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Homotopy mod. C of Spaces of Category 2¹⁾

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The known result of HOPF concerning the cohomology structure of H -spaces may now be restated as follows. An H -space, i.e. a space with a continuous multiplication with unit, has over a field k of characteristic 0 the same cohomology ring as a product of spaces of type (π, n) . Denoting by C the class of finite groups, THOM [7] has shown more, namely that an H -space is equivalent mod. C to a product of spaces of type (π, n) . On the other hand, in the theory of ECKMANN-HILTON [1], the dual of an H -space is a space of LUSTERNIK-SCHNIRELMANN category ≤ 2 . For such spaces we are proving here the dual of the above result of THOM: any finite simply connected CW -complex of category ≤ 2 is equivalent mod. C to an union of spheres with a single common point (here and throughout the paper, C denotes the class of finite groups). The precise result in a slightly more general form is stated in Theorem 2.2.

1. Preliminary lemmas

Let

$$\varphi_k : \pi_r(S^n) \rightarrow \pi_r(S^n)$$

be defined by left composition with a map $S^n \rightarrow S^n$ of degree k , i.e. $\varphi_k(\gamma) = k\iota \circ \gamma$ for any $\gamma \in \pi_r(S^n)$ ($\iota \in \pi_n(S^n)$) is the class of the identity. Then we have for n even [3]

$$\varphi_k(\gamma) = k\gamma + \frac{k(k-1)}{2} [\iota, \iota] \circ H_0(\gamma) + \frac{(k+1)k(k-1)}{3} [\iota, [\iota, \iota]] \circ H_1(\gamma) \quad (1)$$

where H_0 and H_1 are the generalized HOPF invariants of HILTON. As a consequence of (1)

1.1. $q\gamma = 0$, $\gamma \in \pi_r(S^n)$ implies $\varphi_{2q}(\gamma) = 0$ (for n odd it was shown by SERRE that already $\varphi_{2q}(\gamma) = 0$).

Let n be even and let $\pi_{2n-1}(S^n) = Z' + G$, where Z' is infinite cyclic, generated by α and G is finite of order g . Denote by d the classical HOPF invariant of α , i.e. $H_0(\alpha) = d\iota_{2n-1}$, where ι_{2n-1} generates $\pi_{2n-1}(S^{2n-1})$. Let $[\iota, \iota] = s\alpha + \beta$, $\beta \in G$. An easy computation, based on (1), shows that for any $\gamma \in \pi_{2n-1}(S^n)$

1.2. $\varphi_{2mg}(\gamma) = N_0 m \gamma$ where $N_0 = 2g + gsd(2mg - 1)$. Moreover,

1.3. if $\gamma = r\alpha + \delta$, $\delta \in G$ then $\varphi_{2mg}(\gamma) = N_0 rm\alpha$.

1.4. Lemma. Let K be a CW -complex, n an even integer and

$$f : K^{2n-1} \rightarrow S^n$$

¹⁾ The result of this paper was presented to the International Colloquium on Differential Geometry and Topology, Zurich, June 1960 (in absence of the author, by Professor HILTON).

a map such that $f^*(u) = h \in H^n(K, Z)$ where $u \in H^n(S^n, Z)$ is the fundamental class. If the cup-square $h \cup h \in H^{2n}(K, Z)$ is an element of finite order, then there exists a map $\varphi: S^n \rightarrow S^n$ of degree $s \neq 0$ such that $\varphi \circ f/K^{2n-2}$ is extendable over K^{2n} .

Proof. Without loss of generality we may assume, for the sake of convenience, that $\dim K = 2n$. Attach to S^n a $2n$ -cell with characteristic map in class α ; let Y be the resulting space. Let $c^{2n}(f) \in C^{2n}(K, \pi_{2n-1}(S^n))$ be the obstruction to the extension of f . By 1.3, if $\psi: S^n \rightarrow S^n$ has degree $2g$, the obstruction $c^{2n}(\psi \circ f)$ takes on each cell a value which is a multiple of α . Therefore, denoting by $i: S^n \rightarrow Y$ the inclusion, $i \circ \psi \circ f$ can be extended to a map

$$F: K \rightarrow Y.$$

If $u' \in H^n(Y, Z)$ is the fundamental class, then $u' \cup u' = -da$, where a is the fundamental class of $H^{2n}(Y, Z) \approx Z$ and d is the HOPF invariant of α .

