$, $r = p$ and $s = q$, hence $\varphi(t_n) = t_{n-1}^\varepsilon \Delta_Y^{2p} \Delta_D^{2q}$. We conclude that $\varphi = \beta_{p,q} \circ \pi$ if $\varepsilon = 1$ and $\varphi = \chi \circ \beta_{-p,-q} \circ \pi$ if $\varepsilon = -1$.

Case 3: n is even and $p = 0$. Then, again, Σ_n is a surface of genus $\frac{n-2}{2}$ with two boundary components, ∂_1 and ∂_2 , and $\kappa = 1$. We have $\rho_D(t_i) = T_{d_i}$ for $1 \leq i \leq n-1$ and, by Labruère–Paris [28, Proposition 2.12], $\rho_D(\Delta_D) = T_{\partial_1} T_{\partial_2}$. Set $f_i = (\rho_D \circ \varphi)(t_i)$ for all $1 \leq i \leq n$. Then, by the above,

$$f_i = T_{d_i}^\varepsilon T_{\partial_1}^q T_{\partial_2}^q \quad \text{for all } 1 \leq i \leq n-1.$$

In particular, $\mathcal{S}(f_i) = \{[d_i]\}$ for all $1 \leq i \leq n-1$. Since t_n is conjugate in $A[D_n]$ to t_1 , f_n is of the form $f_n = T_{d'}^\varepsilon T_{\partial_1}^q T_{\partial_2}^q$ where d' is a non-separating circle.

For $1 \leq i \leq n-3$ we have $t_i t_n = t_n t_i$, hence $T_{d_i} T_{d'} = T_{d'} T_{d_i}$, and therefore, by Proposition 3.1, $i([d_i], [d']) = 0$. Similarly, we have $i([d_{n-1}], [d']) = 0$. Since $t_{n-2} t_n t_{n-2} = t_n t_{n-2} t_n$, we have $T_{d_{n-2}} T_{d'} T_{d_{n-2}} = T_{d'} T_{d_{n-2}} T_{d'}$, hence, by Proposition 3.1, $i([d_{n-2}], [d']) = 1$. So we can assume that

$d_i \cap d' = \emptyset$ for $1 \leq i \leq n-3$, $d_{n-1} \cap d' = \emptyset$ and $|d_{n-2} \cap d'| = 1$. Moreover, by Theorem 2.1, $(\pi \circ \varphi)(t_{n-1}) = (\pi \circ \varphi)(t_n)$, hence $\theta(f_{n-1}) = \theta(f_n)$, and therefore d' is isotopic to d_{n-1} in Σ_n . By lemma 5.5 it follows that we have one of the following two possibilities.

- (1) d' is isotopic to d_{n-1} in $\Sigma_n \setminus \{x\}$.
- (2) There exists $g \in \text{Ker}(\theta)$ such that $g([d_i]) = [d_i]$ for all $1 \leq i \leq n-1$ and $g([d']) = [d_n]$.

Suppose d' is isotopic to d_{n-1} in $\Sigma_n \setminus \{x\}$. Then $(\rho_D \circ \varphi)(t_n) = T_{d_{n-1}}^\varepsilon T_{\partial_1}^q T_{\partial_2}^q$, hence, since ρ_D is injective, $\varphi(t_n) = t_{n-1}^\varepsilon \Delta_D^q$. We conclude that $\varphi = \beta_{0,q} \circ \pi$ if $\varepsilon = 1$ and $\varphi = \chi \circ \beta_{0,-q} \circ \pi$ if $\varepsilon = -1$.

Suppose there exists $g \in \text{Ker}(\theta)$ such that $g([d_i]) = [d_i]$ for all $1 \leq i \leq n-1$ and $g([d']) = [d_n]$. We have

$$(\rho_D \circ \varphi)(t_i) = T_{d_i}^\varepsilon T_{\partial_1}^q T_{\partial_2}^q = g^{-1} T_{d_i}^\varepsilon T_{\partial_1}^q T_{\partial_2}^q g$$

for all $1 \leq i \leq n-1$ and

$$(\rho_D \circ \varphi)(t_n) = T_{d'}^\varepsilon T_{\partial_1}^q T_{\partial_2}^q = g^{-1} T_{d_n}^\varepsilon T_{\partial_1}^q T_{\partial_2}^q g.$$

By Theorem 3.6 there exists $v \in \text{Ker}(\pi) \subset A[D_n]$ such that $\rho_D(v) = g$. Since, ρ_D is injective it follows that

$$\varphi(t_i) = v^{-1} t_i^\varepsilon \Delta_D^q v \quad \text{for all } 1 \leq i \leq n.$$

We conclude that $\varphi = \text{ad}_{v^{-1}} \circ \gamma_q$ if $\varepsilon = 1$ and $\varphi = \text{ad}_{v^{-1}} \circ \chi \circ \gamma_{-q}$ if $\varepsilon = -1$.

