ORIENTATION-REVERSING PERIODIC PL MAPS
OF LENS SPACES
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Abstract. We complete the classification of all orientation-reversing PL maps of period 4k (k > 1) on lens spaces. All \( \mathbb{Z}_4 \)-actions on the projective 3-space are also classified.

1. Introduction. The 3-sphere and the projective 3-space are the only 3-dimensional lens spaces \( L(p, q) \) which admit orientation-reversing PL maps of period \( n > 4 \) [4]. In [4] all orientation-reversing PL maps of period 4k on the 3-sphere \( S^3 \) are classified for all k. In this paper we show:

**Theorem A.** The projective 3-space \( P^3 \) admits a unique orientation-reversing PL map of period 4k for each k, up to conjugation.

All orientation-reversing PL involutions of lens spaces [6], [8] and all PL involutions of \( P^3 \) [2], [6] are known. As consequences of Theorem A and [3], we have

**Theorem B.** The projective 3-space \( P^3 \) admits exactly four distinct \( \mathbb{Z}_4 \)-actions (PL), up to conjugation.

The cyclic group generated by \( h \) shall be denoted by \( \langle h \rangle \). Two actions of \( \langle h \rangle \) and \( \langle h' \rangle \) on a space \( M \) are said to be conjugate if there exists a homeomorphism \( t \) of \( M \) such that \( tht^{-1} = h' \). We shall denote the fixed-point set of \( h \) by \( \text{Fix}(h) \).

We consider \( S^3 \) as a subset of \( C^2 \), defined by \( \{(z_1, z_2) \in C^2 | z_1 \bar{z}_1 + z_2 \bar{z}_2 = 1 \} \). Define an orientation-reversing homeomorphism \( \lambda' \) of \( S^3 \) by \( \lambda'(z_1, z_2) = (\omega z_1, \bar{z}_2) \), where \( \omega = e^{2\pi i/n} \) and \( n \) is even. Since \( \lambda' \) commutes with the antipodal map of \( S^3 \), there exists an obvious orientation-reversing map \( \lambda \) of period \( n \) on \( P^3 \) induced by \( \lambda' \).

**Remark.** Let \( f \) be an orientation-preserving map of period \( n \) on \( S^3 \) and \( \text{Fix}(f) \neq \emptyset \). Then \( \text{Fix}(f) \) is a simple closed curve. A well-known conjecture, due to P. A. Smith, asserts that \( \text{Fix}(f) \) is unknotted for all \( n \) (see [1]). It follows from a result of F. Waldhausen [12] that the conjecture is true for even period \( n \). Let \( h \) be an orientation-reversing map of period \( n > 2 \) on \( P^3 \).

Then it follows from the Lefschetz fixed-point theorem that \( \text{Fix}(h) \neq \emptyset \). Note

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that $h^2$ is orientation-preserving and $n$ is even. Assuming the Smith conjecture, one can prove that $\pi_1(P^3 - \text{Fix}(h^2))$ is abelian. The following theorem classifies all orientation-reversing periodic maps of $P^3$ modulo the Smith conjecture.

**Theorem C.** Let $h$ be an orientation-reversing PL map of the projective 3-space $P^3$ with period $n > 2$. If $\pi_1(P^3 - \text{Fix}(h^2))$ is abelian, then $h$ is conjugate to $\lambda$.

Let $h$ be a periodic map of a space $M$. Then there exists a homeomorphism $q$ of $M/\langle h^k \rangle$, uniquely determined by $h$, such that $qh = gh$, where $g: M \to M/\langle h^k \rangle$ is the orbit map. We call $q$ the map of $M/\langle h^k \rangle$ induced by $h$. We shall denote the closed unit interval and the $n$-sphere by $I$ and $S^n$, respectively. In this paper all spaces and maps will be in the PL category.

2. **Equivariant product structure.** Let $A$ be the annulus $S^1 \times I$ and let $h$ be a free involution on $A \times I$ such that $h(A \times \{i\}) = A \times \{i\}$ ($i = 0, 1$). The following lemma is essentially a special case of a result of Waldhausen [11].