Let $j: Z \rightarrow \pi_{2n-1}(S^n)$ map Z onto Z' ($j(1) = \alpha$); it induces homomorphisms

$$\begin{aligned} j_*: H^{2n}(K, Z) &\rightarrow H^{2n}(K, \pi_{2n-1}(S^n)), \\ j_*: H^{2n}(Y, Z) &\rightarrow H^{2n}(Y, \pi_{2n-1}(S^n)). \end{aligned}$$

It is easy to check that

$$F^*(j_*(a)) = \gamma^{2n}(\psi \circ f)$$

where $\gamma^{2n}(\psi \circ f)$ is the cohomology class of $c^{2n}(\psi \circ f)$. We further have

$$\begin{aligned} d \cdot \gamma^{2n}(\psi \circ f) &= d \cdot F^*(j_*(a)) = j_*(F^*(d \cdot a)) = -j_*(F^*(u' \cup u')) = \\ &= -j_*(2gh \cup 2gh) = -4g^2 \cdot j_*(h \cup h). \end{aligned}$$

This proves that $\gamma^{2n}(\psi \circ f)$ is an element of finite order, say m . Let $\chi: S^n \rightarrow S^n$ be a map of degree $2mg$. Then 1.2 immediately yields

$$c^{2n}(\chi \circ \psi \circ f) = N_0 m c^{2n}(\psi \circ f)$$

and

$$\gamma^{2n}(\chi \circ \psi \circ f) = N_0 m \gamma^{2n}(\psi \circ f) = 0.$$

This proves the assertion of the lemma.

1.5. Proposition. *Let K be a q -dimensional ($q < \infty$) CW-complex, n an integer and h an arbitrary element of $H^n(K, Z)$, such that the cup-square $h \cup h$ is an element of finite order. There exist an integer $N > 0$ and a map $f: K \rightarrow S^n$ such that $f^*(u) = Nh$, where u is the fundamental class of $H^n(S^n, Z)$.*

This proposition was conjectured by SERRE and proved by him for n odd [5, ch. V, Prop. 2]. For n even the proof is practically the same but uses 1.1 and 1.4.

Remark. In view of 1.5 and of [6, II, 2] we may add to [6, II, 4] the following result:

Let V^n be an orientable closed differentiable n -manifold, k an even number and z a class in $H_{n-k}(V^n, Z)$, whose selfintersection is a class of finite order. Then there exists an integer $N > 0$ such that the class Nz can be realized by means of a submanifold whose normal fibre bundle is trivial.

2. The main theorem

The base point of any space will be denoted by $*$. For any spaces X_1, \dots, X_m . $X_1 \vee \dots \vee X_m$ denotes their union with a single common point $*$. There are obvious retractions $r_j: X_1 \vee \dots \vee X_m \rightarrow X_j$ mapping $X_1, \dots, X_{j-1}, X_{j+1}, \dots, X_m$ onto $*$. If $\varphi_j: X_j \rightarrow Y_j$ are maps, there is a map

$$\varphi_1 \vee \dots \vee \varphi_m: X_1 \vee \dots \vee X_m \rightarrow Y_1 \vee \dots \vee Y_m$$

defined in the obvious way.

In this paper we consider only spaces which have the homotopy type of connected CW -complexes. For such a space, the two following definitions of LUSTERNIK-SCHNIRELMANN category ≤ 2 are equivalent (compare [8, p. 94]).

A) $\text{cat } X \leq 2$ if and only if $X = A_1 \cup A_2$, where A_1 and A_2 are open and contractible in X .

B) $\text{cat } X \leq 2$ if and only if there exists a map

$$\Phi: X \rightarrow X \vee X$$

such that $r_j \circ \Phi \simeq \theta_X: X \rightarrow X$ ($j = 1, 2$) where θ_X is the identity map of X and the homotopies are rel. $*$.

