Algebraic Torsion for Infinite Simple Homotopy Types

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This paper is the last of a series dealing with the problem of giving an algebraic description of the torsion invariant for proper h-cobordisms using the concept of a locally finite infinite matrix. The other two papers are [1] and [6]. The reader should also consult [5]. The main results of this paper are (3.1) and (4.1) which describe the group of proper simple types on a strongly locally finite CW-complex as a K_1-type group $\mathrm{Wh}(\pi)$. The exact sequence (3.6) of [1] allows $\mathrm{Wh}(\pi)$ to be computed in a number of cases.

§ 1. Infinite simple types

In this section we give a definition of infinite simple homotopy type equivalen to the one in [5] but in a form more convenient for our purposes.

Let $\mathscr{C}$ denote the category of strongly locally finite, countable, CW-complexes and proper homotopy classes of continuous maps. Recall from [2] that a CW-complex is strongly locally finite provided it is the union of a countable, locally finite collection of finite subcomplexes. Let $\mathscr{C}^+ \subset \mathscr{C}$ denote the full subcategory whose objects are finite dimensional. A *proper expansion* $K \nearrow L$ in the category $\mathscr{C}$ is an inclusion $K \subset L$ where $L = K \cup (\bigcup_{i=1}^{\infty} L_i)$ and each L_i is a finite subcomplex such that

a) $(L_i - K) \cap (L_j - K) = \emptyset$ for $i \neq j$

b) L_i collapses to $K_i = K \cap L_i$.

A *proper contraction* $L \searrow K$ is the homotopy inverse of a proper expansion $K \nearrow L$. A proper map $f: X \to Y$ is a *proper simple homotopy equivalence* (in $\mathscr{C}$) iff there is a sequence of proper expansions and contractions $X = X_0 \to X_1 \to X_2 \to \cdots X_{n-1} \to X_n = Y$ whose composition is properly homotopic to f. If f is a morphism in $\mathscr{C}^+$, then it is a *proper simple equivalence* (in $\mathscr{C}^+$) provided each map $X_i \to X_{i+1}$ is a morphism in $\mathscr{C}^+$. In particular each proper expansion $K \nearrow L$ in $\mathscr{C}^+$ must satisfy the condition

c) there is an integer n such that $\dim(L_i - K) \leqslant n$ for all i.

Now given the notion of proper simple equivalence in $\mathscr{C}$ we have as in [5] the group $\mathscr{S}(X)$ of proper simple homotopy types of an object X of $\mathscr{C}$. An element of $\mathscr{S}(X)$ is represented by a proper homotopy equivalence $f: X \to Y$ and two such maps $f_0: X \to Y_0$ and $f_1: X \to Y_1$ are considered the same iff there is a simple equivalence $s: Y_0 \to Y_1$ in $\mathscr{C}$ such that $s \circ f_0$ is properly homotopic to f_1. Similarly one has the

[1]) Partially supported by NSF Grant GP-29697

[2]) Partially supported by NSF Grant GP-29073

group of proper simple types $\mathcal{S}^+(X)$ for any object X in $\mathcal{C}^+$. If X is an object of $\mathcal{C}^+$ there is a natural map $\mathcal{S}^+(X) \to \mathcal{S}(X)$ which we show to be an isomorphism in (4.2).

Throughout this paper any CW-complex will always be assumed to be strongly locally finite. We need this in order to say as in [2] that any proper map can be properly deformed to a cellular map – the starting point for the algebraic theory of simple types describing $\mathcal{S}(X)$ as a functor of $\pi_1 X$ and the system of fundamental groups of neighborhoods of infinity. If one works in the category of all locally finite, countable CW-complexes, then $\mathcal{S}(X)$ may be non-zero even though X is simply connected and simply connected at infinity. For example, let $K = e^0 \cup e^1 \cup \cdots$ where e^n is attached to e^{n-1} by collapsing ∂e^n to a point in the interior of e^{n-1}. The property of being strongly locally finite is preserved under proper simple equivalence. Hence, if K' is any subdivision of K which is strongly locally finite, then K and K' are not simply equivalent although they ought to be. This minor technical point could be remedied if one knew that any locally finite CW-complex had a strongly locally finite subdivision. We get around the difficulty by working only with strongly locally finite CW-complexes. In passing we remark that (**) of [5] is false if the category of all locally finite, countable CW-complexes is used. One must stay with strongly locally finite complexes.

Suppose $L = K \cup_{f_i} \{e_i^n\} \cup_{g_j} \{e_j^{n+1}\}$. Suppose the attaching map g_j of some $(n+1)$-cell e_j^{n+1} misses all the n-cells except, say, e_i^n and suppose g_j takes the top hemisphere of ∂e_j^{n+1} homeomorphically onto e_i^n and takes the bottom hemisphere into L. Thus the pair $e_j^n \cup e_j^{n+1}$ forms an elementary expansion. We shall say that e_j^{n+1} *cancels* e_i^n.

