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# THE FIXED POINT SET OF A FINITE GROUP ACTION ON A HOMOLOGY FOUR SPHERE

by Stefano DEMICHELIS

## 1. INTRODUCTION

It is a classical result of P. A. Smith that a finite  $p$ -group acting on a finite dimensional complex with the  $Z/p$  homology of a sphere  $S^k$  has fixed point set  $Z/p$  homologically equivalent to some  $S^k$  with  $k < n$ .

This theorem cannot, in general, be extended to groups of more general type, even if one assumes much more restrictive hypotheses such as a smooth action on a manifold homeomorphic or diffeomorphic to a sphere.

In particular, for every odd  $n \geq 5$ , it is possible to use Brieskorn varieties to produce finite group actions with fixed point set not a homology sphere. Even if the fixed point set is a sphere it can be embedded in a non standard way; for an elementary discussion of this phenomenon see [18] and [15]. For other “strange” actions of groups on higher dimensional spheres and disks the reader is referred to [16].

In low dimensions it is harder to construct such examples, and it may be conjectured that finite group actions on spheres are equivalent or somewhat “close” to linear ones.

On  $S^2$  the situation is the best possible, indeed according to [6], [13] and [8], every finite group of homeomorphisms of  $S^2$  is topologically conjugate to a linear action.

On  $S^3$  it is necessary to assume local linearity, otherwise pathologies such as horned spheres may arise, see [2].

A deep and difficult theorem, conjectured by Smith and proved by combining results of Thurston, Meeks and Yau and Bass, states that every smooth cyclic action on  $S^3$  is conjugate to the linear one; a detailed account can be found in [15].

The first example of a smooth cyclic action on  $S^4$  with fixed point set a knotted  $S^2$  is in [12], for more information see [9] and [17], these actions are obviously not linear.

The aim of this paper is to prove that any locally linear orientation preserving action of a finite group on an homology four sphere has fixed point set homeomorphic to a sphere. In particular there are no one fixed point actions. Besides, if the fixed point set is  $S^0$ , it is proved that the local representations are conjugate.<sup>1)</sup> For a large class of actions, the proof is an elementary application of Smith's theory, using the fact that in dimensions  $\leq 2$  homology spheres are topological spheres. In one remaining case, an action of the icosahedral group, a slightly more complicated argument is needed. This type of argument cannot be extended to dimension 3, as the example in [11] proves.

The motivation for this work came from the paper of Peter Braam and Gordana Matic [3] on group actions and instantons spaces. They prove that a smooth orientation preserving action of a group on a homology sphere whose fundamental group has no nontrivial representations in  $SU(2)$  admits an even number of isolated fixed points and that they come in pair such that the representations around them are conjugate. Also, Furuta proved that there are no actions with one fixed point.

The author wishes to thank Professor William Browder for his patience in listening to him and for his advice, and also Gordana Matic for having explained her work to him.

## 2. STATEMENT OF THE RESULT

In the following " $R$ -homology  $S^n$ " will mean a compact topological manifold whose homology with coefficients in the ring  $R$  is the same as that of  $S^n$ . (Of course in dimensions 0, 1, 2 such a manifold is homeomorphic to a sphere.) To unify some notation, the empty set will be considered a sphere of dimension  $-1$ , all actions will be assumed effective.

**THEOREM 2.1.** *Let  $G$  be a finite group acting locally linearly and preserving the orientation on a  $\mathbb{Z}$ -homology 4-sphere  $\Sigma$ . Then the fixed point set of  $G$  is homeomorphic to a sphere; in particular it never consists of one point.*

Local linearity is assumed to avoid pathologies, every smooth action is locally linear (see e.g. [5]).

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<sup>1)</sup> The author has been informed that this has been proved independently by S. Cappell.

*Observation 2.2.* There is a non-locally linear action of a finite group on a homology four sphere with exactly one fixed point.

*Proof.* Take the one fixed point action of  $A_5$  on the Poincaré's sphere constructed in [11], remove the fixed point and multiply the remaining homology disk by the unit interval to obtain a four homology disk on which the product action has no fixed points. One can extend this action to the one point compactification to obtain a homology  $S^4$  on which  $A_5$  acts fixing only the point at infinity.

