

## Research Article

# Fixed Points of Maps of a Nonaspherical Wedge

**Seung Won Kim,<sup>1</sup> Robert F. Brown,<sup>2</sup> Adam Ericksen,<sup>3</sup>  
Nirattaya Khamsemanan,<sup>4</sup> and Keith Merrill<sup>5</sup>**

<sup>1</sup> Department of Mathematics, College of Science, Kyungsoong University, Busan 608-736, South Korea

<sup>2</sup> Department of Mathematics, University of California, Los Angeles, CA 90095, USA

<sup>3</sup> Department of Mathematics, University of Southern California, Los Angeles, CA 90089, USA

<sup>4</sup> Sirindhorn International Institute of Technology, Thammasat University, Pathum Thani 12121, Thailand

<sup>5</sup> Department of Mathematics, Brandeis University, Belmont, MA 02453, USA

Correspondence should be addressed to Seung Won Kim, kimsww@ks.ac.kr

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Let  $X$  be a finite polyhedron that has the homotopy type of the wedge of the projective plane and the circle. With the aid of techniques from combinatorial group theory, we obtain formulas for the Nielsen numbers of the selfmaps of  $X$ .

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## 1. Introduction

Although compact surfaces were the setting of Nielsen's fixed point theory in 1927 [1], until relatively recently the calculation of the Nielsen number was restricted to maps of very few surfaces. For surfaces with boundary, such calculations were possible on the annulus and Möbius band because they have the homotopy type of the circle. In 1987 [2], Kelly used the commutativity property of the Nielsen number to make calculations for a family of maps of the disc with two holes. We will discuss Kelly's technique in more detail below. The first general algorithm for calculating Nielsen numbers of maps of surfaces with boundary was published by Wagner in 1999 [3]. It applies to many maps and recent research has significantly extended the class of such maps whose Nielsen number can be calculated (see [4–7] and, especially, the survey article [8]). This approach makes use of the fact that a surface with boundary has the homotopy type of a wedge of circles. For the calculation of the Nielsen number, Wagner and her successors employ techniques of combinatorial group theory.

The key properties of surfaces with boundary that are exploited in the Wagner-type calculations are that they have the homotopy type of a wedge and that they are aspherical spaces so their selfmaps are classified up to homotopy by the induced homomorphisms of the fundamental group. The paper [9] studies the fixed point theory of maps of other

aspherical spaces that have the homotopy type of a wedge, for instance the wedge of a torus and a circle. The purpose of this paper is to demonstrate that combinatorial group theory furnishes powerful tools for the calculation of Nielsen numbers, even for maps of a nonaspherical space. We investigate a setting that is not aspherical and hence fundamental group information is not sufficient to classify selfmaps up to homotopy. We obtain explicit, easily calculated formulas for the Nielsen numbers of these maps.

Denote the projective plane by  $P$  and the circle by  $C$ . This paper is concerned with maps of finite polyhedra that have the homotopy type of the wedge  $X = P \vee C$ . If the polyhedron has no local cut points but is not a surface, then the Nielsen number of a map is the minimum number of fixed points among all the maps homotopic to it [10]. However, since a map of such a polyhedron has the homotopy type of a map of  $X$  and the Nielsen number is a homotopy type invariant, we will assume that we are concerned only with maps of  $X$  itself. We identify  $P$  and  $C$  with their images in  $X$  and denote their intersection by  $x_0$ . We need to consider only selfmaps of  $X$  and their homotopies that preserve  $x_0$ . The fundamental group of  $X$  at  $x_0$  is the free product of a group of order two, whose generator we denote by  $a$ , and, choosing an orientation for  $C$ , the infinite cyclic group generated by  $b$ . To simplify notation, throughout the paper we denote the fundamental group homomorphism induced by a map by the same letter as the map because it will be clear from the context whether it represents the map or the homomorphism. Since all maps from  $P$  to  $C$  are homotopic to the constant map, we may assume that  $f_P$ , the restriction of  $f : X \rightarrow X$  to  $P$ , maps  $P$  to itself.

The paper is organized as follows. We will describe in the next section a standard form for the map  $f$  in which the fixed point set is minimal on  $P$  and on  $C$  the fixed point set consists of  $x_0$  together with a fixed point for each appearance of  $b$  or  $b^{-1}$  in the fundamental group element  $f(b)$ . In Section 3 we calculate the Nielsen numbers  $N(f)$  of the maps for which  $f(a) = 1$  by proving that, in that case,  $N(f)$  equals the Nielsen number of a certain selfmap of  $C$  obtained from  $f$  and therefore  $N(f)$  is determined by the degree of that map. In Section 4 we obtain formulas for the Nielsen numbers of almost all maps for which  $f(a) = a$ . The formulas depend on integers obtained from the word  $f(b)$  in the fundamental group of  $X$ . However, the nonaspherical nature of  $X$ , which makes fundamental group information insufficient to determine the homotopy class of a map, requires us to find two different formulas for each word  $f(b)$ . One formula calculates  $N(f)$  in the case that  $f_P$  is homotopic to the identity map whereas the other applies when  $f_P$  belongs to one of the infinite number of homotopy classes that do not contain the identity map. Section 5 then considers the two exceptional cases that are not calculated in Section 4. We demonstrate there that even if the induced fundamental group homomorphisms in these cases vary only slightly from those of Section 4, their Nielsen numbers can differ by an arbitrarily large amount. Section 6 presents the proof of a technical lemma from Section 4.

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## 2. The Standard Form of $f$

Given a map  $f : (X, x_0) \rightarrow (X, x_0)$  where  $X = P \vee C$ , we write

$$f(b) = a^{\epsilon_1} b^{k_1} a b^{k_2} \dots a b^{k_m} a^{\epsilon_2}, \quad (2.1)$$

where  $\epsilon_i = 0, 1$  and  $k_j \neq 0$  for all  $j$ .

Let  $f_C : C \rightarrow X$  denote the restriction of  $f$  to  $C$ . By the simplicial approximation theorem, we may homotope  $f_C$  to a map with the property that the inverse image of  $x_0$  is a finite union of points and arcs. A further homotopy reduces the inverse image of  $x_0$  to a finite set and we view  $C$  as the union of arcs whose endpoints are mapped to  $x_0$ . We then homotope the map restricted to each arc, relative to the endpoints, so that it is a loop in  $X$  that is an embedding except at the endpoints and it represents either  $a, b$  or  $b^{-1}$ . If the restriction of the map to adjacent arcs corresponds to any of  $aa, bb^{-1}$  or  $b^{-1}b$ , we can homotope the map to a map constant at  $x_0$  on both intervals and then shrink the intervals. We will continue to denote the map by  $f_C : C \rightarrow X$ . Starting with  $x_0 = v_0$  and moving along the circle clockwise until we come to a point of  $f_C^{-1}(x_0)$  which we call  $v_1$ , we denote the arc in  $C$  from  $v_0$  to  $v_1$  by  $J_1$ . Continuing in this manner, we obtain arcs  $J_1, \dots, J_n$  where the endpoints of  $J_n$  are  $v_n$  and  $v_0$ . As a final step, we homotope the map so that it is constant at  $x_0$  on arcs  $J_0$  and  $J_{n+1}$  that form a neighborhood of  $x_0$  in  $C$ . Thus we have constructed a map, still written  $f_C : C \rightarrow X$ , that is constant on  $J_0$  and  $J_{n+1}$  and, otherwise, its restriction to an arc is a loop representing  $a, b$  or  $b^{-1}$  according to the form of  $f(b)$  above, in the order of the orientation of  $C$ .

Given a map  $f : X \rightarrow X$ , we may deform  $f$  by a homotopy so that  $f_P$ , its restriction to  $P$ , maps  $P$  to itself. We will make use of the constructions of Jiang in [11] to deform  $f$  so that  $f_P$  has a minimal fixed point set. If  $f(a) = f_P(a) = 1$ , then  $f_P$  belongs to one of two possible homotopy classes and, in both cases, Jiang constructs homotopies of  $f_P$  to a map with a single fixed point, which we may take to be  $x_0$ . Let  $\tilde{f}_P : S^2 \rightarrow S^2$  denote a lift of  $f_P$  to the universal covering space, then the degree of  $\tilde{f}_P$  is determined up to sign and we denote its absolute value by  $d(f_P)$ . If  $f(a) = f_P(a) = a$ , the homotopy class of  $f_P$  is determined by  $d(f_P)$ , which must be an odd natural number. If  $f_P$  is a deformation, that is, it is homotopic to the identity map, then  $d(f_P) = 1$  and Jiang constructs a map homotopic to  $f_P$  with a single fixed point, which we again take to be  $x_0$ . For the remaining cases, where  $d(f_P) \geq 3$ , the Nielsen number  $N(f_P) = 2$  and Jiang constructs maps homotopic to  $f_P$  with two fixed points. We take one of those fixed points to be  $x_0$  and denote the other fixed point by  $y_0$ .

We also homotope  $f$  so that  $f_C$ , its restriction to  $C$ , is in the form described above. The map thus obtained we call the *standard form* of  $f$  and denote it also by  $f : X \rightarrow X$ . We note that, for each  $b$  in  $f(b)$  there is exactly one fixed point of  $f$  in  $C$ , of index  $-1$ , and for each  $b^{-1}$  in  $f(b)$  there is one fixed point, of index 1. The fixed points  $x_0$  and  $y_0$  are of index 1, see [11]. For the rest of the paper, all maps  $f : X \rightarrow X$  will be assumed to be in standard form.