§ 2. Definition of torsion in $\mathcal{C}^+$

In this section we briefly recall the definition of torsion for a proper homotopy equivalence in $\mathcal{C}^+$. For details and terminology see [1] and [6, Chap. I, § 5].

Let X be a non-compact, connected, strongly locally finite CW-complex and let $t: T \to X$ be a tree for X. This means that T is a locally finite, contractible, one dimensional simplicial complex with a base vertex $0 \in T$ such that if $v \in T$ is a vertex different from 0 then at least two 1-cells branch off from v. Furthermore, $t: T \to X$ is required to be a cellular map which is properly $\frac{1}{2}$-connected in the sense that $t^*: H^0(X) \to H^0(T)$ and $t^*: H^0_{\text{end}}(X) \to H^0_{\text{end}}(T)$ are isomorphisms.

The obstruction group $\text{Wh}(X; t)$, which is defined in [6, Chap. I, § 5] to capture the torsion of a proper homotopy equivalence $f: W \to X$ in $\mathcal{C}^+$, is an abelian group which depends only on $\pi_1 X$ and the inverse system of fundamental groups of neighborhoods of infinity in X. Up to isomorphism $\text{Wh}(X; t)$ is also independent of the choice of tree $t: T \to X$. The group $\text{Wh}(X; t)$ can be computed as follows:

First some generalities. Let $t: T \to X$ be any tree for X. The set J of vertices of T

can be partially ordered by letting $u \leqslant v$ iff the arc from v to the base vertex 0 passes through u. Let $|v|$ denote the number of 1-simplices in the arc from v to 0. Let $T_v \subseteq T$ denote the smallest subcomplex containing all vertices w of T with $v \leqslant w$. Let $J' \subset J$ be a cofinal subset (containing the vertex 0) obtained as follows: choose an increasing sequence $0 = n_0 < n_1 < \cdots$. Then let $j \in J'$ iff there is some n_k with $|j| = n_k$. Associated to J' is a tree T' obtained by inserting a 1-simplex between vertices u and v of J' whenever $u < v$ and there is no vertex w of J' with $u < w < v$. The natural map $T' \to T$ is properly $\frac{1}{2}$-connected and the composition $T' \to T \to X$ is a tree for X.

Now start with the original tree $t: T \to X$. Then there is a tree $t': T' \to X$ derived from $t: T \to X$ by the above process and there is a collection $\{X_u\}$ of infinite, connected subcomplexes of X (one subcomplex X_u for each vertex u of T') satisfying the following conditions (cf. [6, Chap. I, § 5]):

a) $X_0 = X$, $X_u \supset X_v$ when $u \leqslant v$, and $t'(T_u) \subset X_u$

b) $X_u \cap X_v = \emptyset$ if $|u| = |v|$ and $u \neq v$

c) for each $n \geqslant 0$, $X - \bigcup_{|v| = n} X_v$ is contained in some finite subcomplex of X

d) given any finite subcomplex K of X, there is some $n \geqslant 0$ such that $K \cap (\bigcup_{|v| = n} X_v) = \emptyset$.

Now for each vertex u of T' let $\pi_u = \pi_1(X_u, t'(u))$. If $u \leqslant v$ define the homomorphism $\gamma_{uv}: \pi_v \to \pi_u$ to be "conjugation" by the path $t'(\alpha_{vu}) \subset X_u$ where $\alpha_{vu} \subset T'_u$ is the arc from u to v. The collection $\pi = \{\pi_u, \gamma_{uv}\}$ is a tree of groups over the set J' of vertices of T'. Let $Z[\pi] = \{Z[\pi_u], \gamma_{uv}\}$ denote the associated tree of group rings. Let $\mathrm{Wh}(\pi)$ be as defined in [1] and [6, Chap. I, § 5]. Then there is an isomorphism

$$\mathrm{Wh}(\pi) \cong \mathrm{Wh}(X; t)$$

See [6, Chap. I, § 5]. The point of using $\mathrm{Wh}(X; t)$ as the obstruction group rather than one of its "representatives" $\mathrm{Wh}(\pi)$ is to make the torsion well defined and independent of various choices such as the X_u above. However in proving certain things one often uses a convenient choice of a $\mathrm{Wh}(\pi)$. Also, there is the basic algebraic exact sequence (see (4.3) below) which relates $\mathrm{Wh}(\pi)$ with the $\mathrm{Wh}(\pi_u)$ and $\tilde{K}_0(\pi_u)$ and allows one to compute $\mathrm{Wh}(\pi)$ in a number of cases.