**Lemma 2.1.** There exists an isotopy of $A \times I$, keeping $A \times \{i\}$ invariant, after which a product structure on $A \times I$ and an involution $g$ on $A$ are obtained so that $h(x, t) = (g(x), t)$ for $(x, t) \in A \times I$. The isotopy can be chosen constant on $A \times \{0\}$.

Suppose that $A \times I$ is a regular neighborhood of an invariant simple closed curve $J$, or equivalently $\pi_1(A \times I - J) = \mathbb{Z} \oplus \mathbb{Z}$. The following lemma further claims that the isotopy in Lemma 2.1 can be chosen, after which $J = S^1 \times \{1/2\} \times \{1/2\}$.

**Lemma 2.2.** There exists an isotopy of $A \times I$, keeping $A \times \{i\}$ invariant, after which a product structure on $A \times I$ and an involution $g$ on $A$ are obtained so that $h(x, t) = (g(x), t)$ for $(x, t) \in A \times I$ and $J = S^1 \times \{1/2\} \times \{1/2\}$.

**Proof.** We will show that there exists an invariant annulus $H$ properly embedded in $A \times I$ such that $\partial H$ meets each $S^1 \times \{i\} \times (0, 1)$ ($i = 1, 0$) in a simple closed curve and $J \subset \text{Int} H$. Then $H$ separates $A \times I$ into two invariant components, each of which is homeomorphic to $S^1 \times I \times I$. Define a product structure on each component $S^1 \times I \times I$ as in Lemma 2.1. We may assume that $J = S^1 \times \{1/2\} \subset S^1 \times I \approx H$. Now repairing the cut along $H$ defines the required product structure of $A \times I$.

Let $M = A \times I / \langle h \rangle$ and $g: A \times I \to M$ be the orbit map. Then $M$ is a homeomorphic to $c \times I$, where $c$ is either an annulus or a möbius band. It is not difficult to see that $M$ is a regular neighborhood of $g(J)$. Therefore, there exists a properly embedded surface $H'$ in $M$ such that each component of $\partial M - (g(A \times \{0, 1\}))$ meets $H'$ in a simple closed curve, where $H'$ is a regular neighborhood of $g(J)$ in $H'$ (see Lemma 2.1). Then $H = g^{-1}(H')$ is an annulus as desired.
3. Proof of Theorem A.

(3.1) Consider an orientation-reversing map \( h \) of period \( 4k \) on \( P^3 \). It follows from the Lefschetz fixed-point theorem that \( \text{Fix}(h) \neq \emptyset \). Since \( h^{2k} \) is an involution of \( P^3 \), \( \text{Fix}(h^{2k}) \) is a disjoint union of two simple closed curves, say \( F \) and \( F' \) (see [2]). Let \( N = P^3 / \langle h^{2k} \rangle \) and \( d: P^3 \to N \) be the orbit map. Let \( L = d(F) \) and \( L' = d(F') \). Then \( N \) is homeomorphic to \( S^3 \) and

\[
\pi_1(N - L - L') = \mathbb{Z} \oplus \mathbb{Z}
\]

(see [2]). Let \( f \) be the map of \( N \) induced by \( h \). Since \( f \) is an orientation-reversing map of \( N \) (of period \( 2k \)) and \( d(\text{Fix}(h)) \subset \text{Fix}(f) \), \( \text{Fix}(h) \) consists of two points, say \( x \) and \( \bar{x} \). Let \( y = d(x) \) and \( \bar{y} = d(\bar{x}) \). We may assume that \( \{x, \bar{x}\} \subset F' \). Then \( \text{Fix}(f) = \{y, \bar{y}\} \subset L' \). Notice that if \( k > 1 \), \( \text{Fix}(f^2r) \) \( (1 < r < k) \) is a simple closed curve. Hence \( \text{Fix}(h^{2r}) \) is a simple closed curve, and it is easy to see that \( \text{Fix}(h^{2r}) = F' \) for each \( r \), \( r \equiv 0 \pmod{k} \). Let \( M = N / \langle f^2 \rangle \), \( g: N \to M \) be the orbit map (of course, \( M = N \) if \( k = 1 \)). Then \( M \) is again homeomorphic to \( S^3 \) (see [3]). Let \( T \) be the map of \( M \) induced by \( f \). Then \( T \) is an orientation-reversing involution. Let \( J = g(L), J' = g(L'), \bar{z} = g(\bar{y}), \) and \( z = g(y) \). Notice that \( \text{Fix}(T) = \{z, \bar{z}\} \subset J' \) and \( T \) interchanges the two open arcs \( J' - \{z, \bar{z}\} \). Since \( \pi_1(N - L - L') = \mathbb{Z} \oplus \mathbb{Z} \), it can be seen that \( \pi_1(M - J - J') = \mathbb{Z} \oplus \mathbb{Z} \) (see [3]).