Our tools for calculating the Nielsen numbers come from Wagner's paper [3] which we will describe in the specific setting of selfmaps of  $X$ . Let  $x_p$  be a fixed point of  $f$  in  $C$  which is distinct from  $x_0$ , then  $x_p$  lies in an arc corresponding to an element  $b$  or  $b^{-1}$  in  $f(b)$ ; we write  $x_p \in b$  or  $x_p \in b^{-1}$ . We identify this element by writing  $f(b) = V_p b \bar{V}_p$  or  $f(b) = V_p b^{-1} \bar{V}_p$ . The *Wagner tails*  $W_p, \bar{W}_p \in \pi_1(X, x_0)$  of the fixed point  $x_p$  are defined by  $W_p = V_p$  and  $\bar{W}_p = \bar{V}_p^{-1}$  if  $x_p \in b$  and by  $W_p = V_p b^{-1}$  and  $\bar{W}_p = \bar{V}_p^{-1} b$  if  $x_p \in b^{-1}$ .

We will use the following results of Wagner.

**Lemma 2.1** (see [3, Lemma 1.3]). *For any fixed point  $x_p$  of  $f$  on  $C$ ,*

$$f(b) = W_p b \bar{W}_p^{-1}. \quad (2.2)$$

**Lemma 2.2** (see [3, Lemma 1.5]). *If  $x_p$  and  $x_q$  are fixed points of  $f : X \rightarrow X$  on  $C$ , then  $x_p$  and  $x_q$  are in the same fixed point class if and only if there exists  $z \in \pi_1(X, x_0)$  such that*

$$z = W_p^{-1} f(z) W_q. \quad (2.3)$$

Wagner's Lemma 1.5 concerns the case  $Y \vee C$  where  $Y$  is a wedge of circles. However, the same proof establishes the statement of Lemma 2.2 for  $X = P \vee C$ . When (2.3) holds, we will say that  $x_p$  and  $x_q$  are  $f$ -Nielsen equivalent by  $z$  or, when the context is clear, more briefly that  $x_p$  and  $x_q$  are *equivalent*.

### 3. The $f(a) = 1$ Case

If  $Y$  is an aspherical polyhedron and a map  $f : Y \vee C \rightarrow Y \vee C$  induces a homomorphism of the fundamental group that is trivial on the  $\pi_1(Y, x_0)$  factor of  $\pi_1(Y \vee C, x_0)$ , then  $f$  is homotopic to the map  $f_C \pi$  where  $\pi : X \rightarrow C$  is the retraction sending  $Y$  to  $x_0$ . Therefore, by the commutativity property of the Nielsen number,  $N(f) = N(f_C \pi) = N(\pi f_C)$ . Since  $\pi f_C : C \rightarrow C$ , its Nielsen number is easily calculated. This is the technique that Kelly used, with  $Y = C$ , in [2] to construct his examples. If  $Y$  is not aspherical, then a map  $f$  that induces a homomorphism that is trivial on the  $\pi_1(Y, x_0)$  factor need not be homotopic to  $f_C \pi$ . However, when  $Y = P$ , we will prove that it is still true that  $N(f) = N(\pi f_C)$ .

We note that since, in the  $f(a) = 1$  case, all fixed points of  $f$  lie in  $C$ , then the fixed point sets of  $f$  and of  $\pi f_C$  consist of the same points. Moreover, the fixed point index of each fixed point is the same whether we view it as a fixed point of  $f$  or of  $\pi f_C$ . We will demonstrate that the fixed point classes of  $f$  and of  $\pi f_C$  are also the same, and thus the Nielsen numbers are equal.

Since  $C$  is a circle with fundamental group generated by  $b$ , the condition corresponding to Wagner's for  $x_p$  and  $x_q$  to be in the same fixed point class of  $\pi f_C : C \rightarrow C$  in [3, Lemma 1.5] is that there exist an integer  $r$  such that

$$b^r = \pi(W_p)^{-1} \pi f_C(b^r) \pi(W_q). \quad (3.1)$$

That is, there exists  $z \in \pi_1(X, x_0)$  such that

$$\pi(z) = \pi(W_p)^{-1} \pi f_C(\pi(z)) \pi(W_q). \quad (3.2)$$

Although Wagner's paper [3] assumes reduced form for map and  $\pi f_C(b)$  may not be in reduced form, in fact that condition is not used in the proof of [3, Lemma 1.5] so the existence of  $z$  satisfying (3.2) is still equivalent to the statement that  $x_p$  and  $x_q$  are in the same fixed point class of  $\pi f_C$ . Corresponding to the previous terminology, in this case we will say that  $x_p$  and  $x_q$  are  $\pi f_C$ -Nielsen equivalent by  $\pi(z)$ .

We have

$$f(b) = a^{\varepsilon_1} b^{k_1} a b^{k_2} \dots a b^{k_m} a^{\varepsilon_2}, \quad (3.3)$$

where  $\epsilon_i = 0, 1$  and  $k_j \neq 0$  for all  $j$ . Let  $k$  be the sum of the  $k_j$  from 1 to  $m$ . Similarly, for an element  $z \in \pi_1(X, x_0)$ , we write

$$z = a^{\eta_1} b^{\ell_1} a b^{\ell_2} \dots a b^{\ell_n} a^{\eta_2} \quad (3.4)$$

where, as before,  $\eta_i = 0, 1$  and  $\ell_j \neq 0$  for all  $j$ . Let  $\ell$  be the sum of all the  $\ell_j$  from 1 to  $n$ . The retraction  $\pi : X \rightarrow C$  induces  $\pi : \pi_1(X, x_0) \rightarrow \pi_1(C, x_0)$  such that  $\pi(a) = 1$  and  $\pi(b) = b$  and thus  $\pi(f(b)) = b^k$  and  $\pi(z) = b^\ell$ . For fixed points  $x_p, x_q$ , define  $g = W_p^{-1}W_q$ , then  $\pi(g) = b^v$  for some integer  $v$ .

**Lemma 3.1.** *If  $f(a) = 1$ , then the following are equivalent:*

- (1)  $x_p$  and  $x_q$  are  $f$ -Nielsen equivalent by  $z$ ,
- (2)  $x_p$  and  $x_q$  are  $\pi f_C$ -Nielsen equivalent by  $\pi(z)$ ,
- (3)  $\ell = k\ell + v$ .

*Proof.* (1) $\Rightarrow$ (2) If  $x_p$  and  $x_q$  are  $f$ -Nielsen equivalent by  $z$ , there exists  $z \in \pi_1(X, x_0)$  such that

$$z = W_p^{-1}f(z)W_q \quad (3.5)$$

so

$$\pi(z) = \pi(W_p)^{-1}\pi f(z)\pi(W_q). \quad (3.6)$$

Every element of finite order in the fundamental group of  $X$  is a conjugate of an element of finite order in  $a$  or in  $b$ . Therefore,  $f_p(a) = 1$  implies that  $f(a) = 1$  so we have  $f(z) = f_C(\pi(z))$  and thus

$$\pi(z) = \pi(W_p)^{-1}\pi f_C(\pi(z))\pi(W_q). \quad (3.7)$$

As we noted above, (3.7) implies that  $x_p$  and  $x_q$  are  $\pi f_C$ -Nielsen equivalent by  $\pi(z)$ .

(2) $\Rightarrow$ (3) If  $x_p$  and  $x_q$  are  $\pi f_C$ -Nielsen equivalent by  $\pi(z)$ , then we have (3.7). Since  $\pi(z) = b^\ell$ , we see that

$$\begin{aligned} b^\ell &= \pi(W_p^{-1}f(z)W_q) \\ &= \pi(W_p)^{-1}\pi(f(b))^\ell\pi(W_p)\pi(g) \\ &= \pi(f(b))^\ell\pi(g) = (b^k)^\ell b^v. \end{aligned} \quad (3.8)$$

and conclude that  $\ell = k\ell + v$ .