We will briefly indicate how to define the torsion

$$\tau(L, K) \in \mathrm{Wh}(\pi) \cong \mathrm{Wh}(L; t)$$

of an inclusion $K \to L$ where K is a proper deformation retract of L and $\dim(L - K) < \infty$. Here $\pi = \{\pi_u, \gamma_{uv}\}$ is the tree of groups corresponding to any choice of a tree $t': T' \to L$ derived from $t: T \to L$ as above and any choice of a system $\{L_u\}$ satisfying (a) through (d) with respect to $t': T' \to L$. The definition of $\tau(L, K)$ given below is in the spirit of [4]. Using the general machinery of [6, Chap. I, § 5] and [1] it is not hard to see that this approach to torsion for infinite simple types is equivalent to the one worked out in [6, Chap. I, § 5] which follows the lines of [3]. The argument showing the equivalence is entirely similar to the one in the compact case.

For any CW-complex X, let $\tilde{X}$ denote the universal covering space $p:\tilde{X}\to X$. If $Y\subset X$, let $\tilde{Y}=p^{-1}(Y)$.

By condition (a) above $t'(u)\in L_u$ for every vertex u of T'. Select a fixed lifting $\hat{u}\in\tilde{L}_u$ of $t'(u)$. If v is a vertex of T' and $u\leqslant v$, let $v'\in\tilde{L}_u$ be the lifting of $t'(v)\in L_u$ obtained as the end point of the lifting of the path $t(\alpha_{vu})$ to a path in $\tilde{L}_u$ starting at $\hat{u}$. Here α_{vu} denotes the arc from u to v in T'_u. If v is a vertex of T' with $u\leqslant v$ there is a unique map $\tilde{L}_v\to\tilde{L}_u$ covering the inclusion $L_v\to L_u$ such that $\hat{v}\in\tilde{L}_v$ goes to $v'\in\tilde{L}_u$. Furthermore, if $u\leqslant v\leqslant w$ the map $\tilde{L}_w\to\tilde{L}_u$ is the composition $\tilde{L}_w\to\tilde{L}_v\to\tilde{L}_u$.

The next choice we make is to select a locally finite collection Λ of paths $\alpha(\sigma)$ from the barycenters of cells σ of L to the images $t'(\alpha(\sigma))$ of vertices $u(\sigma)$ of T' such that if $\sigma\subset L_u$ then $\alpha(\sigma)\subset L_u$. If $\sigma\subset L_u$ the path $\alpha(\sigma)$ determines a path $\beta_u(\sigma)$ from σ to $t'(u)$ in L_u: first follow $\alpha(\sigma)$ to $t'(u(\sigma))$ and then follow $t'(\alpha_{u,u(\sigma)})$ to $t'(u)$. Here $\alpha_{u,u(\sigma)}$ is the arc in T' from $u(\sigma)$ to u.

If X is any CW-complex, let X^n denote the n-skeleton of X.

Now define the based $Z[\pi]$-module $C_n(L,K)$ as follows:

$$C_n(L,K)=\{C_n(L,K)_u\}$$

where for each vertex u of T'

$$C_n(L,K)_u=H_n(\overline{L^n_u},\overline{L^{n-1}_u}\cup\overline{(L^n_u\cap K)})$$

The "bar" is taken with respect to the universal cover $\tilde{L}_u\to L_u$. The $Z[\pi_u]$-module $C_n(L,K)_u$ is free with one basis element for each n-cell of L_u-K. The basis element corresponding to an n-cell σ of L_n-K is given by the lifting of σ to $\tilde{L}_u$ determined by the path $\beta_u(\sigma)$. If $u\leqslant v$ the map $\tilde{L}_v\to\tilde{L}_u$ determines a homomorphism $C_n(L,K)_v\to$ $\to C_n(L,K)_u$ and in fact we have an injection

$$C_n(L,K)_v\otimes_{Z[\pi_v]}Z[\pi_u]\to C_n(L,K)_u$$

whose image is the free submodule generated by the n-cells of L_u-K which lie in L_v-K. The boundary operators $\partial^u_n:C_n(L,K)_u\to C_{n-1}(L,K)_u$ are compatible with the maps $C_n(L,K)_v\to C_n(L,K)_u$ and therefore define a morphism of $Z[\pi]$-modules

$$\partial_n:C_n(L,K)\to C_{n-1}(L,K)$$

which satisfies $\partial_{n-1}\circ\partial_n=0$. This gives a chain complex

$$(C_*,\partial_*)=\{C_n(L,K),\partial_n\}$$

of based $Z[\pi]$-modules. In fact, if $S^n=\{S^n_u\}$ is the tree of sets over J' where S^n_u

consists of the n-cells of $L_u - K$, then $C_n(L, K)$ is the free $Z[\pi]$-module generated by S^n. Since $\dim(L-K)<\infty$ at most finitely many of the chain groups $C_n(L, K)$ are not zero.