The main tool in the proof of Theorem 2.1. will be the classical result due to Smith (see [19]):

**THEOREM 2.3.** *Let  $Z/p$ ,  $p$  a prime, act on a  $Z/p$  homology  $S^n$ , then the fixed point set is a  $Z/p$  homology  $S^k$ ; if  $p$  is odd,  $n - k$  is even.*

### 3. SOLVABLE GROUPS

In the four dimensional case it is easy to deduce from Theorem 2.3. the Corollary:

**COROLLARY 3.1.** *Let  $G$  be a solvable group acting locally linearly and orientation preserving on  $\Sigma$ , then the fixed point set is a sphere.*

*Proof of the Corollary.* Let  $\{I\} = H_0 \subset H_1 \subset H_2 \subset G$  be a composition series such that every  $H_{i+1}$  is normal in  $H_i$  and the quotients are cyclic of prime order  $p_i$ . By Smith theorem  $X = \text{Fix}(H_i)$  is a  $Z/p$  homology sphere, the action is not trivial so  $X$  cannot be the whole  $\Sigma$ ; nor can it be 3-dimensional, for otherwise some element of  $H_1$  would interchange the two components of  $\Sigma - X$  and so reverse the orientation. Hence  $X$  has to be of dimension less than or equal to 2 and so a topological sphere.

For  $i > 1$ ,  $\text{Fix}(H_{i-1})$  is invariant under  $H_i$  and the latter's action factorizes through  $H_i/H_{i-1}$ , so  $\text{Fix}(H_i) = \text{Fix}(H_{i-1}/H_i \mid \text{Fix}(H_{i-1}))$ ; applying repeatedly the argument above and using the fact that now all the spaces involved are spheres, the statement follows.

If  $x_0 \in \Sigma^G$ , the fixed set of  $G$  on  $\Sigma$ , the assumption of local linearity gives a representation  $G \xrightarrow{\rho} SO(4)$ , faithful since  $G$  acts effectively, this allows us to think of  $G$  as a finite subgroup of  $SO(4)$  and to study it we look at the central extension:

$$3.2 \quad 0 \rightarrow C_2 \rightarrow SO(4) \rightarrow SO(3) \times SO(3) \rightarrow 0$$

where  $\pi = (\pi_+, \pi_-)$  is given by the representation onto the self-dual and anti-self-dual forms in  $R^4$ , and  $C_2$  is  $\{\pm I\}$  the center of  $SO(4)$ .

Observe that  $\pi^{-1}(\Delta)$ , where  $\Delta$  is the diagonal in  $SO(3) \times SO(3)$ , is the image of the “suspension” map from  $O(3)$  into  $SO(4)$ :

$$M \rightarrow \begin{pmatrix} \det M & 0 \\ 0 & M \end{pmatrix}$$

We state now two elementary facts which will become useful in the following:

LEMMA 3.3. *If  $\alpha \in SO(4)$  has at least one eigenvalue = 1 then its image  $\pi(\alpha) = (\alpha_+, \alpha_-)$  in  $SO(3) \times SO(3)$  is conjugate to an element of  $\Delta$ , i.e.,  $v^{-1}\alpha_+v = \alpha_-$  for some  $v \in SO(3)$ .*

LEMMA 3.4. *The fixed space of an element of  $SO(4)$  always has even dimension.*

Consider the diagram

$$3.5 \quad \begin{array}{ccc} SO(4) & \xrightarrow{\pi} & SO(3) \times SO(3) \\ \cup & & \cup \cup \\ G \cdot C_2 = \tilde{G} & \xrightarrow{\pi} & G_0 \subset G_1 \times G_2 \\ j \cup & & \\ G & & \end{array}$$

where the  $G_i$ s ( $i=1, 2$ ) are the images of the projections  $\pi_i$  of  $G_0$  into the two  $SO(3)$ s;  $j$  is either the identity or the inclusion of a subgroup of index 2 in  $\tilde{G} = \pi^{-1}(\pi(G))$  in the latter case  $\pi \circ j$  appear as  $G_i$ . Luckily, finite subgroups of  $SO(3)$  are well known (see e.g. [20]): they can be divided into four types:

- i. cyclic groups  $C_n$ ,
- ii. dihedral groups  $D_{2m}$ ,
- iii. the tetrahedral group,
- iv. the octahedral group,
- v. the icosahedral group.

All the first four types consist of solvable groups. It is easy to show that the class of solvable groups is closed under the operations of taking

products, subgroups and central extensions, so  $G$  falls in the hypothesis of Corollary 3.1. in all cases, except the one in which at least one  $G_i$  is the icosahedral group. This is isomorphic to  $A_5$ , the alternating group on five letters and this identification will be fixed from now on.