(3) $\Rightarrow$ (1) Suppose that  $\ell = k\ell + v$ . Since  $f(a) = 1$ , then  $f(g) = f(b)^v$ . If  $k = 1$ , it must be that  $v = 0$ . So, if we let  $z = g$ , then  $f(z) = f(g) = f(b)^v = 1$  and thus

$$W_p^{-1}f(z)W_q = W_p^{-1}W_q = g = z, \quad (3.9)$$

that is,  $x_p$  and  $x_q$  are  $f$ -Nielsen equivalent by this  $z$ . If  $k \neq 1$ , we define  $U_p = b(\overline{W_p})^{-1}$  and, again using the hypothesis  $f(a) = 1$ , we can write  $f(U_p) = f(b)^r$  for some integer  $r$ . That hypothesis also implies that

$$f(f(b)) = f(a^{\epsilon_1} b^{k_1} a b^{k_2} \dots a b^{k_m} a^{\epsilon_2}) = f(b)^k. \quad (3.10)$$

Now writing  $f(b) = W_p b (\overline{W_p})^{-1} = W_p U_p$ , we see that

$$U_p W_p = U_p (W_p U_p) U_p^{-1} = U_p f(b) U_p^{-1}. \quad (3.11)$$

If we let  $z = (U_p W_p)^\ell g$  then, since  $k\ell + v = \ell$ , we have

$$\begin{aligned} f(z) &= f((U_p W_p)^\ell g) = f((U_p f(b) U_p^{-1})^\ell g) \\ &= f(U_p f(b)^\ell U_p^{-1} g) \\ &= f(b)^r (f(b)^k)^\ell f(b)^{-r} f(b)^v \\ &= f(b)^{k\ell+v} = f(b)^\ell = (W_p U_p)^\ell. \end{aligned} \quad (3.12)$$

Therefore,

$$W_p^{-1} f(z) W_p = W_p^{-1} (W_p U_p)^\ell (W_p g) = (U_p W_p)^\ell g = z \quad (3.13)$$

which again means that  $x_p$  and  $x_q$  are  $f$ -Nielsen equivalent by  $z$ .  $\square$

Since Lemma 3.1 has demonstrated that the fixed point classes of  $f$  and of  $\pi f_C$  are identical and the Nielsen number of a map of the circle is determined by its degree, we have

**Theorem 3.2.** *Let  $\pi : \pi_1(X, x_0) \rightarrow \pi_1(C, x_0)$  be induced by retraction. If  $f : X \rightarrow X$  is a map such that  $f(a) = 1$  and  $\pi(f(b)) = b^k$ , then*

$$N(f) = N(\pi f_C) = |1 - \deg(\pi f_C)| = |1 - k|. \quad (3.14)$$

#### 4. The $f(a) = a$ Case

Let  $f : (X, x_0) \rightarrow (X, x_0)$  be a map, where  $X = P \vee C$ , such that  $f(a) = a$ . We will use Lemma 2.2 to calculate the Nielsen number of most such maps. We write

$$f(b) = a^{\epsilon_1} b^{k_1} a b^{k_2} \dots a b^{k_m} a^{\epsilon_2}, \quad (4.1)$$

where  $\epsilon_i = 0, 1$  and  $k_j \neq 0$  for all  $j$ . Suppose that  $\epsilon_2 = 1$ . Then there is a map  $h : (X, x_0) \rightarrow (X, x_0)$  that induces the homomorphism  $h(\cdot) = a f(\cdot) a$ , that is,  $h(a) = a$  and

$h(b) = a^{\varepsilon_1+1}b^{k_1}ab^{k_2}\dots ab^{k_m}$ . (2.3) of Lemma 2.2 is satisfied for  $f$  if and only if it is satisfied for  $h$ . Thus, we can assume that  $\varepsilon_2 = 0$  in  $f(b)$  and we write

$$f(b) = a^\varepsilon b^{k_1} ab^{k_2} \dots ab^{k_m} = a^\varepsilon c d c^{-1}, \quad (4.2)$$

where  $\varepsilon = 0, 1$  and either  $d = a$  or  $d$  is cyclically reduced, which means that  $dd$  is a reduced word. Then, for some integers  $r$  and  $t$ ,

$$c = b^{k_1} ab^{k_2} \dots b^{k_r} ab^t, \quad d = b^{k_{r+1}-t} a \dots ab^{k_{m-r}+t}, \quad (4.3)$$

where  $t$  may be zero. If  $t \neq 0$ , then either  $k_{r+1} = t$  or  $k_{m-r} = -t$ . Let  $r = 0$  when  $c = b^t$ .

Now suppose that fixed points  $x_p$  and  $x_q$  are equivalent by

$$z = a^{\eta_1} b^{\ell_1} ab^{\ell_2} \dots ab^{\ell_n} a^{\eta_2}, \quad (4.4)$$

where  $\eta_i = 0, 1$  and  $\ell_j \neq 0$  for all  $j$ . Let  $L$  denote the sum of the  $|\ell_i|$  from 1 to  $n$  and let

$$R = W_p^{-1} f(z) W_q = W_p^{-1} a^{\eta_1} (a^\varepsilon c d c^{-1})^{\ell_1} a \dots a (a^\varepsilon c d c^{-1})^{\ell_n} a^{\eta_2} W_q \quad (4.5)$$

be the right-hand side of the (2.3) of Lemma 2.2.

Denote the length of a word  $w$  in  $\pi_1(X, x_0)$  by  $|w|$ , where the unit element is of length zero.

**Lemma 4.1.** *Suppose  $x_p$  and  $x_q$  are equivalent fixed points of  $f$ . If  $\varepsilon = 0$  and  $d \neq a$ , then  $W_p = \overline{W}_q$  or  $\overline{W}_p = W_q$ .*

*Proof.* Suppose that  $\varepsilon = 0$  and  $d \neq a$ . Then

$$R = W_p^{-1} a^{\eta_1} c d^{\ell_1} c^{-1} a \dots a c d^{\ell_n} c^{-1} a^{\eta_2} W_q. \quad (4.6)$$

*Case 1.*  $\eta_1 = 1$  and  $\eta_2 = 1$ .

Since  $\varepsilon = 0$  so that  $f(b)$  starts and ends with  $b$  or  $b^{-1}$ , it follows that one of those elements ends  $W_p^{-1}$  and one of them starts  $W_q$ . Since  $\eta_1 = \eta_2 = 1$ , we see that  $R$  is reduced ( $c$  may be 1) and therefore

$$\begin{aligned} |R| &= |W_p| + |W_q| + (n+1)|a| + 2n|c| + L|d| \\ &> (n+1) + L \quad (\text{because } |W_p| + |W_q| > 0) \\ &= |z|. \end{aligned} \quad (4.7)$$

This is a contradiction and thus there is no solution in this case.

*Case 2.*  $\eta_1 = 0$  and  $\eta_2 = 1$ . ( $\eta_1 = 1$  and  $\eta_2 = 0$  is similar.)

If there is no cancellation between  $W_p^{-1}$  and  $d^{\ell_1}$ , then we can see that the solution  $z$  does not exist as in Case 1. Suppose there is a cancellation between  $W_p^{-1}$  and  $d^{\ell_1}$ . Suppose  $\ell_1 < 0$

and write  $d = d_1 d_2$  where  $d_2^{-1}$  is the part of  $d^{-1}$  that is cancelled by  $W_p^{-1}$ , then  $W_p^{-1} = \widehat{W}_p^{-1} d_2 c^{-1}$ . By Lemma 2.1,

$$cdc^{-1} = f(b) = W_p b \overline{W}_p^{-1} = cd_2^{-1} \widehat{W}_p b \overline{W}_p^{-1} \quad (4.8)$$

so  $d = d_1 d_2 = d_2^{-1} d_0 d_2$ , for some word  $d_0$ , which contradicts the assumption that  $d$  is cyclically reduced. Thus  $\ell_1 > 0$  so we may write  $z = bz'$  and we have

$$\begin{aligned} bz' &= W_p^{-1} f(bz') W_q \\ &= W_p^{-1} f(b) f(z') W_q \\ &= W_p^{-1} (W_p b \overline{W}_p^{-1}) f(z') W_q \quad (\text{by Lemma 2.1}) \\ &= W_p^{-1} (W_p b \overline{W}_p^{-1}) cd^{(\ell_1-1)} c^{-1} a \cdots acd^{\ell_n} c^{-1} a W_q. \end{aligned} \quad (4.9)$$

and thus

$$z' = \overline{W}_p^{-1} cd^{(\ell_1-1)} c^{-1} a \cdots acd^{\ell_n} c^{-1} a W_q. \quad (4.10)$$

We have shown that  $\ell_1$  cannot be negative and, if  $\ell_1 = 1$  then  $z'$  begins with  $\overline{W}_p^{-1} a$  which cannot be reduced since  $\varepsilon = 0$  implies that  $\overline{W}_p^{-1}$  ends with either  $b$  or  $b^{-1}$ . So suppose  $\ell_1 > 1$  and  $\overline{W}_p^{-1}$  cancels part of  $d^{(\ell_1-1)}$ . Then  $\overline{W}_p^{-1}$  must end with  $c^{-1}$  to cancel  $c$  and, since  $\overline{W}_p^{-1}$  is either  $\overline{V}_p$  or  $b^{-1} \overline{V}_p$ , further cancellation would cancel parts of  $dd$ . But  $d$  is cyclically reduced and therefore we conclude that there is no further cancellation. Thus, as in Case 1, there are no solutions  $z'$  to this equation.

*Case 3.*  $\eta_1 = 0$  and  $\eta_2 = 0$ .

If  $n \geq 2$ , then an argument similar to that of Case 2 applies. Thus we may assume that  $n = 1$ , which implies that  $z = b$  or  $z = b^{-1}$ . Suppose that  $z = b$ , then

$$b = W_p^{-1} f(b) W_q = W_p^{-1} (W_p b \overline{W}_p^{-1}) W_q = b \overline{W}_p^{-1} W_q. \quad (4.11)$$

and so  $\overline{W}_p = W_q$ . Similarly, if  $z = b^{-1}$ , then  $W_p = \overline{W}_q$ .  $\square$

**Lemma 4.2.** *Suppose  $x_p$  and  $x_q$  are equivalent fixed points of  $f$ . If  $\varepsilon = 1$  and  $d \neq a$ , then  $W_p = \overline{W}_q$  or  $\overline{W}_p = W_q$ .*

The proof of Lemma 4.2 is similar to that of Lemma 4.1, but it requires the analysis of a greater number of cases, so we postpone it to Section 6.