Let $r: L\times I\to L$ be a proper deformation retraction of L down into K. We can assume r is cellular by [2, Th. 1.7]. For each vertex u of T' choose a cofinite subcomplex N_u of L_u (i.e., $L_u - N_u$ has only finitely many cells) such that

i) $N_0 = L_0$ and $N_u \supset N_v$ whenever $u \leqslant v$

ii) $r(N_u \times I) \subset L_u$.

The map $r: N_u\times I\to L_u$ has a unique lifting $r_u: \bar{N}_u \times I \to \tilde{L}_u$ such that r_u restricted to $\bar{N}_u \times 0$ is the inclusion and such that whenever $u\leqslant v$ there is a commutative diagram

$$\begin{array}{ccc} \bar{N}_v \times I & \xrightarrow[r_v]{} & \tilde{L}_v \\ \downarrow & & \downarrow \\ \bar{N}_u \times I & \xrightarrow[r_u]{} & \tilde{L}_u \end{array}$$

Let $\hat{C}_n(L, K)_u \subset C_n(L, K)_u$ be the free $Z[\pi]$-submodule generated by the n-cells of $L_u - K$ belonging to $N_u - K$ and let $i_u: \hat{C}_n(L, K)_u \to C_n(L, K)_u$ denote the inclusion map. The maps $r_u: \bar{N}_u \times I \to \tilde{L}_u$ induce coboundary operators

$$d_u^n: \hat{C}_n(L, K)_u \to C_{n+1}(L, K)_u$$

compatible with the morphisms $\hat{C}_n(L, K)_v \to \hat{C}_n(L, K)_u$ and $C_n(L, K)_v \to C_n(L, K)_u$ such that for each vertex u of T'

$$\partial_{n+1}^u \circ d_u^n + d_n^{n-1} \circ \hat{\partial}_n^u = \begin{cases} id, & \text{for} \quad u = 0 \\ i_u + \text{finite matrix}, & \text{for} \quad u > 0 \end{cases}$$

Here $\hat{\partial}_n^u: \hat{C}_n(L, K)_u \to \hat{C}_{n-1}(L, K)_u$ is the restriction of ∂_n^u. Thus the collection $d^n = \{d_u^n\}$ defines a germ $d^n: C_n(L, K) \to C_{n+1}(L, K)$ such that on the germ level we have

$$\partial_{n+1} \circ d^n + d^{n-1} \circ \partial_n = id. \tag{$*$}$$

This shows that (C_*, ∂_*) is an acyclic complex of based modules over the tree of rings $Z[\pi]$ and as in [6, Chap. I, § 5] we can define the torsion to be

$$\tau(L, K) = \tau(C_*, \partial_*) \in \mathrm{Wh}(\pi) \tag{2.1}$$

Now here is the way to define $\tau(L, K)$ in the spirit of [4]: By replacing d^n with $d^n \circ \partial_{n+1} \circ d^n$ (if necessary) we can assume that $d^{n+1} \circ d^n = 0$. Let $C_{\text{ev}} = \oplus_{0 \leqslant k} C_{2k}$ and $C_{\text{odd}} = \oplus_{0 \leqslant k} C_{2k+1}$. The formula $(*)$ implies that $\partial_{\text{ev}} + d^{\text{ev}}: C_{\text{ev}} \to C_{\text{odd}}$ is an isomorphism on the germ level whose inverse is $\partial_{\text{odd}} + d^{\text{odd}}: C_{\text{odd}} \to C_{\text{ev}}$. Let the trees of sets S_{ev} and S_{odd} be defined as the disjoint unions of trees of sets

$$S_{ev} = \coprod_{0 \geq k} S^{2k} \quad \text{and} \quad S_{odd} = \coprod_{0 \geq k} S^{2k+1}$$

Then C_{ev} is the free $Z[\pi]$-module generated by S_{ev} and C_{odd} is the free $Z[\pi]$-module generated by S_{odd}. Let J' denote the standard tree of sets $\{J'_u\}$ determined by the partially ordered set J' of vertices of T'; that is $J'_u = \{v \mid u \in J' \text{ and } u \leq v\}$. Let $F[J'; \pi]$ denote the free $Z[\pi]$-module generated by the tree of sets J'. As in [1, Prop. 2.2] choose proper bijections $h: S_{ev} \amalg J' \to J'$ and $g: S_{odd} \amalg J' \to J'$. Let $H: C_{ev} \oplus \oplus F[J'; \pi] \to F[J'; \pi]$ and $G: C_{odd} \oplus F[J'; \pi] \to F[J'; \pi]$ be the induced germ isomorphisms. Then $G \circ (\partial_{ev} + d^{ev}) \circ H^{-1}$ is an invertible germ taking $F[J'; \pi]$ to itself and we have

$$\tau(L, K) = \langle G \circ (\partial_{ev} + d^{ev}) \circ H^{-1} \rangle \in \mathrm{Wh}(\pi). \tag{2.2}$$

The torsion $\tau(L, K)$ is independent of the choice of the liftings $\hat{u}$ of the vertices $t'(u)$ and also of the choice of base paths Λ.