(3.2) A product structure will be defined on the complement of a regular neighborhood of \( J' \) in \( M \). Take small invariant balls \( B \) and \( \bar{B} \) in \( M - J \), containing \( z \) and \( \bar{z} \), respectively, such that \( B \cap \bar{B} = \emptyset \). Again take a small invariant regular neighborhood of \( \text{cl}(J' - B - \bar{B}) \) in \( \text{cl}(M - B - \bar{B}) - J \) so that it has two components, say \( K \) and \( K' \). Let \( \bar{M} = B \cup \bar{B} \cup K \cup K' \). Then \( \bar{M} \) is a regular neighborhood of \( J' \). Let \( \bar{M} = \text{cl}(M - \bar{M}) \). Since

\[
\pi_1(M - J - J') = \mathbb{Z} \oplus \mathbb{Z},
\]

it follows from a result of J. Stallings [10] that \( \bar{M} \) is homeomorphic to a solid torus \( D^2 \times S^1 \) and it is also an invariant regular neighborhood of \( J \). Parametrize \( \bar{M} \) in terms of \( A \times I \) \( (A = S^1 \times I) \) such that

\[
\partial A \times I \approx \text{cl} \left( \partial (K \cup K') - B - \bar{B} \right), \quad A \times \{0\} \approx \text{cl} \left( \partial B - k - K' \right)
\]

and

\[
A \times \{1\} \approx \text{cl} \left( \partial B - k - K' \right).
\]

(3.3) Let \( h_i \) \( (i = 1, 2) \) be an orientation-reversing map of period \( 4k \) on \( P^3 \). In connection with \( h_i \), a symbol such as \( q_i \) shall be used to represent the same object as \( q \) where \( q \) is a symbol in (3.1) and (3.2). We will define an equivalence \( t \) of \( M_1 \) onto \( M_2 \) such that \( T_2^i t = t T_1^i \), \( t(J_i) = J_2 \), and \( t(J'_i) = J'_2 \). Since \( J \) is isotopic to \( S^1 \times I \times \{1/2\} \times \{1/2\} \) in \( A \times I \) (after parametrizing \( \bar{M} \)), it follows from Lemma 2.2 that there exists an equivalence \( t \) between \( T_1|\bar{M}_1 \) and \( T_2|\bar{M}_2 \) such that \( t(J_i) = J_2, t(\partial B_1 - K_i - K'_i) = \partial B_2 - K_2 - K'_2 \) and \( t(\partial B_2 - K_2 - K'_2) = \partial B_2 - K_2 - K'_2 \). Since each \( T_i \) interchanges \( K_i \) and \( K'_i \), and \( T_i|B_i \) \( (T_i|B_i \) resp.) is essentially the cone over \( T_i|\partial B_i \) \( (T_i|\partial B_i \) resp.) (see
Since \( \pi_1(N_i - L_i) = \mathbb{Z} \) and \( \text{Fix}(f^r_i) = L_i \), there exists a lifting equivalence \( s \) between \( f_1 \) and \( f_2 \) such that \( g_2 s = \theta_1 \) (see the following diagram). Let \( \tilde{N}_i = g_i^{-1}(\bar{M}_i) \) and \( \tilde{P}_i = d_i^{-1}(\tilde{N}_i) \). Then \( \tilde{N}_i \) and \( \tilde{P}_i \) are invariant regular neighborhoods of \( L_i \) and \( F_i \), which are homeomorphic to \( D^2 \times S^1 \), respectively. Our plan is to find a lifting \( r \) of \( P^3 \) such that the following diagram commutes.