Suppose  $x_p, x_q$  are fixed points of  $f$  with  $x_p \in b$  and  $x_q \in b$ , then  $W_p = W_q$  implies  $x_p = x_q$  because  $f$  is in standard form; the same is true in the case  $x_p \in b^{-1}$  and  $x_q \in b^{-1}$ . In these cases,  $\overline{W}_p = \overline{W}_q$  also implies  $x_p = x_q$ . On the other hand, if  $x_p \in b^{-1}$  and  $x_q \in b$  or  $x_p \in b$  and  $x_q \in b^{-1}$ , then  $W_p \neq W_q$  and  $\overline{W}_p \neq \overline{W}_q$ . Thus, in our setting, the only ways that



two distinct fixed points  $x_p$  and  $x_q$  of  $f$  can be *directly related* in the sense of [3, page 47] are if  $W_p = \overline{W}_q$  or if  $W_q = \overline{W}_p$ . The point of Lemmas 4.1 and 4.2 is that, if two fixed points in  $C$  are equivalent, then they *must* be directly related rather than related by intermediate fixed points. It is this property that permits the calculations of Nielsen numbers that occupy the rest of this section.

We continue to assume that  $f$  is in standard form and  $f(a) = a$ . If  $f_p$  is a deformation, then  $x_0$  is the only fixed point of  $f$  on  $P$ . Otherwise, there is another fixed point of  $f$  on  $P$  denoted by  $y_0$  and both  $x_0$  and  $y_0$  are of index 1, see [11]. We again write  $x_p \in b$  or  $x_p \in b^{-1}$  depending on whether  $f$  maps the arc containing  $x_p$  to  $b$  or to  $b^{-1}$ . The fixed points of  $f$  on  $C$  are  $x_0, x_1, x_2, \dots, x_{K-1}, x_K$ , ordered so that  $x_1$  lies in the arc corresponding to the first appearance of  $b$  or  $b^{-1}$  in  $f(b)$ . Moreover, for  $w$  a subword of  $f(b)$ , we write  $x_p \in w$  if  $x_p$  lies in an arc corresponding to an element of  $w$ . Let  $K_d$  denote the number of fixed points  $x_p$  such that  $x_p \in d$ .

**Lemma 4.3.** *Suppose  $f_p$  is not a deformation and, if  $\epsilon = 1$ , suppose also that  $d \neq a$ . If  $\epsilon = 1$  and  $x_1 \in b$ , then  $y_0$  and  $x_1$  are equivalent. Otherwise,  $y_0$  is not equivalent to any other fixed point of  $f$ .*

*Proof.* Let  $x_j \in C$  be a fixed point of  $f$  and let  $\gamma^+$  and  $\gamma^-$  denote the arcs of  $C$  going from  $x_0$  to  $x_j$  in the clockwise and counterclockwise directions, respectively. Then  $f(\gamma^+) = W\gamma^+$  and  $f(\gamma^-) = \overline{W}\gamma^-$ , where  $W$  and  $\overline{W}$  are the Wagner tails of  $x_j$ . The fixed points  $y_0$  and  $x_j$  are equivalent if and only if there is a path  $\beta$  in  $X$  from  $y_0$  to  $x_j$  such that the loops  $\gamma^+\beta^{-1}f(\beta)(\gamma^+)^{-1}$  and  $\gamma^-\beta^{-1}f(\beta)(\gamma^-)^{-1}$  represent the identity element of  $\pi_1(X, x_0)$ . Using a homotopy, we may assume that  $\beta$  is of the form  $\alpha z \gamma^+$  or  $\alpha z \gamma^-$  where  $\alpha$  is a path in  $P$  from  $y_0$  to  $x_0$  and  $z$  is a loop in  $X$  based at  $x_0$ . Since, by [11], the fixed points  $y_0$  and  $x_0$  are not  $f_p$ -Nielsen equivalent, then  $[\alpha^{-1}f(\alpha)] = a$ , the only nonidentity element of  $\pi_1(P, x_0)$ .

If  $\beta = \alpha z \gamma^+$ , then  $y_0$  and  $x_j$  are equivalent by  $\beta$  if and only if

$$\begin{aligned} 1 &= [\gamma^+\beta^{-1}f(\beta)(\gamma^+)^{-1}] \\ &= [\gamma^+(\gamma^+)^{-1}z^{-1}\alpha^{-1}f(\alpha)f(z)W\gamma^+(\gamma^+)^{-1}] \\ &= z^{-1}af(z)W \end{aligned} \tag{4.12}$$

which is equivalent to  $az = f(z)W$ , for some  $z$  which we now view as an element of  $\pi_1(X, x_0)$ . If  $\beta = \alpha z \gamma^-$  then, similarly,  $y_0$  and  $x_j$  are equivalent by  $\beta$  if and only if  $az = f(z)\overline{W}$ .

There is no solution  $z$  to  $az = f(z)W$  or  $az = f(z)\overline{W}$  for which  $\epsilon = 0$  since  $az$  starts with  $a^{\eta+1}$  but  $f(z)W$  and  $f(z)\overline{W}$  will start with  $a^\eta$ . If  $\epsilon = 1$ , and  $\ell_1 < 0$ , then there is no solution either since, again,  $az$  starts with  $a^{\eta+1}$  and  $f(z)W$  starts with  $a^\eta$ . If  $\epsilon = 1$ ,  $\ell_1 > 0$  and  $k_1 < 0$ , then there is no solution since  $az$  starts with  $a^{\eta+1}b$  but  $f(z)W$  starts with  $a^{\eta+1}b^{-1}$ . If  $\epsilon = 1$ ,  $\ell_1 = 0$  and  $k_1 < 0$ , then there is no solution since  $az = a^{\eta+1}$  but  $f(z)W$  contains at least one  $b$  or  $b^{-1}$ . So suppose that  $\epsilon = 1$ ,  $\ell_1 \geq 0$  and  $k_1 > 0$ . This means that  $x_1 \in b$  with  $W = a$  so  $x_1$  is equivalent to  $y_0$  by letting  $z = a$ . However, no other fixed point is equivalent to  $y_0$  because it would then also be equivalent to  $x_1$  and, in this case, every  $W$  starts with  $a$  and no  $\overline{W}$  starts with  $a$  so, since we assumed  $d \neq a$ , we may conclude from Lemma 4.2 that no such equivalence is possible.  $\square$

We now have the tools we will need to calculate the Nielsen number  $N(f)$  for almost all maps  $f : X \rightarrow X$  such that  $f(a) = a$ . (The remaining cases will be computed in Section 5.) We continue to write  $f(b) = a^\epsilon c d c^{-1}$  where  $\epsilon = 0, 1$ .

**Theorem 4.4.** *If  $\epsilon = 0$ ,  $c = 1$ ,  $d \neq a$  and  $f_P$  is not a deformation, then*

$$N(f) = \begin{cases} K & \text{if } d \neq b, \quad k_1 > 0, \\ K + 2 & \text{if } k_1 < 0. \end{cases} \quad (4.13)$$

*Proof.* Since  $d$  is cyclically reduced, if  $k_1 > 0$  then  $k_m > 0$  also and thus, for  $x_p = x_j$  where  $j = 2, 3, \dots, K - 1$ , the Wagner tail  $W_p$  starts with  $b$  and  $\overline{W}_p$  starts with  $b^{-1}$  so, by Lemma 4.1, no two of the fixed points  $x_2, \dots, x_{K-1}$  are equivalent. However,  $x_1$  and  $x_K$  are equivalent to  $x_0$  so, since  $y_0$  is an essential fixed point class by Lemma 4.3, there are  $K$  essential fixed point classes. If  $k_1 < 0$  none of the fixed points on  $C$  are equivalent to each other, nor is  $y_0$  equivalent to any of them.  $\square$

In standard form, each  $b^{k_j} \subseteq f(b)$  is represented by  $|k_j|$  consecutive arcs in  $C$  and there is a first arc and a last arc with respect to the orientation of  $C$ , which correspond to the first and last appearance, respectively, of  $b$  or  $b^{-1}$  in  $b^{k_j}$ . We will refer to the fixed points in these arcs as the *first* and *last* fixed points in  $b^{k_j}$ .

We say that a fixed point  $x_p$  *cancel*s a fixed point  $x_q$  if  $x_p$  and  $x_q$  are equivalent and one is of index 1 and the other is of index  $-1$ .