In [6, Chap I, § 5] the torsion is shown to be invariant under subdivision and to be additive in the following sense: Let $M \subset L \subset K$ where M is a proper deformation retract of L and L is a proper deformation retract of K. Let $t: T \to L$ be a tree for L. Then

$$\tau(K, M) = \tau(K, L) + i_* \tau(L, M) \tag{2.3}$$

where $i_*: \mathrm{Wh}(L; t) \to \mathrm{Wh}(K; i \circ t)$ is the isomorphism induced by the inclusion $i: L \subsetneq K$

Now let $f: X \to Y$ be a proper homotopy equivalence in the category $\mathscr{C}^+$ and let $t: T \to Y$ be a tree. Deform f properly to a proper cellular map $\hat{f}$ and as in [6, Chap I, § 5] define

$$\tau(f) = r_* \tau(M_{\hat{f}}, X) \in \mathrm{Wh}(Y; t) \tag{2.4}$$

where $r: M_f \to Y$ is the standard deformation retraction. If $i: K \subsetneq L$ is an inclusion and K is a deformation retraction of L then $\tau(i) = \tau(L, K)$. This is Lemma 20 of Chap I. of [6]. By Lemma 21 of Chap I of [6] the torsion $\tau(f)$ doesn't depend on the choice of cellular "approximation" $\hat{f}$. Furthermore the following additivity property holds (Lemma 22 of Chap I of [6]): Let $f: X \to Y$ and $g: Y \to X$ be proper homotopy equivalences. Let $t: T \to Y$ be a tree. Then

$$\tau(g \circ f) = \tau(g) + g_* \tau(f) \tag{2.5}$$

where g induces the isomorphism $g_*: \mathrm{Wh}(Y; t) \to \mathrm{Wh}(Z; g \circ t)$.

LEMMA 2.5. *Suppose $f:X\to Y$ is a simple equivalence in the category $\mathscr{C}^+$. Then* $\tau(f)=0$.

Proof. The additivity property of torsion reduces the argument to showing that $\tau(L,K)=0$ where $K\nearrow L$ is an expansion in $\mathscr{C}^+$. Write $L=K\cup(\bigcup_{i+1}^{\infty} L_i)$ where L_i is a finite subcomplex which collapses to $K_i=K\cap L_i$ and $\dim(L_i-K)\leqslant n$ for all i. Each L_i can be collapsed to K_i by performing elementary collapses in order of decreasing dimension. The additivity property again reduces the problem to showing that $\tau(L,K)=0$ whenever each $K_i\nearrow L_i$ is a sequence of elementary expansions of dimension k. However the torsion certainly vanishes in this case because $\partial_{ev}+d^{ev}=\partial_k:C_k(L,K)\to C_{k-1}(L,K)$ is a blocked germ [1, §2] with each block being a product of elementary matrices.

Now let X be an object of $\mathscr{C}^+$ and let $t:T\to X$ be a tree for X. Let $[f]\in\mathscr{S}^+(X)$ be represented by a proper homotopy equivalence $f:X\to Y$. Choose a proper homotopy inverse $g:Y\to X$ of f and as in [6, Chap. I, § 5] let

$$\tau^+(f)=\tau(g)\in \mathrm{Wh}(X;t). \tag{2.6}$$

Then (2.4) and (2.5) imply that (2.6) gives a well defined homomorphism

$$\tau^+:\mathscr{S}^+(X)\to \mathrm{Wh}(X;t) \quad .$$

and we show in the next section that this is an isomorphism.

§ 3. τ^+ is an isomorphism

In this section we prove

THEOREM 3.1. *Let X be an object of $\mathscr{C}^+$ and let $t:T\to Y$ be a tree for X. Then*

$$\tau^+:\mathscr{S}^+(X)\to \mathrm{Wh}(X;t)$$

is an isomorphism.

First we prove that τ^+ is injective.

Let $f:X\to Y$ be a cellular proper homotopy equivalence and let M_f be the mapping cylinder of f.