\[
\begin{array}{ccc}
(P^3, \bar{P}_1, F_1) & \xrightarrow{d_1} & (N_1, \tilde{N}_1, L_1) & \xrightarrow{g_1} & (M_1, \bar{M}_1, J_1) \\
\downarrow r & & \downarrow s & & \downarrow t \\
(P^3, \bar{P}_2, F_2) & \xrightarrow{d_2} & (N_2, \tilde{N}_2, L_2) & \xrightarrow{g_2} & (M_2, \bar{M}_2, J_2)
\end{array}
\]

To do this, it is enough to show that \( (s' d'_i)_* (\pi_1(\partial \bar{P}_i)) = d'_i (\pi_1(\partial \bar{P}_i)) \), where \( s' : \partial \tilde{N}_1 \to \partial \tilde{N}_2 \) and \( d' : \partial \bar{P}_i \to \partial \tilde{N}_i \) are the maps such that \( s' = s|\partial \bar{N}_1 \) and \( d' = d_i|\partial \bar{P}_i \). In (3.5) and (3.6) we select some special generators of \( \pi_1(\partial \bar{P}_i) \) and \( \pi_1(\partial \bar{N}_i) \). In (3.7) we conclude the proof.

(3.5) Let \( q_i \) be the orbit map of \( T_i \) and let \( Q_i = q_i(\bar{M}_i) \). Since \( t \) is an equivalence between \( T_1 \) and \( T_2 \), there exists a homeomorphism \( \hat{t} \) between the orbit spaces of \( T_1 \) and \( T_2 \) such that \( \hat{t} q_1 = q_2 t \). Let \( q_i(J_i) = l_i \). It follows from Lemma 2.2 that \( Q_i \) is a nonorientable disk bundle over \( l_i \) (see also (3.2)). Therefore one can find an annulus \( A_1 \) in \( Q_1 \) such that \( \text{Int}(A_1) \subset \text{Int}(Q_1) \) and \( \partial A_1 \) consists of \( l_1 \) and a simple closed curve \( c_1 \) on \( \partial Q_1 \). Let \( A_2 = t(A_1) \). Then \( A_2 \) is an annulus in \( Q_2 \) such that \( \text{Int}(A_2) \subset \text{Int}(Q_2) \) and \( \partial A_2 \) consists of \( l_2 \) and a simple closed curve \( c_2 \) on \( \partial Q_2 \).

(3.6) Let \( v_i = q_i \cdot (g_i|\tilde{N}_i) \). Then, since \( v_i : \tilde{N}_i \to Q_i \) is the covering projection generated by \( \langle f_i|\tilde{N}_i \rangle \), we see that \( v_i^{-1}(A_i) \) is an annulus in \( \tilde{N}_i \) such that \( \partial (v_i^{-1}(A_i)) \) consists of \( l_i \) and a simple closed curve \( v_i^{-1}(c_i) \) on \( \partial \tilde{N}_i \), and \( \text{Int}(v_i^{-1}(A_i)) \subset \text{Int}(\tilde{N}_i) \) (recall that \( L_i \) is invariant under \( f_i \)). On the other hand, there exists a properly embedded disk \( D_i \) in \( \bar{P}_i \) such that \( D_i \cap h_i^{2r}(D_i) = \emptyset \) (1 < \( r < k \)), \( h_i^{2r}(D_i) = D_i \), and \( \partial D_i \) does not bound a disk in \( \partial \bar{P}_i \) (letting \( h_i = h_i|\bar{P}_i \), then \( h_i^{2k} \) is the only nontrivial element of \( \langle h_i \rangle \) with nonempty fixed point set, and one may use the argument in the proof of Lemma 2.8 of [3]). Let \( \alpha_i \) be the element of \( \pi_1(\partial \bar{P}_i) \) represented by the path \( \partial D_i \) and \( \beta_i \) be another element of \( \pi_1(\partial \bar{P}_i) \) such that \( \alpha_i \) and \( \beta_i \) generate \( \pi_1(\partial \bar{P}_i) \). Let \( \gamma_i \) and \( \xi_i \) be the elements of \( \pi_1(\partial \tilde{N}_i) \) represented by \( d_i(\partial D_i) \) and \( v_i^{-1}(c_i) \). Since \( d_i(\partial D_i) \) bounds a disk in \( \tilde{N}_i \) and \( v_i^{-1}(c_i) \) is homotopic to the center circle of \( N_i \) \((\approx D^2 \times S^1)\), we see that \( \gamma_i \) and \( \xi_i \) generate \( \pi_1(\partial \tilde{N}_i) \). Since \( v_2 s = \hat{t} v_1 \), we may assume (by the choice of \( c_i \)) that \( s'_* (\xi_i) = \xi_2 \) (recall that \( s' = s|\partial \bar{N}_i \)). Since \( d_i(\partial D_i) \) bounds a disk in \( \tilde{N}_i \), we may assume that \( s'_* (\gamma_i) = \gamma_2 \).