If $\text{cat } X \leq 2$ define

$$\Phi_m: X \rightarrow \underbrace{X \vee \dots \vee X}_{m\text{-fold}} \quad (2)$$

by

$$\Phi_2 = \Phi, \quad \Phi_m = (\underbrace{\theta_X \vee \dots \vee \theta_X}_{(m-2)\text{-fold}} \vee \Phi) \circ \Phi_{m-1}. \quad (2')$$

It follows readily that

$$2.1. \quad r_j \circ \Phi_m \simeq \theta_X, \quad j = 1, \dots, m.$$

2.2. Theorem. Let K be a connected and simply connected CW -complex whose homology groupes are finitely generated in each dimension and let C be the class of finite groups. If $\text{cat } K \leq 2$, there exists for any integer $r > 1$ a map

$$f: K^{r+1} \rightarrow L$$

where L is an union of spheres, such that

$$f_*: H_i(K^{r+1}, Z) \rightarrow H_i(L, Z)$$

and

$$f_* : \pi_i(K^{r+1}) \rightarrow \pi_i(L)$$

are C -monomorphisms for $i < r$ and C -epimorphisms for $i \leq r$.

2.3. Corollary. *If $\dim K < \infty$, we may choose Y and the map $f: K \rightarrow L$ such that*

$$f_* : H_i(K, Z) \rightarrow H_i(L, Z)$$

and

$$f_* : \pi_i(K) \rightarrow \pi_i(L)$$

are C -isomorphisms in all dimensions.

Remark. If the homology of K is not finitely generated, then Theorem 2.2 is not true. A counter example is provided by a complex $K' = K'(Q, 2)$ such that $H_i(K', Z) = 0$ for $i \neq 0, 2$ and $H_2(K', Z) = Q$ where Q is the group of rationals.

Proof of 2.2. Since all cup-products in K vanish (see [2]) it follows from 1.5 that for any cohomology class $h \in H^i(K^{r+1}, k)$, $i \leq r$, where k is the field of rationals, there exists a map

$$g : K^{r+1} \rightarrow S^i$$

and a class $u \in H^i(S^i, k)$ such that

$$g^*(u) = h.$$

Let h_1, h_2, \dots, h_m be a base of $\sum_{i=1}^r H^i(K^{r+1}, k)$. Choose for each j , ($j = 1, \dots, m$) a map

$$g_j : K^{r+1} \rightarrow S_j$$

where S_j is a sphere of the corresponding dimension, such that

$$g_j^*(u_j) = h_j, \quad u_j \in H^{n_j}(S_j, k), \quad n_j = \dim S_j. \quad (3)$$

Let

$$\Phi_m : K \rightarrow \underbrace{K \vee \dots \vee K}_{m\text{-fold}}$$

be as in (2). We may assume that Φ_m is cellular; then Φ_m induces a map

$$\bar{\Phi}_m : K^{r+1} \rightarrow K^{r+1} \vee \dots \vee K^{r+1}.$$

Consider the map

$$g_1 \vee \dots \vee g_m : K^{r+1} \vee \dots \vee K^{r+1} \rightarrow S_1 \vee \dots \vee S_m = L.$$

It is easy to check, by means of 2.1 (where all homotopies may be chosen cellular) and (3) that $f : K^{r+1} \rightarrow Y$, $f = (g_1 \vee \dots \vee g_m) \circ \bar{\Phi}_m$ induces isomorphisms

$$f^* : H^i(L, k) \rightarrow H^i(K^{r+1}, k)$$

in dimensions $i \leq r$. Applying the known results of SERRE [5, ch. III, Th. 3 and Prop. 1] we obtain the conclusion of the theorem.