LEMMA 3.2. *There is an inclusion $X\subsetneq M$ with X a proper deformation retract of M such that the pair (M,X) is simply equivalent* rel X *in $\mathscr{C}^+$ to the pair (M_f,X) and such that $M-X$ has cells in only two dimensions.*

The proof of this is a straight forward generalization to the proper category of the argument for Lemma 3 of [7]. In fact, M can be chosen to have cells only in dimensions $n+1$ and n where $n \geqslant \max(\dim X, \dim Y)$. Thus M can be constructed to have cells only in dimensions $2k$ and $2k-1$ where $2k-1 \geqslant \max(\dim X, \dim Y)$.

Now suppose $f: X \to Y$ represents an element of $\mathscr{S}^+(X)$ on which τ^+ vanishes. Replace M_f by M as above. Choose $t': T' \to X$ and $\{X_u\}$ as in § 2. Choose a collection $\{M_u\}$ satisfying (a) through (d) of §2 as follows: Let

$M'_u = X_u \cup \{(2k-1)$-cells of M whose attaching maps lie in $X_u\}$. Then set

$M_u = M'_u \cup \{2k$-cells of M whose attaching maps lie in $M'_u\}$. Assume that $2k \geqslant 4$ and let $\tau = \{\tau_u, \gamma_{uv}\}$ be the tree of groups where $\pi_u = \pi_1(M_u, t'_{(u)}) \simeq \pi_1(X_u, t'(u))$. Since $\tau^+(f) = 0$ we know that $\tau = \tau(M, X) \in \mathrm{Wh}(\pi) \cong \mathrm{Wh}(M; t)$ also vanishes. The torsion τ is represented by the germ

$$\partial = \partial_{2k}: C_{2k}(M, X) \to C_{2k-1}(M, X).$$

Since $\tau = 0$ we know by Lemma 2.7 of [1] that after stabilization of ∂ to $(\partial \oplus 1) \oplus \cdots \oplus 1$ it is possible to find blocked germs $A = \sum_{0 \leqslant u} A^u$ and $B = \sum_{0 \leqslant u} B_u$ of $C_{2k}(M, X)$ to itself such that

$$[(\partial \oplus 1) \oplus \cdots \oplus 1] \cdot A \cdot B = P$$

where $P: C_{2k}(M, X) \to C_{2k-1}(M, X)$ is a π-permutation germ. We also know that each of the square matrices A^u and B^u is a product of elementary matrices over $Z[\pi_u]$. Since P is a π-permutation germ it has a matrix representative $\{P_u\}$ where $P_u: C_{2k} \times (M, X)_u \to C_{2k-1}(M, X)_u$ satisfies P_u(basis element) $= \pm g \cdot$(basis element) where $g \in \pi_u$. The stabilization of ∂ to $(\partial \oplus 1) \oplus \cdots \oplus 1$ is achieved geometrically by stabilizing M; that is, we replace M by $M \cup \{e_u^{2k-1} \cup e_u^{2k}\}$ where each pair $e_u^{2k-1} \cup e_u^{2k}$ is an elementary expansion attached to the vertex $t'(u) \in X$. To simplify notation we shall still denote the stabilized ∂ and the stabilized M by ∂ and M. Let $S = \{S_u\}$ denote the tree of sets over J' where $S_u = 2k$-cells of $M_u - X$. Since A is blocked we can (as in §2 of [1]) replace the tree $S = \{S_u\}$ by an equivalent tree of sets $D = \{D_u\}$ with $D_u \subset S_u$ and we can amalgamate A so that $\hat{D}_u = D_u - \bigcup_{u<v} D_v$ is a finite set which is the support of A^u; that is, A^u is an invertible $Z[\pi_u]$-homomorphism from $F_u = F[\hat{D}_u; \pi_u]$ to itself.

Recall the following: Suppose $L = K \cup_f e^n$ where $f: S^{n-1} \to K$ is the attaching map. If f is deformed by a homotopy $H: S^{n-1} \times I \to K$ to a map $g: S^{n-1} \to L$ then $L' = K \cup_g e^n$ has the same simple type as L. Let $W = K \cup_H (e^n \times I)$ where $H: S^{n-1} \times I \to K$ is the attaching map. Then $L \nearrow W \searrow L'$ is the simple equivalence from L to L'. Also recall that if $K_0 \to K_1 \to \cdots \to K_{n-1} \to K_n$ is a sequence of elementary expansions and/or contractions then there is a complex W containing K_0 and K_n such that $K_0 \nearrow W \searrow K_n$ and $\dim W \leqslant \max(\dim K_i)$.