**Theorem 4.5.** *If  $\epsilon = 0$ ,  $d \neq a$ ,  $c \neq 1$  but  $t = 0$  and  $f_P$  is not a deformation, then*

$$N(f) = \begin{cases} K_d + 2r - 1 & \text{if } d \neq b, \quad k_{r+1} > 0, \\ K_d + 2r & \text{otherwise.} \end{cases} \quad (4.14)$$

*Proof.* If  $x_p \in b^{k_j} \subseteq c$  and  $k_j > 0$  then, if  $x_p$  is not the first fixed point, it cancels one  $x_q \in b^{-k_j} \subseteq c^{-1}$  because  $W_p = \overline{W}_q$ . The only fixed point of  $b^{-k_j}$  not so cancelled is the first one. If  $k_j < 0$ , then all but the last fixed point of  $b^{k_j}$  cancels a fixed point of  $b^{-k_j}$  with only the last fixed point not cancelled. One of  $x_1$  and  $x_K$  is cancelled by  $x_0$  but each remaining uncanceled fixed point in  $c$  and  $c^{-1}$  is an essential fixed point class. Thus, including  $y_0$ , there are  $2r$  fixed point classes outside of  $d$ . Let  $x_p \in b^{k_{r+1}}$  such that  $V_p = c$  and  $x_q \in b^{k_{m-r}}$  such that  $\overline{V}_q = c^{-1}$ . Then  $x_p$  and  $x_q$  are equivalent if and only if  $k_{r+1} > 0$  since that implies  $k_{m-r} > 0$  and thus to  $W_p = \overline{W}_q = c$ . We conclude that the number of essential fixed point classes in  $d$  is  $K_d - 1$  if  $d \neq b$  and  $k_{r+1} > 0$  and  $K_d$  otherwise.  $\square$

**Theorem 4.6.** *If  $\epsilon = 0$ ,  $d \neq a$  and  $t \neq 0$ , and  $f_P$  is not a deformation, then*

$$N(f) = \begin{cases} K_d + 2r & \text{if } k_{r+1} - t > 0 \text{ or } k_{n-r} + t > 0, \\ K_d + 2r + 2 & \text{if } k_{r+1} - t < 0 \text{ or } k_{n-r} + t < 0. \end{cases} \quad (4.15)$$

*Proof.* If  $k_{r+1} - t > 0$  then, since  $c$  ends with  $b^t$  and  $d$  begins with  $b^{k_{r+1}-t}$ , a negative  $t$  would produce cancellations in the reduced word  $f(b)$ , so we have  $0 < t < k_{r+1}$ . Since  $d$  is cyclically reduced, it must be that  $k_{n-1} + t = 0$ . As in the previous proof, there are  $r$  fixed points in each of  $c$  and  $c^{-1}$  that do not cancel,  $x_0$  is cancelled by  $x_1$  but  $y_0$  is an essential fixed point class. Similarly, in each of  $b^t$  and  $b^{-t}$  there is one fixed point that is not cancelled. However,

there exist  $x_p \in d$  and  $x_q \in c^{-1}$  such that  $W_p = \overline{W}_q = c$  and they cancel each other, so  $N(f) = K_d + 2r$ . If  $k_{r+1} - t < 0$  then there is one uncanceled fixed point in each of  $b^t$  and  $b^{-t}$ , and no fixed point in  $d$  is cancelled, so  $N(f) = K_d + 2r + 2$ . The other cases are symmetric to these.  $\square$

In each of Theorems 4.4, 4.5, and 4.6, we assume that  $f_P$  is not a deformation, so  $y_0$  is an essential fixed point class of  $f$ . If  $\epsilon = 0$  and  $d \neq a$  but  $f_P$  is a deformation, let  $h : (X, x_0) \rightarrow (X, x_0)$  be a map such that  $h(x) = f(x)$  for all  $x \in C$  but the restriction of  $h$  to  $P$  is not a deformation though it induces a homomorphism mapping  $a$  to itself. Then  $N(f) = N(h) - 1$  by Lemma 4.3 and  $N(h)$  can be calculated by the previous theorems. We note that, since  $f$  and  $h$  induce the same fundamental group homomorphism, this difference in the Nielsen numbers reflects the nonaspherical nature of  $X$ . This completes the calculation of  $N(f)$  in the case that  $\epsilon = 0$  and  $d \neq a$ .

**Theorem 4.7.** *Suppose  $\epsilon = 1$  and  $d \neq a$ . If  $f_P$  is not a deformation, then*

$$N(f) = \begin{cases} 1 & \text{if } c = 1, \quad d = b, \\ K + 2 & \text{if } k_1 < 0, \quad k_m < 0, \\ K - 2 & \text{if } k_1 > 0, \quad k_m > 0, \\ K & \text{if } k_1 \cdot k_m < 0. \end{cases} \quad (4.16)$$

*If  $f_P$  is a deformation, then*

$$N(f) = \begin{cases} K + 1 & \text{if } k_m < 0, \\ K - 1 & \text{if } k_m > 0. \end{cases} \quad (4.17)$$

*Proof.* By Lemma 4.2, no two among the fixed points  $x_1, \dots, x_{K-1}$  can be equivalent because, for each one,  $W_p$  begins with  $a$  and  $\overline{W}_p$  does not. Suppose  $k_1 < 0$  and  $k_m < 0$ . If  $f_P$  is not a deformation then, using Lemma 4.3, we see that each of  $y_0, x_0, x_1, \dots, x_K$  is an essential fixed point class so  $N(f) = K + 2$  whereas, if  $f_P$  is a deformation, then  $N(f) = K + 1$ . If  $k_1 > 0$  and  $k_m > 0$ , then  $x_K$  cancels  $x_0$ . If  $f_P$  is not a deformation then, by Lemma 4.3,  $y_0$  cancels  $x_1$  so  $N(f) = K - 2$  except when  $K = 1$ . However, if  $f_P$  is a deformation, then  $x_1$  is an essential fixed point class so  $N(f) = K - 1$ . If  $k_1 < 0$  and  $k_m > 0$  then  $x_K$  cancels  $x_0$  whereas if  $y_0$  is fixed by  $f$ , then it is an essential fixed point class so  $N(f) = K$  if  $f_P$  is not a deformation and  $N(f) = K - 1$  if it is. Finally, suppose  $k_1 > 0$  and  $k_m < 0$ . If  $f_P$  is not a deformation, then  $y_0$  cancels  $x_1$  by Lemma 4.3 so  $N(f) = K$ . If  $f_P$  is a deformation, then each of  $x_0, x_1, \dots, x_K$  is an essential fixed point class and  $N(f) = K + 1$ .  $\square$

## 5. The Exceptional Cases

The only cases remaining occur when  $f(a) = a$  and  $f(b) = a^\epsilon c a c^{-1}$  for  $\epsilon = 0, 1$ .

We will make use of the following result concerning Wagner tails.

**Lemma 5.1.** *Let  $x_p$  and  $x_q$  be fixed points of  $f$  in  $C - \{x_0\}$ . If one of  $W_p^{-1}W_q, \overline{W}_p^{-1}\overline{W}_q, W_p^{-1}\overline{W}_q$  or  $\overline{W}_p^{-1}W_q$  is in the kernel of  $f$ , then  $x_p$  is equivalent to  $x_q$ .*

*Proof.* Let  $W_{pq}$  denote the word in the hypotheses that is in the kernel of  $f$ . If  $W_{pq} = W_p^{-1}W_q$  let  $z = W_{pq}$ , if  $W_{pq} = \overline{W}_p^{-1}W_q$  let  $z = W_{pq}b^{-1}$ , if  $W_{pq} = W_p^{-1}\overline{W}_q$  let  $z = bW_{pq}$  and if  $W_{pq} = \overline{W}_p^{-1}\overline{W}_q$  let  $z = bW_{pq}b^{-1}$ . Using Lemma 2.1, we verify that  $W_p^{-1}f(z)W_q = z$ , so  $x_p$  is equivalent to  $x_q$  by Lemma 2.2.  $\square$

If  $\epsilon = 0$ , so  $f(a) = a$  and  $f(b) = cac^{-1}$ , then the kernel of  $f$  is the normal closure of the subgroup of  $G$  generated by  $b^2$ . Let  $h : G \rightarrow H = G/\ker(f)$  be the quotient homomorphism, then there is a homomorphism  $\bar{f} : H \rightarrow H$  such that  $hf = \bar{f}h$ . Setting  $h(a) = \bar{a}$  and  $h(b) = h(b^{-1}) = \bar{b}$ , we note that

$$\bar{f}(\bar{b}) = \bar{a}^\eta \bar{b} \bar{a} \cdots \bar{a} \bar{b} \bar{a}^\eta, \quad (5.1)$$

where  $\eta = 0$  or  $1$ . Let  $U$  denote the number of appearances of  $\bar{b}$  in  $\bar{f}(\bar{b})$ .

**Theorem 5.2.** *Suppose  $f(a) = a$  and*

$$f(b) = cac^{-1} = b^{k_1} a \cdots ab^{k_r} ab^{-k_r} a \cdots ab^{-k_1}. \quad (5.2)$$

*If  $f_P$  is not a deformation, then*

$$N(f) = \begin{cases} 2 & \text{if } U = 0, \\ U & \text{if } U \neq 0. \end{cases} \quad (5.3)$$

*and, if  $f_P$  is a deformation, then*

$$N(f) = \begin{cases} U - 1 & \text{if } \eta = 0, \quad U \neq 0, \\ U + 1 & \text{otherwise.} \end{cases} \quad (5.4)$$

*Proof.* As in the proof of Theorem 4.5, if  $k_j > 0$  then each fixed point  $x_p$  of  $b^{k_j} \subseteq c$  except the first one cancels a fixed point  $x_q \in b^{-k_j}$  because  $W_p = \overline{W}_q$ , leaving only the first fixed point of  $b^{-k_j}$  uncanceled in this way. If  $k_j < 0$ , it is the last fixed point of  $b^{k_j}$  and the last of  $b^{-k_j}$  that are the only fixed points that are not cancelled in this way. However, further cancellations take place. If  $k_j$  is even, let  $x_p$  and  $x_q$  be the uncanceled fixed points of  $b^{k_j}$  and  $b^{-k_j}$  respectively. Then  $W_p^{-1}W_q = b^{|k_j|}$  is in the kernel of  $f$  so the fixed points cancel by Lemma 5.1.