(3.7) We claim that \( \bar{v}_i^{-1}(c_i) \) is connected, where \( \bar{v}_i = v_i d_i \). Suppose that it was disconnected. Recall that \( d'_i = d_i|\partial \tilde{P}_i \). Since \( d'_i \) is a double covering projection generated by \( h_i^{2k} |\partial \tilde{P}_i \) and \( v_i^{-1}(c_i) \) is connected, we see that \( \bar{v}_i^{-1}(c_i) \)
has two components, say \(a, b\), and, hence, \(h^{2k}(a) = b\). Since \(\tilde{\varphi}\) is a covering projection generated by \(h|\partial P\), \(a \cup b\) is invariant under \(h\) (and \(h^k\)), and either \(h_i(a) = b_i\) or \(h_i(a) = a_i\) occurs. Therefore we see that \(h^{2k}(a_i) = a_i\), which is a contradiction to the fact that \(h_i^{2k}(a_i) = b_i\). Hence \(\tilde{\varphi}^{-1}(c_i)\) is connected. This implies that there is no element \(\phi_i\) of \(\pi_i(\partial P)\) such that \(d_i\phi_i = \xi_i\). We may assume (by the choice of \(D_i\) in \(P_i\)) that \(d_i\phi_i(x_i) = x_{i+1}\) and \(d_i\phi_i(y_i) = y_{i-1}\), for some \(m_i\). Note that \(m_i\) must be odd (otherwise, \(\xi_i \in d_i\phi_i(P_i)\)). Therefore, \(d_i\phi_i(\pi_i(\partial P))\) is generated by \(\gamma_i^2\) and \(\gamma_i\). Since \(s_i(\gamma_i^2) = \gamma_i^2\) and \(s_i(\gamma_i) = \gamma_i\), we have a lifting \(\tilde{r}\) of \(P - F - F'[\). One may extend \(\tilde{r}\) to a homeomorphism \(r\) of \(P^3\) such that \(d_r = s d_i\). This completes the proof.

4. Proof of Theorem C.

(4.1) Consider an orientation-reversing map \(h\) of period \(n\) on \(P^3\). In §3 we have proved the case where \(n = 4k\). Now assume that \(n = 2k, k \text{ odd } > 1\). Since \(h^k\) is an involution on \(P^3\), \(\text{Fix}(h^k)\) is a projective plane \(P\) plus an isolated point \(x\) (see [6]). Since the period of \(h^2\) is \(k\) (odd), \(\text{Fix}(h^{2r})\) \((1 < r < k)\) is a simple closed curve (see [3]). Let \(F = \text{Fix}(h^2)\). Let \(\xi: S^3 \to P^3\) be the natural projection. Since \(\pi_i(P^3) = Z_2\), it can be seen that \(\xi^{-1}(F)\) is a simple closed curve [3], [7]. Since \(\pi_i(P^3 - F)\) is abelian, \(\pi_i(S^3 - \xi^{-1}(F)) = Z\) (see [9]). Therefore, \(\pi_i(P^3 - F) = Z\) (for a proof, see [7]).

(4.2) Since \(\pi_i(P^3 - F) = Z\) and \(k\) is odd, the orbit space \(M = P^3/\langle h^2 \rangle\) is homeomorphic to \(P^3\) (see [3]). Since \(P \cup \{x\}\) is invariant under \(h\), we see that \(h(x) = x\). Since \(\text{Fix}(h) \subset F\), \(\text{Fix}(h)\) consists of \(x\) and a point \(y\) of \(F\). Since \(h^2\) and \(h^k\) generate the group \(\langle h \rangle\), \(F \cap P = \{y\}\). Furthermore, since \(h\) interchanges the sides of \(P\) in a small neighborhood of \(y\), \(F\) meets \(P\) at \(y\) locally piercingly. Let \(g: P^3 \to M\) be the orbit map and let \(J = g(F)\). Since \(\pi_i(P^3 - F) = Z\), it can be seen that \(\pi_i(M - J) = Z\) (see [3]). Let \(T\) be the involution of \(M\) induced by \(h\). Since \(gh^k = Tg\), we see that \(\text{Fix}(i) = g(P) \cup g(x)\). Let \(\tilde{P} = g(P)\) and \(z = g(x)\). Then \(\tilde{P}\) is a projective plane and \(T\) interchanges the two open arcs of \(J - \{z, g(y)\}\). Note that \(\tilde{P}\) is one-sided in \(M\).