Remark. Set $K^{r+1} = A$, $L = B$; in order to apply SERRE's results, quoted above, we must assume that $\pi_2(A) \rightarrow \pi_2(B)$ is an epimorphism. In fact, this restriction may be removed. We may assume that f is an inclusion. Further, passing if necessary to singular polytopes, we may also assume that B is a simplicial complex with the strong (metric) topology and A is a subcomplex (the strong topology and the weak one on a simplicial complex yield spaces of the same homotopy type [4]).

Let Y be the space of paths in B beginning at the base point and ending in A . According to [4], Y is sufficiently smooth in order to admit an universal covering space; as noticed by SERRE [5, ch. III, Remarque 3], this is sufficient for the validity of his Théorème 3 without the above assumption concerning the second homotopy groups.

3. Concluding remarks

The notion of space of category ≤ 2 may be relativized by introducing spaces of category ≤ 2 mod. C . Namely, with the notations of the beginning of the previous section, $\text{cat } X \leq 2$ (mod. C) if there is a map

$$\Phi : X \rightarrow X \vee X$$

such that $r_j \circ \Phi$, $j = 1, 2$ are C -isomorphisms in homology. Obviously

3.1. Remark. *Theorem 2.2 remains true if we replace $\text{cat } K \leq 2$ by $\text{cat } K \leq 2$ (mod. C).*

In view of Theorem 2.2 all computations mod. C of the homotopy groups of a simply connected space X of category ≤ 2 with finitely generated singular homology groups reduce to similar computations for an union of spheres, a problem solved by HILTON [3]. For, we may replace X by its singular polytope $P(X)$ whose category is also ≤ 2 [2]. It results that for a space X of category ≤ 2 the HUREWICZ homomorphism $\pi_n(X) \rightarrow H_n(X)$ is always a C -epimorphism; its kernel consists mod. C of iterated WHITEHEAD products. This means that the homology groups of X (their free part) entirely determine mod. C its homotopy groups. This enables us to prove

3.2. Corollary. *For any two simply connected CW-complexes K and L with finitely generated homology groups in each dimension, the groups $\pi_n(K \vee L)$ are determined mod. C by $\pi_n(K)$, $\pi_n(L)$, $H_*(\Omega K, k)$ and $H_*(\Omega L, k)$ (where k is the field of rationals).*

Proof. As is well known

$$\pi_n(K \vee L) = \pi_n(K) + \pi_n(L) + \pi_n(K \square L)$$

where $K \square L$ is the space of paths in $K \times L$ beginning in the subspace

$K \times * \cup * \times L$ and ending at the base point. It is easy to see that

$$K \square L = EK \times \Omega L \cup \Omega K \times EL \subset EK \times EL = E(K \times L),$$

where $\Omega K, \Omega L$ are the loop spaces and $EK, EL, E(K \times L)$ are the spaces of paths ending at $*$. Applying the relative KÜNNETH theorem to $(EK, \Omega K) \times (EL, \Omega L)$ we obtain

$$H_n(K \square L, k) = \sum_{\substack{p, q = n-1 \\ p, q > 0}} H_p(\Omega K, k) \otimes H_q(\Omega L, k).$$

Or the other hand, by [4], $K \square L$ has the homotopy type of a CW-complex and by 2.4 below, $\text{cat}(K \square L) \leq 2$. Then, as we have remarked, the homology groups $H_*(K \square L, k)$ determine $\pi_n(K \square L)$ and 2.3 is proved.

2.4. Lemma. $\text{cat}(K \square L) \leq 2$.

Proof. Let U be a contractible open neighbourhood of $*$ in K and V be such a neighbourhood of $*$ in L . Then $K \square L$ has the homotopy type of the space Z of paths in $K \times L$, beginning in $K \times V \cup U \times L$ and ending at $*$.

$$Z = EK \times E_0 L \cup E_0 K \times EL$$

where $E_0 K \subset EK$ consists of paths beginning in U and $E_0 L \subset EL$ of paths beginning in V . It suffices to prove that $\text{cat } Z \leq 2$. This is true since Z is the union of the following two open contractible sets

$$\begin{aligned} A &= EK \times E_0 L \cup EU \times EL \\ B &= E_0 K \times EL \cup EK \times EV. \end{aligned}$$

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