#### 4. NON SOLVABLE GROUPS

We will prove Theorem 2.1 case by case. We start with the Lemma:

LEMMA 4.1. *If  $G$  contains  $C_2$ , then  $\text{Fix}(G)$  is  $S^0$ .*

*Proof.*  $\text{Fix}(G) = \text{Fix}(G/C_2 \text{Fix}(C_2))$ .  $\text{Fix}(C_2)$  is a homology sphere by Smith's theorem and is zero dimensional since around the chosen fixed point the non trivial element of  $C_2$  acts like the matrix  $-I$ , which has an isolated fixed point. The action of  $G/C_2$  on  $S^0$  has to be trivial since the fixed point set is required not to be empty.

By renumbering the factors and changing basis if necessary, we may assume  $G_2$  equal to  $A_5$ , with  $G_2 \xrightarrow{i} SO(3)$  the standard representation of  $A_5$ . Then  $G_0$  is a subgroup of  $G_1 \times A_5$  mapping onto both factors and to study it in more detail we look at the kernel of the second projection:  $G_0 \xrightarrow{\pi_2} A_5$ . This subgroup consists of elements of the form  $(k, I)$  with  $k \in G_1$ ; we denote it by  $K_1$ .

For convenience we distinguish three cases:

*Case 1.*  $K_1$  is a non-trivial subgroup of  $SO(3)$ , not isomorphic to  $A_5$ ,

*Case 2.*  $K_1$  is isomorphic to  $A_5$ ,

*Case 3.*  $K_1$  is trivial.

*Proof in case 1.* The surjection  $G \rightarrow A_5$  has non trivial kernel  $K = j^{-1}(\pi^{-1}(K_1)) \subset G$ , this group is solvable since  $K_1$  is,  $\pi$  is a central extension and  $j$  is an injection. By Corollary 3.1.,  $\text{Fix}(K)$  is a sphere of dimension 2 and  $\text{Fix}(G)$  is the fixed point set of an  $A_5$  acting on it, so it is easy to see that the only actions admitting some fixed points are the trivial ones.

*Proof in case 2.* Since  $A_5$  is not properly contained in any finite subgroup of  $SO(3)$ ,  $K_1$  has to be equal to the whole  $G_1$ .

So  $G_0 \subset A_5 \times A_5 \subset SO(3) \times SO(3)$  and contains  $K_1 = A_5 \times \{I\}$ , it follows that  $G_0$  is the whole  $A_5 \times A_5$ . Observe that the two inclusions of  $A_5$  in  $SO(3)$  do not necessarily agree.

We claim that  $G$  in the diagram 3.5 must contain  $C_2$ , for if not  $j \circ \pi$  would be an isomorphism  $G \rightarrow A_5 \times A_5$  and its inverse would split the extension

$$0 \rightarrow C_2 \rightarrow \tilde{G} \rightarrow A_5 \rightarrow A_5 \rightarrow 0$$

This is not possible (see the appendix). Now apply Lemma 4.1. to end the proof.

*Proof in case 3.* If  $K_1$  is trivial the projection  $G_0 \xrightarrow{\pi_2} A_5$  is an isomorphism and the composition  $\phi = \pi_1 \circ \pi_2^{-1}: A_5 \rightarrow G_1$  is a map onto, with graph  $G_0$ . The homomorphic images of  $A_5$  are only the trivial group and  $A_5$  itself, since  $A_5$  is simple.

If  $G_1 = \phi(A_5)$  is trivial,  $G_0$  is equal to  $\{I\} \times A_5$ . As in case 2 the extension

$$0 \rightarrow C_2 \rightarrow G \rightarrow \{I\} \times A_5$$

is not split, so  $G$  contains  $C_2$  and  $\text{Fix}(G) = S$  by 4.1. If  $G_1 = \phi(A_5)$  is isomorphic to  $A_5$ ,  $G_0 \subset G_1 \times G_2$  is a copy of  $A_5$  too, mapped into  $SO(3) \times SO(3)$  according to  $d(x) = (h(x); i(x))$ , where  $h(x)$  is some irreducible representation and  $i(x)$  is the standard one specified before. The arguments in [22] can be used to prove that there are exactly two equivalence classes of representations of  $A_5$  into  $SO(3)$ .

So there are two subcases:

- a.  $h$  is  $x \rightarrow u^{-1}i(x)u$ , with  $u \in SO(3)$ ,
- b.  $h$  is conjugate to the composition  $\bar{i}: A_5 \xrightarrow{\sigma} A_5 \xrightarrow{i} SO(3)$  and  $\sigma$  is conjugation by the cycle  $(\bar{i}_2)S_5$  on  $A_5$ .

a. If the coordinate system around the fixed point chosen at the beginning is linearly changed according to some  $\tilde{u} \in SO(4)$ , the representation  $\rho: G \rightarrow SO(4)$  becomes  $\tilde{u}\rho(x)\tilde{u}^{-1}$ .