Now write each matrix A^u as a product of elementary matrices of the form $e_{ij}(\lambda)$: $F_u \to F_u$ where $\lambda = \pm g$ for $g \in \pi_u$. For each u use this product to perform a sequence of deformations of the attaching maps of the $2k$-cells in $\hat{D}_u$ over one another as in the "handle addition" lemma of [7, Lemma 4]. At any step in the process the attaching map of a cell e^{2k} in $\hat{D}_u$ is deformed with support contained in $M'_u \cup$ (other $2k$-cells in $\hat{D}_u$). This procedure changes M by a proper simple equivalence in $\mathscr{C}^+$ to a complex M' such the boundary map $\partial': C_{2k}(M', X) \to C_{2k-1}(M', X)$ is just the germ $\partial \cdot A$. Repeat the process using a block decomposition of the germ B to get a complex M'' such that $\partial'': C_{2k}(M'', X) \to C_{2k-1}(M'', X)$ is just $\partial \cdot A \cdot B = P$. Since P is a π-permutation germ the attaching maps of the $2k$-cells can be deformed in a locally finite way so that each $2k$-cell cancels just one $(2k-1)$-cell and misses all the others. This says M'' is properly simply equivalent in $\mathscr{C}^+$ to a complex which collapses to X. We conclude that $\tau^+: \mathscr{S}^+(X) \to \mathrm{Wh}(X; t)$ is injective.

It is easy to show that τ^+ is surjective: Let $t': T' \to X$ and $\{X_u\}$ be as in §2 and let $A: F[J'; \pi] \to F[J'; \pi]$ be an invertible germ. For each vertex u of T' attach a 4-cell e^4_u to X by collapsing ∂e^4_u to the point $t'(u)$. Now attach 5-cells e^5_u in a locally finite way using the germ A. This gives a complex M which has X as a proper deformation retract by [2, Th. 3.1] or [5, Prop IV]. Also $\tau(X \to M) = [A] \in \mathrm{Wh}(\pi) \cong \mathrm{Wh}(X; t)$. This completes the proof that τ^+ is an isomorphism.

§ 4. Torsion in the category $\mathscr{C}$

Although the methods of §2 don't directly define the torsion of a proper homotopy equivalence $f: X \to Y$ in the category $\mathscr{C}$ it is possible to prove

THEOREM 4.1. *Let X be an object of $\mathscr{C}$ and let $t: T \to X$ be a tree. There is an isomorphism*

$$\mathscr{S}(X) \cong \mathrm{Wh}(X; t).$$

A consequence of (3.1) and (4.1) is

COROLLARY 4.2. *If X is an object of $\mathscr{C}^+$, then $\mathscr{S}^+(X) \to \mathscr{S}(X)$ is an isomorphism.*

Proof of (4.1). Let $t': T' \to X$ and $\{X_u\}$ be as in §2. Let $\pi = \{\pi_u, \gamma_{uv}\}$ be the associated tree of groups. Recall the exact sequence (3.6) of [1]:

$$\prod_{0<u} \mathrm{Wh}(\pi_u) \xrightarrow{I-S} \prod_{0\leqslant u} \mathrm{Wh}(\pi_u) \xrightarrow{\Delta} \mathrm{Wh}(\pi) \xrightarrow{\partial} \prod_{0<u} \tilde{K}_0(\pi_u) \xrightarrow{I-S} \prod_{0\leqslant u} \tilde{K}_0(\pi_u) \tag{4.3}$$

Let

$$\mathrm{Wh}(\pi)' = \mathrm{Coker}\,[\prod_{0<u} \mathrm{Wh}(\pi_u) \xrightarrow{I-S} \prod_{0\leqslant u} \mathrm{Wh}(\pi_u)]$$

Let

$$\tilde{K}_0(\pi)' = \mathrm{Ker}\,[\prod_{0<u} \tilde{K}_0(\pi_u) \xrightarrow{I-S} \prod_{0\leqslant u} \tilde{K}_0(\pi_u)]$$

Then there is the exact sequence

$$0 \to \mathrm{Wh}(\pi)' \to \mathrm{Wh}(\pi) \to \tilde{K}_0(\pi)' \to 0 \tag{4.4}$$

In [5] the following exact sequence is constructed:

$$0 \to \mathrm{Wh}(\pi)' \to \mathcal{S}(X) \to \tilde{K}_0(\pi)' \to 0 \tag{4.5}$$

Hence to prove (4.1) it suffices by the "5-lemma" to construct a homomorphism $\mathrm{Wh}(\pi) \to \mathcal{S}(X)$ which induces a map from the sequence (4.4) to the sequence (4.5). This was essentially done in the proof of (3.1): Take an invertible germ $A: F[J'; \pi] \to \to F[J'; \pi]$ and construct a complex $M(A)$ containing X as a proper deformation retract by attaching one 4-cell e_u^4 to the vertex $t'(u) \in X$ and then attaching the 5-cells e_u^5 in a locally finite way using the germ A. The argument of §3 proving the injectivity of τ^+ shows that $M(A)$ is simply equivalent to $M(A \cdot E)$ whenever E is a blocked germ $E = \sum_u E^u$ such that each E^u is a product of elementary matrices over $Z[\pi_u]$. Stabilization of A to $A \oplus 1$ only changes $M(A)$ by adding elementary expansions. Hence the proper simple type of $M(A)$ doesn't change when A is varied by the defining relations of $\mathrm{Wh}(\pi)$ and we get the required homomorphism $\mathrm{Wh}(\pi) \to \mathcal{S}(X)$.