Suppose that  $k_i$  and  $k_j$ , for  $i < j \leq r$ , are odd numbers and

$$g = ab^{k_{i+1}} a \cdots ab^{k_{j-1}} a \quad (5.5)$$

is in the kernel of  $f$ , and thus in the kernel of  $h$  as well. Let  $x_p \in b^{k_i}$ ,  $x_{p'} \in b^{k_j}$ ,  $x_q \in b^{-k_i}$  and  $x_{q'} \in b^{-k_j}$  be fixed points in  $C - \{x_0\}$  that were not cancelled in the previous step. If  $k_i \cdot k_j < 0$ , then  $x_p$  cancels  $x_{p'}$  and  $x_q$  cancels  $x_{q'}$  whereas if  $k_i \cdot k_j > 0$ , then  $x_p$  cancels  $x_{q'}$  and  $x_q$  cancels  $x_{p'}$ . We will demonstrate these cancellations only in the case  $k_i > 0$  and  $k_j < 0$  because the other three cases are similar. Since  $g$  is in the kernel of  $f$ , then  $W_p^{-1}W_{p'} = b^{k_i} g b^{k_j}$  and  $\overline{W}_q^{-1}\overline{W}_{q'} = g$  are also in the kernel, so  $p$  and  $p'$  cancel, as do  $q$  and  $q'$ , by Lemma 5.1.

After all the cancellations, let  $x_p \in b^{k_i}, x_q \in b^{k_j}$  be adjacent fixed points in  $C - \{x_0\}$  among those that remain. Writing

$$f(b) = g_1 b^{k_i} g_2 b^{k_j} g_3, \quad (5.6)$$

it must be that  $k_i$  and  $k_j$  are odd and  $h(g_2) \neq 1$ . Therefore

$$\bar{f}(\bar{b}) = \bar{f}h(b) = hf(b) = h(g_1 b^{k_i} g_2 b^{k_j} g_3) = h(g_1) \bar{b} \bar{a} \bar{b} h(g_3) \quad (5.7)$$

so that  $x_p$  and  $x_q$  contribute two copies of  $\bar{b}$  to  $\bar{f}(\bar{b})$ . We conclude that there are  $U$  fixed points remaining in  $C - \{x_0\}$ .

None of the remaining fixed points in  $C - \{x_0\}$  are equivalent. Let  $x_s \in b^{k_s}$  and  $x_t \in b^{k_t}$  be two such fixed points, so  $U \geq 2$ . We claim that there is no solution to the equation

$$\bar{z} = h(W_s^{-1}) \bar{f}(\bar{z}) h(W_t) \quad (5.8)$$

for any  $\bar{z} = h(z)$ , which implies that  $x_s$  and  $x_t$  are not equivalent since (2.3) of Lemma 2.2 then has no solution. We first show that  $\bar{z} = 1$  is not a solution to (5.8) because  $W_s^{-1} W_t$  is not in the kernel of  $h$ . Let

$$g_{st} = a b^{k_{s+1}} a \cdots a b^{k_{t-1}} a \quad (5.9)$$

then  $g_{st}$  cannot be in the kernel of  $h$  since, otherwise,  $x_s$  and  $x_t$  would have been eliminated previously. If  $k_s < 0$  and  $k_t > 0$ , then  $W_s^{-1} W_t = g_{st}$  whereas if  $k_s > 0$  and  $k_t < 0$  then  $W_s^{-1} W_t = b^{k_s} g_{st} b^{k_t}$  which also cannot be in the kernel of  $h$  since  $k_s$  and  $k_t$  are odd. If  $k_s k_t > 0$  then, if  $W_s^{-1} W_t$  is in the kernel of  $h$ , there must exist  $u$  with  $s < u < t$  and  $k_u$  odd, and both  $g_{su}$  and  $g_{ut}$  are in the kernel of  $h$ . But that would have eliminated these fixed points, so we have proved that  $\bar{z} = 1$  is not a solution to (5.8). The argument that there is no solution  $\bar{z}$  to (5.8) with  $|\bar{z}| \geq 1$  depends on word length considerations like those in the proofs of Lemmas 4.1 and 4.2, which we therefore omit, and we conclude that none of the remaining fixed points in  $C - \{x_0\}$  are equivalent.

Suppose  $U \neq 0$  and let  $x_v$  and  $x_w$  be the first and last uncanceled fixed points in  $C - \{x_0\}$ , respectively. Assume that  $\eta = 0$ , then either  $x_v$  or  $x_w$  is cancelled by  $x_0$ . The reason is that, since  $f(b) = cac^{-1}$ , it must be that  $x_v \in b^{k_v}$  implies that  $x_w \in b^{-k_v}$ . If  $k_v > 0$ , then  $f(W_v) = h(W_v) = 1$  so  $x_v$  is cancelled by  $x_0$  because  $W_0^{-1} f(W_v) W_v = W_v$  so (2.3) of Lemma 2.2 is satisfied with  $z = W_v$ . Similarly, if  $k_v < 0$ , then  $x_w$  is cancelled by  $x_0$  because  $f(\bar{W}_w) = 1$  and therefore (2.3) is satisfied by setting  $z = b \bar{W}_w$ . On the other hand, if  $\eta = 1$ , then  $x_0$  is not equivalent to any of the remaining fixed point in  $C$  because, under this condition, there is no solution to (5.8) above when  $W_s = 1$  or  $W_t = 1$ . Thus, if  $f_p$  is a deformation so there are no fixed points other than  $x_0$  on  $P$  in the standard form of  $f$ , we see that  $N(f) = U - 1$  if  $\eta = 0$  and  $N(f) = U + 1$  if  $\eta = 1$ . If  $U = 0$ , then  $x_0$  is the only uncanceled fixed point and  $N(f) = 1$ .

Now suppose  $f_p$  is not a deformation so the standard form of  $f$  has a fixed point  $y_0$  in  $P - \{x_0\}$ . If  $U = 0$  then  $y_0$  and  $x_0$  are the only fixed point that do not cancel, so  $N(f) = 2$ . If  $\eta = 0$ , then  $y_0$  is not equivalent to any other fixed point by the following argument. Let  $W$  and  $\bar{W}$  denote the Wagner tails of  $x_j$ . As in the proof of Lemma 4.3,  $y_0$  and  $x_j$  are equivalent

if and only if  $az = f(z)W$  or  $az = f(z)\overline{W}$  for some  $z$  and therefore, in the quotient group  $G/\ker(f)$ , we would have  $\overline{a}\overline{z} = \overline{f(\overline{z})}h(W)$  or  $\overline{a}\overline{z} = \overline{f(\overline{z})}h(\overline{W})$ . Since  $\eta = 0$ , there is no such  $z$  because  $\overline{a}\overline{z}$  starts with  $\overline{a}^{\eta+1}$  but  $\overline{f(\overline{z})}$  starts with  $a^\eta$ . Since we have seen that one of  $x_v$  or  $x_w$  is cancelled by  $x_0$ , we conclude that  $N(f) = U$ . If  $\eta = 1$ , then, in contrast to Lemma 4.3,  $y_0$  does cancel a fixed point in  $C$ . Let  $z$  be the Wagner tail  $W_v$  of  $x_v$  then, since  $h(z) = \overline{a}$ , we see that  $f(z) = a$  so  $f(z)W_v = aW_v$  and therefore  $y_0$  cancels  $x_v$ . Thus we again conclude that  $N(f) = U$ .  $\square$

*Example 5.3.* Let  $c = (b^2a)^r b^{-1}$  and define maps  $f, g : X \rightarrow X$  such that  $f(a) = g(a) = a$  but  $f_P$  and  $g_P$  are not deformations,  $f(b) = cac^{-1}$  and  $g(b) = cabc^{-1}$ . Then  $\overline{f(\overline{b})} = \overline{b}\overline{a}\overline{b}$  so, by Theorem 5.2,  $N(f) = U = 2$ . On the other hand, by Theorem 4.6,  $N(g) = 2r + 1$ . Thus, the class of maps in Theorem 5.2 are truly very exceptional in their fixed point behavior compared to those of Section 4.

In the final case, where  $\epsilon = 1$  so  $f(a) = a$  and  $f(b) = acac^{-1}$ , the kernel of  $f$  is the normal closure of the subgroup of  $G$  generated by  $(ab)^2$ . Let  $H$  again be the quotient group of  $G$  by the normal closure of  $b^2$ . Define  $k : G \rightarrow H$  by  $k(a) = \overline{a}$  and  $k(b) = \overline{ab}$ , then there is a homomorphism  $\overline{f} : H \rightarrow H$  such that  $kf = \overline{f}k$  given by  $\overline{f}(\overline{a}) = \overline{a}$  and

$$\overline{f}(\overline{b}) = \overline{f}k(ab) = kf(ab) = k(cac^{-1}) = \overline{a}^\eta \overline{b}\overline{a} \cdots \overline{a}\overline{b}\overline{a}^\eta \quad (5.10)$$

where  $\eta = 0$  or  $1$ . Let  $V$  denote the number of appearances of  $\overline{b}$  in  $\overline{f}(\overline{b})$ .