Case 4: n is odd and $p = 0$. Then, again, Σ_n is a surface of genus $\frac{n-1}{2}$ with one boundary component, ∂ , and $\kappa = 2$. We have $\rho_D(t_i) = T_{d_i}$ for $1 \leq i \leq n-1$ and, by Labruère–Paris [28, Proposition 2.12], $\rho_D(\Delta_D^2) = T_\partial$. Set $f_i = (\rho_D \circ \varphi)(t_i)$ for all $1 \leq i \leq n$. Then, by the above,

$$f_i = T_{d_i}^\varepsilon T_\partial^q \quad \text{for all } 1 \leq i \leq n-1.$$

In particular, $\mathcal{S}(f_i) = \{[d_i]\}$ for all $1 \leq i \leq n-1$. Since t_n is conjugate in $A[D_n]$ to t_1 , f_n is conjugate to f_1 in $\mathcal{M}(\Sigma_n, x)$, hence f_n is of the form $f_n = T_{d'}^\varepsilon T_\partial^q$ where d' is a non-separating circle.

For $1 \leq i \leq n-3$ we have $t_i t_n = t_n t_i$, hence $T_{d_i} T_{d'} = T_{d'} T_{d_i}$, and therefore, by Proposition 3.1, $i([d_i], [d']) = 0$. Similarly, we have $i([d_{n-1}], [d']) = 0$. Since $t_{n-2} t_n t_{n-2} = t_n t_{n-2} t_n$, we have $T_{d_{n-2}} T_{d'} T_{d_{n-2}} = T_{d'} T_{d_{n-2}} T_{d'}$, hence, by Proposition 3.1, $i([d_{n-2}], [d']) = 1$. So, we can assume that $d_i \cap d' = \emptyset$ for $1 \leq i \leq n-3$, $d_{n-1} \cap d' = \emptyset$ and $|d_{n-2} \cap d'| = 1$. Moreover, by Theorem 2.1, $(\pi \circ \varphi)(t_{n-1}) = (\pi \circ \varphi)(t_n)$, hence $\theta(f_{n-1}) = \theta(f_n)$, and therefore d' is isotopic to d_{n-1} in Σ_n . By lemma 6.1 it follows that we have one of the following three possibilities.

- (1) d' is isotopic to d_{n-1} in $\Sigma_n \setminus \{x\}$.
- (2) There exists $g \in \text{Ker}(\theta)$ such that $g([d_i]) = [d_i]$ for all $1 \leq i \leq n-1$ and $g([d']) = [d_n]$.
- (3) There exists $g \in \text{Ker}(\theta)$ such that $g([d_i]) = [d_i]$ for all $1 \leq i \leq n-2$, $g([d_{n-1}]) = [d_n]$ and $g([d']) = [d_{n-1}]$.

If d' is isotopic to d_{n-1} in $\Sigma_n \setminus \{x\}$, then we prove as in the case where n is even that $\varphi = \beta_{0,q} \circ \pi$ if $\varepsilon = 1$ and $\varphi = \chi \circ \beta_{0,-q} \circ \pi$ if $\varepsilon = -1$. Similarly, if there exists $g \in \text{Ker}(\theta)$ such that $g([d_i]) = [d_i]$ for all $1 \leq i \leq n-1$ and $g([d']) = [d_n]$, then we prove as in the case where n is even that $\varphi = \text{ad}_{v^{-1}} \circ \gamma_q$ if $\varepsilon = 1$ and $\varphi = \text{ad}_{v^{-1}} \circ \chi \circ \gamma_{-q}$ if $\varepsilon = -1$, where v is an element of $\text{Ker}(\pi) \subset A[D_n]$.

Suppose there exists $g \in \text{Ker}(\theta)$ such that $g([d_i]) = [d_i]$ for all $1 \leq i \leq n-2$, $g([d_{n-1}]) = [d_n]$ and $g([d']) = [d_{n-1}]$. We have

$$\begin{aligned}(\rho_D \circ \varphi)(t_i) &= T_{d_i}^\varepsilon T_\partial^q = g^{-1} T_{d_i}^\varepsilon T_\partial^q g \quad \text{for } 1 \leq i \leq n-2, \\(\rho_D \circ \varphi)(t_{n-1}) &= T_{d_{n-1}}^\varepsilon T_\partial^q = g^{-1} T_{d_n}^\varepsilon T_\partial^q g, \\(\rho_D \circ \varphi)(t_n) &= T_{d'}^\varepsilon T_\partial^q = g^{-1} T_{d_{n-1}}^\varepsilon T_\partial^q g.\end{aligned}$$

By Theorem 3.6 there exists $v \in \text{Ker}(\pi) \subset A[D_n]$ such that $\rho_D(v) = g$. Since ρ_D is injective it follows that

$$\begin{aligned}\varphi(t_i) &= v^{-1} t_i^\varepsilon \Delta_D^{2q} v \quad \text{for } 1 \leq i \leq n-2, \\ \varphi(t_{n-1}) &= v^{-1} t_n^\varepsilon \Delta_D^{2q} v, \quad \varphi(t_n) = v^{-1} t_{n-1}^\varepsilon \Delta_D^{2q} v.\end{aligned}$$

We conclude that $\varphi = \text{ad}_{v^{-1}} \circ \zeta \circ \gamma_q$ if $\varepsilon = 1$ and $\varphi = \text{ad}_{v^{-1}} \circ \zeta \circ \chi \circ \gamma_{-q}$ if $\varepsilon = -1$. \square

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