§ 5. The proper *s*-cobordism theorem

Now that $\mathcal{S}^+(X)$ and $\mathcal{S}(X)$ have been described in algebraic terms the proper *s*-cobordism theorem of [5] can be reformulated.

Recall that a smooth, piecewise linear or topological cobordism W^n from M_-^n to M_+^n is a proper *h*-cobordism provided the inclusions $M_- \subsetneq W$ and $M_+ \subsetneq W$ are proper homotopy equivalences. Suppose M_-, M_+, W are all non-compact and let $t: T \to M_-$ be a tree.

THEOREM 5.1. *Let $n \geqslant 6$. There is a well defined torsion element $\tau(W; M_-, M_+) \in \mathrm{Wh}(M_-; t)$ which vanishes iff $(W; M_-, M_+)$ is isomorphic to $(M_- \times [0, 1]; M_- \times 0, M \times 1)$. Every element of $\mathrm{Wh}(M_-; t)$ can be realized as the torsion of some proper h-cobordism on M_-.*

This is just the statement of the combined theorems (3.1) and (4.2) above together with Theorem III of [5]. Alternatively, for a direct proof that elements of $\mathrm{Wh}(M_-; t)$ classify proper *h*-cobordisms on M_- one can mimic the argument in the compact case using the methods of §3 in the setting of handlebody theory.

Here are some examples. Compare with [5].

a) Suppose M_- is simply connected and simply connected at infinity. Then it is possible to choose a tree $t':T'\to M_-$ and a collection $\{(M_-)_u\}$ such that each $(M_-)_u$ is simply connected. Thus $\pi=\{\pi_u, \gamma_{uv}\}$ is a tree of trivial groups and (4.3) shows that $\mathrm{Wh}(\pi)\cong\mathrm{Wh}(M_-;t)$ vanishes. Hence any proper h-cobordism on such an M is trivial.

b) Suppose M_- has just one stable end ε with fundamental group $\pi_1\varepsilon$ such that $\pi_1\varepsilon\to\pi_1 M_-$ is an isomorphism. Then (3.10) of [1] implies that $\mathrm{Wh}(M_-;t)=0$ and hence any proper h-cobordism on M_- is trivial. In particular, for any non-compact M_-, any proper h-cobordism on $M_-\times R^2$ is trivial.

There are algebraic product and duality formulae similar to the ones in the compact case. Compare with [5].

Let $(W; M_-, M_+)$ be a proper h-cobordism and let N be a compact manifold. Let $t:T\to M_-$ be a tree.

Product formula (see Lemma 23 of [6]).

$$\tau(W\times N; M_-\times N, M_+\times N)=\chi(N)\cdot i_*\tau(W; M_-, M_+)$$

where $\chi(N)$ is the Euler class of N and $i_*:\mathrm{Wh}(M_-;t)\to\mathrm{Wh}(M_-\times N;t)$ is the induced homomorphism.

Remark. By constrast to the above suppose $(W^n; M_-, M_+)$ is a proper h-cobordism (compact or non-compact) and let N be a non-compact manifold. If $n\geqslant 6$ then the proper h-cobordism $(W\times N; M_-\times N, M_+\times N)$ is trivial.

The torsion of a proper h-cobordism $(W; M_-, M_+)$ can be computed in $\mathrm{Wh}(W;t)$ where there is a conjugation $-:\mathrm{Wh}(W;t)\to\mathrm{Wh}(W;t)$ defined as follows: choose $t':T'\to W$ and $\{W_u\}$ as in §2. For each vertex u of T' there is the orientation homomorphism $w_u:\pi_u\to Z_2=\{+1,-1\}$. If $u\leqslant v$, then $w_v=w_u\circ\gamma_{uv}$. Define the conjugation $-:\pi\to\pi$ to be the collection of compatible conjugations $-:\pi_u\to\pi_u$ where $\bar{g}=w_u(g)\,g^{-1}$ for $g\in\pi_u$. The conjugation on π induces one on $\mathrm{Wh}(\pi)\cong\mathrm{Wh}(W;t)$ by taking any invertible germ $A:F[J';\pi]\to F[J';\pi]$ to $\bar{A}=$conjugate transpose of A.

Duality formula (see [6, Chap I, §5])

$$\tau(W; M_+, M_-)=(-1)^{n-1}\,\bar{\tau}(W; M_-, M_+).$$

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Received January 22, 1972