If  $\pi(\tilde{u}) = (u; 1)$ ;  $i$  is left unchanged and  $h$  is replaced by  $i$ . So  $G_0$  is contained in the diagonal and  $G \in \tilde{G} \in \text{Im}(O(3))$ .

Recall that when  $G$  contains  $C_2$ ,  $\text{Fix}(G) = S^0$  by Lemma 4.1.

LEMMA 4.2. *If  $G \neq C_2$ ,  $\text{Fix}(G) = S^1$ .*

*Proof.*  $G$  is isomorphic to  $A_5$  and has to be contained in  $\text{Im}(SO(3))$  so its representation has a one dimensional fixed space, which implies  $\text{Fix}(G)$  1-dimensional at  $x_0$ . Now  $A_5$  contains  $A_4$  (named tetrahedral group when sitting in  $SO(3)$ ), so  $\text{Fix}(A_5) \in \text{Fix}(A_4)$ ,  $A_4$  is solvable and hence

$\text{Fix}(A_4)$  is a sphere. It cannot be  $S^2$  since the representation of  $A_4$  in  $SO(3)$  is irreducible, so it is  $S^1$ . The only closed 1-dimensional submanifold of  $S^1$  is  $S^1$  itself, so  $\text{Fix}(G) = S^1$ .

b. As in subcase a., a linear change in coordinates allows us to assume that  $h$  is actually  $\tilde{i}$ , and as before if  $G_2 \in G$  the proposition is proved applying 4.1.

If it is not the case, let  $\alpha$  correspond to the cycle  $(12345) \in A_5$ ,  $\beta$  to  $(123)$  and  $\gamma$  to  $(345)$ . We observe that  $\beta$  and  $\gamma$  generate  $A_5$  and so:

1.  $\text{Fix}(A_5) = \text{Fix}(\beta) \cap \text{Fix}(\gamma)$ ,
2.  $\text{Fix}(A_5) \subset \text{Fix}(\alpha)$ .

We claim that  $\text{Fix}(\alpha)$  is  $S^0$ . According to Smith's theorem it is enough to prove that the representation of  $\alpha$  around  $x_0$  has an isolated fixed point, i.e. is the sum of two irreducible complex ones.

If not by Lemma 3.3  $(\bar{i}(\alpha); i(\alpha))$  would be conjugate in  $SO(3) \times SO(3)$  to an element on the diagonal. From the explicit description of  $i$  and  $\bar{i}$  (see the end of section 7.1 of [22]), it follows that they send all the five cycles to non conjugate elements in  $SO(3)$ , so this is impossible, and  $\text{Fix}(\alpha) = S^0$ .

As for  $\beta$  and  $\gamma$ , their images under  $(\bar{i}, i)$  are conjugate to elements on the diagonal, by 3.3 and 3.4 their fixed point sets have two-dimensional components, and so by Smith's theorem they are copies of  $S^2$ .

So  $\text{Fix}(G)$  is the intersection of a couple of  $S^2$ 's and is contained in  $\text{Fix}(\alpha)$  which is  $S^0$ . If this set is empty or equal to  $S^0$ , the proposition follows. If it were a single point, it would be a transverse intersection, by local linearity, but it is not possible since a homology  $S^4$  does not contain any two cycles with intersection number odd. This ends the proof.

## 5. LOCALLY LINEAR REPRESENTATION

Let's now consider the case of  $G$  acting on a homology  $S^4$  with two fixed points,  $P_0$  and  $P_1$ .

**THEOREM 5.1.** *The unoriented representations of  $G$  around  $P_0$  and  $P_1$  are linearly equivalent.*<sup>1)</sup>

*Proof.* It will suffice to show that the characters associated to the representations around the  $P_i$ 's agree on every cyclic subgroup  $C_k$  of  $G$ .

<sup>1)</sup> See the note in the introduction.

Observe that by Lemma 3.4 and Smith's theorem the fixed point set of an element of  $G$  different from the identity is either  $S^0$  or  $S^2$ .

Let  $g$  generate  $C_k$ , we distinguish three cases:

1.  $\text{Fix}(g^r) = \{P_1; P_2\}$  for every  $r \equiv 0 \pmod k$ ,
2.  $\text{Fix}(g) = S^2$ ,
3.  $\text{Fix}(g) = \{P_1; P_2\}$  but  $\text{Fix}(g^n) = S^2$  for some  $g^n \neq id$ .

Case 1. The hypothesis means that the action is semifree and the claim follows from the work of Atiyah and Bott, see [1] and [14].