**Theorem 5.4.** *Suppose  $f(a) = a$  and  $f(b) = acac^{-1}$ . If  $f_P$  is not a deformation, then*

$$N(f) = \begin{cases} 2 & \text{if } V = 0, \\ V & \text{if } V \neq 0. \end{cases} \quad (5.11)$$

and, if  $f_P$  is a deformation, then

$$N(f) = \begin{cases} V - 1 & \text{if } \eta = 0, \quad V \neq 0, \\ V + 1 & \text{otherwise.} \end{cases} \quad (5.12)$$

*Proof.* Let  $\varphi, \psi : X \rightarrow X$  be maps such that  $\varphi_P = \psi_P = id_P$  and  $\varphi_C$  and  $\psi_C$  are maps in standard form representing homomorphisms such that  $\varphi(b) = ab$  and  $\psi(b) = cac^{-1}$  so  $f = \psi \circ \varphi$ . Let  $e = \varphi \circ \psi$ , then  $N(f) = N(e)$  by the commutativity property of the Nielsen number. We note that  $e(a) = a$  and  $e(b) = \varphi \circ \psi(b) = \varphi(cac^{-1}) = \varphi(c)a\varphi(c)^{-1}$  so  $e$  or a map  $e' : X \rightarrow X$  that induces  $e'(a) = a$  and  $e'(b) = ae(b)a$  satisfies the hypotheses of Theorem 5.2. Since (2.3) of Lemma 2.2 is satisfied for  $e$  if and only if it is satisfied for  $e'$ , we may assume that we can apply Theorem 5.2 to  $e$ . Thus if  $e_P$  is not a deformation, then  $N(f) = 2$  if  $U = 0$ , and  $N(f) = U$  if  $U \neq 0$ , and if  $e_P$  is a deformation, then  $N(f) = U - 1$  if  $\eta = 0$  and  $U \neq 0$ , and  $N(f) = U + 1$  otherwise, where  $U$  is the number of appearances of  $\overline{b}$  in  $\overline{e}(\overline{b})$ , where  $he = \overline{e}h$  for  $h : G \rightarrow g/\ker(e)$ . Since  $\varphi_P = \psi_P = id_P$ , then  $f_P$  is a deformation if and only if  $e_P$  is a deformation. Noting that  $k = h \circ \varphi$ , we have  $\overline{f} = \overline{e}$  so  $V = U$  and the conclusion of the theorem follows.  $\square$

*Example 5.5.* Let  $c = (ba)^r b^{-1}$  for  $r \geq 1$  and define maps  $f, g : X \rightarrow X$  such that  $f(a) = g(a) = a$  but  $f_p$  and  $g_p$  are not deformations,  $f(b) = acac^{-1}$  and  $g(b) = acabc^{-1}$ . Then, by Theorem 5.4,  $N(f) = V = 2$  if  $r$  is even and  $N(f) = 4$  if  $r$  is odd. On the other hand,  $N(g) = 2r + 2$  by Theorem 4.7 and we find that the maps of Theorem 5.4 also have very different fixed point behavior compared to the maps of Section 4.

## 6. Proof of Lemma 4.2

Suppose  $x_p$  and  $x_q$  are equivalent fixed points of  $f$  where  $f(b) = acdc^{-1}$  and  $d \neq a$ . Lemma 4.2 asserts that either  $W_p = \overline{W}_q$  or  $\overline{W}_p = W_q$ . We now present the proof of this assertion.

In the notation introduced at the beginning of Section 4, we write

$$z = a^{\eta_1} b^{\ell_1} a b^{\ell_2} \dots a b^{\ell_n} a^{\eta_2}, \quad (6.1)$$

$$\begin{aligned} R &= W_p^{-1} f(z) W_q = W_p^{-1} a^{\eta_1} (acdc^{-1})^{\ell_1} a (acdc^{-1})^{\ell_2} \dots a (acdc^{-1})^{\ell_n} a^{\eta_2} W_q \\ &= W_p^{-1} a^{\lambda_1} c d^{\delta_1} (c^{-1} a c d^{\delta_1})^{|\ell_1|-1} g_1 i d^{\delta_2} (c^{-1} a c d^{\delta_2 a})^{|\ell_2|-1} g_2 \\ &\quad \dots g_{n-1} d^{\delta_n} (c^{-1} a c d^{\delta_n})^{|\ell_n|-1} c^{-1} a^{\lambda_2} W_q, \end{aligned} \quad (6.2)$$

where  $\lambda_i = 0, 1$ ,

$$\delta_i = \begin{cases} 1 & \text{if } \ell_i > 0, \\ -1 & \text{if } \ell_i < 0, \end{cases} \quad g_i = \begin{cases} 1 & \text{if } \ell_i \cdot \ell_{i+1} > 0, \\ c^{-1} a c & \text{if } \ell_i \cdot \ell_{i+1} < 0. \end{cases} \quad (6.3)$$

Let  $G$  be the sum of the  $|g_i|$ .

*Case 1.* There are no cancellations between  $W_p^{-1}$  and the first  $d^{\delta_1}$  nor between the last  $d^{\delta_n}$  and  $W_q$ . As in Case 1 of Lemma 4.1, we will prove that there are no equivalent fixed points  $x_p$  and  $x_q$  for which  $W_p^{-1}$  and  $W_q$  possess these noncancellation properties.

*Subcase 1.1.*  $|d| \geq 3$ . Then,

$$\begin{aligned} |R| &= |W_p^{-1} a^{\lambda_1} c| + |c^{-1} a^{\lambda_2} W_q| + 2(L - n)|c| + (L - n)|a| + G + L|d| \\ &\geq 3L \quad (\text{because } |d| \geq 3) \\ &\geq n + 1 + L \quad (\text{because } L \geq n \geq 1) \\ &\geq \eta_1 + \eta_2 + n - 1 + L \\ &= |z|. \end{aligned} \quad (6.4)$$

Since  $R = z$ , all equalities must hold, and thus we have

$$\eta_1 = \eta_2 = 1, \quad L = n = 1, \quad W_p^{-1} a^{\lambda_1} c = 1, \quad c^{-1} a^{\lambda_2} W_q = 1, \quad G = 0. \quad (6.5)$$

This implies that  $z = aba$  or  $z = ab^{-1}a$ , and  $R = d$  or  $R = d^{-1}$ . Since  $z = R$ , we conclude that  $d = aba$  or  $d = ab^{-1}a$ , which is contrary to the hypothesis that  $d$  is cyclically reduced.

*Subcase 1.2.*  $|d| = 2$ . We first consider the case of  $|c| \geq 1$  and then the case of  $|c| = 0$ . For  $|c| \geq 1$ , we have

$$\begin{aligned}
|R| &= |W_p^{-1}a^{\lambda_1}c| + |c^{-1}a^{\lambda_2}W_q| + 2(L-n)|c| + (L-n)|a| + G + L|d| \\
&= |W_p^{-1}a^{\lambda_1}c| + |c^{-1}a^{\lambda_2}W_q| + (2|c|+1)(L-n) + G + 2L \\
&\geq |W_p^{-1}a^{\lambda_1}c| + |c^{-1}a^{\lambda_2}W_q| + (2|c|+1)(L-n) + G + n + L \\
&\geq \eta_1 + \eta_2 + n - 1 + L \quad (\text{because of the claim below}) \\
&= |z|.
\end{aligned} \tag{6.6}$$

*Claim 1.*  $|W_p^{-1}a^{\lambda_1}c| + |c^{-1}a^{\lambda_2}W_q| + (2|c|+1)(L-n) + G \geq \eta_1 + \eta_2 - 1$ . The inequality is obvious except for the case of  $L = n$ ,  $G = 0$  and  $\eta_1 = \eta_2 = 1$ . In that case, we know that all the  $\ell_i$  have the same sign and therefore either  $\lambda_1$  or  $\lambda_2$  is equal to zero. Since  $|c| \geq 1$ , if  $\lambda_1 = 0$  then  $|W_p^{-1}a^{\lambda_1}c| > 0$  and if  $\lambda_2 = 0$  then  $|c^{-1}a^{\lambda_2}W_q| > 0$ . Since  $R = z$ , the equalities above must hold and so we have

$$L = n, \quad |W_p^{-1}a^{\lambda_1}c| + |c^{-1}a^{\lambda_2}W_q| + G = \eta_1 + \eta_2 - 1. \tag{6.7}$$

Since  $\eta_i \leq 1$ , this implies that  $G = 0$  and thus all  $\ell_i$  have the same sign. Suppose that  $\eta_1 = 0$  and  $\eta_2 = 1$ . (The case of  $\eta_1 = 1$  and  $\eta_2 = 0$  is similar.) Since all  $\ell_i$  have the same sign,  $a^{\lambda_1} = a^{\lambda_2}$  and therefore  $W_p = a^{\lambda_1}c = a^{\lambda_2}c = W_q$ . If  $V_p \neq V_q$ , that would imply either that  $x_p \in b$  and  $x_q \in b^{-1}$  or  $x_p \in b^{-1}$  and  $x_q \in b$  in adjacent arcs in  $C$ , contrary to the assumption that  $f(b)$  is reduced. Thus  $V_p = V_q$  which, since  $f$  is in standard form, would imply  $x_p = x_q$ , a contradiction. Now suppose that  $\eta_1 = 1$  and  $\eta_2 = 1$ . All the  $\ell_i$  have the same sign; suppose it is negative and thus all  $\ell_i = -1$ . Then  $|W_p^{-1}ac| + |c^{-1}W_q| = 1$  where  $\epsilon_1 = 1$  implies that  $W_q \neq c$  so  $W_q = 1, c = b$  or  $b^{-1}$  and  $W_p^{-1}ac = 1$  so  $R = (d^{-1})^n c^{-1}$ . If  $c = b$  then either  $d = ba$  and thus  $z = R = (ab^{-1})^n b^{-1}$  or  $d = ab^{-1}$  and thus  $z = R = (ba)^n b^{-1}$ , both of which contradict the assumption that  $\eta_2 = 1$ . If  $c = b^{-1}$ , substituting  $d = ab$  or  $d = b^{-1}a$  again leads to a contradiction, now to  $\eta_2 = 1$ . If all  $\ell_i = 1$  then, similarly, all cases lead to a contradiction to the assumption that  $\eta_1 = 1$ .