(4.3) Triangulate \(M\) so that \(\text{Fix}(T)\) and \(J\) are subcomplexes, and \(T\) becomes simplicial. Let \(U\) be the simplicial neighborhood of \(\tilde{P}\) in \(M\). Let \(B\) be the closed star of \(z\) in \(M\). We may assume that \(B \cap U = \emptyset\). Note that \(T|B\) is essentially a cone over \(T|\partial B\) (see [8]). Consider the double covering \(\gamma: M' \to M\) obtained from \(M\) by cutting along \(\tilde{P}\). Since \(\partial U \approx S^2\), we see that \(\text{cl}(M - U)\) is homeomorphic to a 3-cell, and \(M'\) is a 3-sphere \(S^3\). Since \(\pi_i(M - J) = Z\), we see that \(\pi_i(M' - J') = Z\) where \(J' = \gamma^{-1}(J)\). Therefore \(J'\) is unknotted in \(M'\) (see [9]).

(4.4) Now consider the two orientation-reversing maps \(h_1\) and \(h_2\) of \(P^3\) with period \(2k\), \(k\) odd \(> 1\). As in (3.3), we use symbols \(q_i\) in connection with \(h_i\) \((i = 1, 2)\) whenever a symbol \(q\) has appeared in (4.2). Let \(\phi_i = \text{cl}(M_i - U_i - B_i)\).
Let $K_i$ be the simplicial neighborhood of $\text{cl}(J_i - U_i - B_i)$ in $Q_i$ such that $K_i$ has two components. Since $\gamma_i^{-1}(U_i)$ is a product neighborhood $S_i \times [-1, 1]$ of $\gamma_i^{-1}(\tilde{P}_i)$ ($\approx S^2$) such that $S_i \times \{0\} = \gamma_i^{-1}(\tilde{P}_i)$, each component of $\text{cl}(M'_i - \gamma_i^{-1}(U_i \cup B_i))$ is homeomorphic to $S^2 \times I$ and it is exactly a copy of $Q_i$. Therefore, since $J_i$ is unknotted in $M_i$, a product structure on $\text{cl}(Q_i - K_i)$ can be defined in terms of $A \times I$ ($A = S^1 \times I$) such that $\text{cl}(\partial B_i - K_i) \approx A \times \{0\}$, $\text{cl}(\partial U_i - K_i) \approx A \times \{1\}$ and $\text{cl}(\partial K_i - B_i - U_i) \approx S^1 \times \{0, 1\} \times I$. Furthermore the product structure can be chosen so that there exists an involution $f$ on $A$ such that $T_i(x, t) = (f(x), t)$ for $(x, t) \in A \times I$ (see §2). Notice that $T_i$ interchanges the two components of $K_i$. Therefore, the orbit space of $T_i|\text{cl}(M_i - B_i - U_i)$ is homeomorphic to $P^2 \times I$ (see also [8]) and, letting $G_i = M_i/\langle T_i \rangle$ and $k_i: M_i \to G_i$ be the orbit map, there exists a homeomorphism $\alpha$ of $G_i$ to $G_2$ such that $(ak_i)(z_1) = k_2(z_2)$, $(ak_i)(J_i) = k_2(J_2)$, and $(ak_i)(\tilde{P}_i) = k_2(\tilde{P}_2)$. Hence there exists an equivalence $\beta$ between $T_1$ and $T_2$ such that $\beta(J_1) = J_2$. Since $\pi_1(M_i - J_i) = Z$, one may conclude by the lifting theorem that $h_1$ and $h_2$ are conjugate in the usual way.

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