Case 2. The action of  $C_k$  on the normal bundle of the fixed  $S^2$  defines an element  $N$  of  $K_{C_k}(S^2)$ . Since  $C_k$  acts trivially on  $S^2$  the two inclusions  $P_i \rightarrow S^2$  are obviously  $C_k$  homotopic so that the diagram:

$$\begin{array}{ccc} & K_{C_k}(P_2) & \\ [N] \in K_{C_k}(S^2) & \nearrow & \searrow \\ & K_{C_k}(P_1) & \nearrow \end{array} \quad R(C_k)$$

commutes. This means that the representation of  $C_k$  in the normal component to  $S^2$  are conjugate, the tangential representations are of course both the identity, so the statement is proved.

Case 3. We can assume, by [8], that the action on  $S^2 = \text{Fix}(g^n)$  is linear.  $S^2$  has zero intersection number in  $\Sigma$  so its normal bundle  $N$  can be identified to  $S^2 \times R^2$ , and we fix a trivialization. Denote a point of  $S^2 - \{P_1; P_2\}$  by  $(x, t)$  with  $x \in S^1$  and  $t \in (0, 1)$ . Let  $C_0$  be the space  $\{\phi: S^1 \rightarrow SO(2) \mid \deg \phi = 0\}$ , it is an abelian group by pointwise multiplication and a  $C_k$  module with structure given by:

$$(h\phi)(x) = \phi(hx), h \in C_k \quad \text{and} \quad x \in S^1 \subset S^2$$

acted on by the obvious induced action.

By [5], chapter VI, prop. 11.1, the action is given by a  $\theta_t$  such that

1.  $\theta_t \in Z^1(C_k; C_0)$  and depends continuously on  $t \in [0, 1]$ .
2.  $\theta_i(h)(x)$  is constant on  $x \in S^1$  and equal to the representation of  $h$  at  $P_i$  for  $i = 0; 1$ .

A change in the trivialization adds to each  $\theta_t$  a coboundary so there is a well defined continuous family  $\theta_t: [0, 1] \rightarrow H^1(C_k; C_0)$ .

A straightforward calculation shows that  $H^1(C_k; C_0) = H^2(C_k; Z) = C_k$ . Since  $\theta_t$  is continuous it has to be constant, so  $\theta_0 = \theta_1$  and by 2. the

two normal representations are equal. In the topological case, by the results of Cappel and Shaneson topological equivalence of matrices in dimension 4 implies linear equivalence, so the statement of Theorem 5.1 makes sense also for a group of homeomorphism.

The proof given can be adapted to this more general case provided that the followings are true:

1. the topological Atiyah-Singer signature formula holds,
2. a locally flat  $S^2$  in  $\Sigma$  has a normal bundle,
3. the argument in case 3 works with  $\text{Homeo}(S^1)$  instead of  $SO(2)$ .

Assertion 1 is proved, in the case of the semi-free action, in [21], page 188; assertion 2 follows from the work of Freedman, see [10]; assertion 3 is proved using the retraction  $\text{Homeo}(S^1)$  into  $SO(2)$  given by the Poincaré number, see [7].

## APPENDIX

LEMMA. *The extensions:*

$$\begin{array}{ccccccc}
 0 & \rightarrow & C_2 & \rightarrow & \tilde{A}_5 & \rightarrow & A_5 & \rightarrow & 0 \\
 & & & & \downarrow & & \downarrow & & \\
 0 & \rightarrow & C_2 & \rightarrow & A_5 \times A_5 & \rightarrow & A_5 \times A_5 & \rightarrow & 0 \\
 & & & & \downarrow & & \downarrow^{(h, h')} & & \\
 0 & \rightarrow & C_2 & \rightarrow & SO(4) & \rightarrow & SO(3) \times SO(3) & \rightarrow & 0
 \end{array}$$

are not split,  $h$  and  $h'$  can be any nontrivial representations of  $A_5$  and  $f$  is either  $(\text{Id} \times \{I\})$  or  $(\{I\} \times \text{Id})$ .

*Proof.* Standard theory of group extensions and cohomology (see [4]) allows us to reduce to the:

PROPOSITION. *Any non trivial homomorphism  $A_5 \xrightarrow{i} SO(3)$  induces an isomorphism  $Z/2 = H^2(BSO(3); Z/2) \xrightarrow{i} H^2(BA_5; Z/2) = Z/2$ .*

*Proof of the Proposition.* If the corresponding extension is split, then  $Z/2 \times A_5 \subset S^3$ , but  $A_5 = 60$  so there exists a  $Z/2 \subset A_5$  so  $Z/2 \times Z/2$  would act freely on  $S^3$ , which cannot happen.

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