Suppose that  $|c| = 0$ . Since  $|d| = 2$ , we have  $d = b^2$  or  $d = b^{-2}$ , which is a subword of  $R = z$  and thus  $L \geq n + 1$ . Therefore,

$$\begin{aligned}
|R| &= |W_p^{-1}a^{\lambda_1}c| + |c^{-1}a^{\lambda_2}W_q| + (L-n)|a| + G + L|d| \\
&= |W_p^{-1}a^{\lambda_1}c| + |c^{-1}a^{\lambda_2}W_q| + (L-n) + G + 2L \\
&\geq |W_p^{-1}a^{\lambda_1}c| + |c^{-1}a^{\lambda_2}W_q| + 2 + n + L \quad (\text{because } L \geq n + 1) \\
&> \eta_1 + \eta_2 + n - 1 + L \\
&= |z|
\end{aligned} \tag{6.8}$$

This is a contradiction so, if there are no such cancellations, there cannot be a solution to (2.3) of Lemma 2.2.

*Subcase 1.3.*  $d = b$  or  $b^{-1}$ . If  $c = 1$ , then  $f(b) = b$  or  $f(b) = b^{-1}$  and the lemma is obviously true. Thus we assume that  $|c| \geq 1$ . We will consider only the case  $d = b$  because the other is similar. Since we suppose  $x_p$  and  $x_q$  equivalent, we are assuming there exists  $z$  such that  $z = R$ . But then, as in Subcase 1.2, we will show that, for any choice of  $z$  we have  $|R| = |W_p^{-1}f(z)W_q| > |z|$ .



We will do it by dividing  $z$  into subwords such that their image under  $f$  is reduced in  $R$  and of greater word length. We first consider each subword  $ab^{\ell_i}$  of  $z$  for which  $|\ell_i| \geq 2$ . Then  $f(ab^{\ell_i}) = a(acbc^{-1})^{\ell_i}$  contains the subword  $b^{\delta_i}(c^{-1}acb^{\delta_i})^{\ell_i}$  that is reduced in  $R$  and

$$|b^{\delta_i}(c^{-1}acb^{\delta_i})^{\ell_i}| \geq 4(|\ell_i| - 1) + 1 = |\ell_i| + (3|\ell_i| - 3) > |\ell_i| + 1 = |ab^{\ell_i}| \quad (6.9)$$

because  $|\ell_i| \geq 2$ , so  $|f(ab^{\ell_i})| > |ab^{\ell_i}|$ .

Now consider a subword of  $z$  of the form  $b^{\ell_j}ab^{\ell_{j+1}}a \cdots ab^{\ell_{j+r}}ab^{\ell_{j+r+1}}$  where  $\ell_{j+1} = \cdots = \ell_{j+r} = 1$  but  $\ell_j \neq 1$  and  $\ell_{j+r+1} \neq 1$ . Suppose  $\ell_j < 0$  (or  $j = 0$ ) and  $\ell_{j+r+1} < 0$  (or  $j + r = n$ ). Then  $f(ab^{\ell_{j+1}}a) \cdots ab^{\ell_{j+r}} = f(aba \cdots ab)$  contains a subword  $ab^r c^{-1}$  which is reduced in  $R$ . In the case  $r = 1$  we have  $|ab| < |cbc^{-1}|$ , so we consider  $r \geq 2$ . Since we are assuming that  $z = R$ , it must be that  $b^{\ell_k} = b^r$  for some  $k$ . Since  $r \geq 2$ , it follows that  $f(ab^{\ell_k})$  contains a subword  $b(c^{-1}acb)^{r-1}$  that is reduced in  $R$  and

$$\begin{aligned} |ab^{\ell_{j+1}}a \cdots ab^{\ell_{j+r}}| + |ab^{\ell_k}| &= 2r + (r + 1) < (r + 2) + (4r - 3) \\ &\leq |cb^r c^{-1}| + |b(c^{-1}acb)^{r-1}| \\ &\leq |f(ab^{\ell_{j+1}}a \cdots ab^{\ell_{j+r}})| + |f(ab^{\ell_k})|. \end{aligned} \quad (6.10)$$

If, instead,  $\ell_j \geq 2$  and  $\ell_{j+r+1} < 0$  (or  $j + r = n$ ), then

$$f(ab^{\ell_j}ab^{\ell_{j+1}}a \cdots ab^{\ell_{j+r}}) = acb(c^{-1}acb)^{\ell_j-1}b^r c^{-1} \quad (6.11)$$

contains  $cb^{r+1}c^{-1}$  as a subword that is reduced in  $R$ . The assumption that  $z = R$  then implies that  $b^{\ell_k} = b^{r+1}$  for some  $k$ . The length of the image under  $f$  of the subword of  $z$  consisting of  $ab^{\ell_k}$  and  $ab^{\ell_j}ab^{\ell_{j+1}}a \cdots ab^{\ell_{j+r}}$  is greater than that of the word itself. The same holds for the appropriate choice of subwords of  $z$  when  $\ell_j \neq 1$  and  $\ell_{j+r+1} \geq 2$ .

Suppose instead that we consider a subword of  $z$  of the form  $b^{\ell_j}ab^{\ell_{j+1}}a \cdots ab^{\ell_{j+r}}ab^{\ell_{j+r+1}}$  where now  $\ell_{j+1} = \cdots = \ell_{j+r} = -1$  but  $\ell_j \neq -1$  and  $\ell_{j+r+1} \neq -1$ . An analysis like that just presented again leads to the conclusion that  $f$  increases the word length of subwords of  $z$ . Thus we have established that  $|z| < |R|$  and consequently there are no solutions to (2.3) of Lemma 2.2.

*Case 2.* Suppose there is a cancellation between  $W_p^{-1}$  and the first  $d^{\delta_1}$  but no cancellation between the last  $d^{\delta_n}$  and  $W_q$ . If  $\ell_1 > 0$  and  $\eta_1 = 1$  or  $\ell_1 < 0$  and  $\eta_1 = 0$ , then  $R$  begins with  $W_p^{-1}c$  and no such cancellation is possible. If  $\ell_1 < 0$  and  $\eta_1 = 1$ , an argument like that of Case 2 of Lemma 4.1 shows that a cancellation would contradict the assumption that  $d$  is cyclically reduced. Thus, we can conclude that  $\ell_1 > 0$  and  $\eta_1 = 0$  so  $z = bz'$  and so, similarly to Lemma 4.1,

$$z' = \overline{W_p}^{-1}(acdc^{-1})^{\ell_1-1}a(acdc^{-1})^{\ell_2} \cdots a(acdc^{-1})^{\ell_n}a^{\eta_2}W_q. \quad (6.12)$$

There are no further cancellations and thus, as in the previous case, there is no solution to (2.3) unless  $z' = 1$  so that  $z = b$  and  $\overline{W_p} = W_q$ .

*Case 3.* Suppose there is no cancellation between  $W_p^{-1}$  and the first  $d^{\delta_1}$  but there is cancellation between the last  $d^{\delta_n}$  and  $W_q$ . An argument similar to that of Case 2 demonstrates that  $z = z'b^{-1}$  but then a solution is possible only if  $z' = 1$  and thus that  $\overline{W}_q = W_p$ .

*Case 4.* Suppose that there is a cancellation between  $W_p^{-1}$  and the first  $d^{\delta_1}$  and also between  $W_q$  and the last  $d^{\delta_n}$ . Following Cases 2 and 3, we conclude that  $z = bz'b^{-1}$  and that

$$z' = \overline{W}_p^{-1} (acdc^{-1})^{\ell_1-1} a(acdc^{-1})^{\ell_2} \cdots a(acdc^{-1})^{\ell_n+1} \overline{W}_q. \quad (6.13)$$

There are now no cancellations so  $z' = 1$  and  $\overline{W}_p = \overline{W}_q$ . Since  $f$  is in standard form, the condition  $\overline{W}_p = \overline{W}_q$  also implies that  $x_p = x_q$  and thus there is no solution of this type.

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