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Given a representation $\phi: SO(m) \rightarrow SO(q)$ write

$$J_\phi = J \circ \phi_*: \pi_r SO(m) \rightarrow \pi_{r+q}(S^q),$$

where J denotes the usual Hopf-Whitehead homomorphism. For example, if $q > m$ and ϕ is the inclusion then

$$(6.2) \quad J_\phi = (-1)^{m-q} \Sigma_*^{m-q} J,$$

by (3.2) of [5] (cf. [8]). If $q = 2m$ and $\phi = 1 \oplus 1$ it is easily seen that

$$(6.3) \quad J_\phi = 2(-1)^m \Sigma_*^m J.$$

Consider the function-space $N = N(S^p, S^q)$ of pointed maps $S^p \rightarrow S^q$. We identify $\pi_i(N)$ ($i=0, 1, \dots$) with $\pi_{i+p}(S^q)$ in the standard way (see [15]). Let G be a topological group and let

$$\phi: G \rightarrow SO(p), \quad \psi: G \rightarrow SO(q)$$

be representations of G . We regard S^p, S^q as pointed G -spaces using ϕ, ψ , respectively. Choose a principal G -bundle P over S^n with classifying element $\theta \in \pi_{n-1}(G)$, and take $E_1 = P_{\#}(S^p), E_2 = P_{\#}(S^q)$. Then the operator D in our exact sequence is given

$$(6.4) \quad D\alpha = \alpha \circ \Sigma_*^{r+p-q+1} J_\psi \theta - J_\phi \theta \circ \Sigma_*^{n+p-q-1} \alpha,$$

where $\alpha \in \pi_{r+p+1}(S^q)$. The case $r = 1$ of this result will be needed in §8 below.

7. THE ADJOINT G -BUNDLE

Let X be any space and let P be a principal G -bundle over X . We regard P as a (right) G -space in the usual way. By a *principal automorphism* we mean an equivariant fibre-preserving map of P into itself. By the *adjoint G -bundle* we mean the sectioned bundle $Q = P_{\#}G$, where G acts on itself by conjugation. Note that Q is a group ex-space since G is a group G -space. We can construct Q from $G \times P$ by identifying

$$(7.1) \quad (gag^{-1}, b) \sim (a, bg) \quad (a \in G, b \in P)$$

for all $g \in G$. The group ex-structure is given by

$$\{a_1, b\} \cdot \{a_2, b\} = \{a_1 \cdot a_2, b\} \quad (a_1, a_2 \in G),$$

where $\{ \ , \ }$ denotes the equivalence class of $(\ , \)$. Every principal automorphism f of P determines a cross-section $f': X \rightarrow Q$ as follows.

Given $x \in X$ choose any $b \in P_x$; then $fb = bg$, for some $g \in G$, and we define $f'x = \{g, b\}$. This correspondence establishes an isomorphism between the group of principal automorphisms of P and the group of cross-sections of Q .

Any element c of the centre of G determines a G -map $c_{\#}$ for any G -space A . Notice that $c_{\#}$ is a principal automorphism in the case of P and that the corresponding cross-section $c'_{\#}$ of Q is given by $c'_{\#} \{b\} = \{c, b\}$. When X is a sphere these central cross-sections of Q can be analysed as follows.

Take $X = S^n$ ($n \geq 2$), so that P is a principal G -bundle over S^n . Let B^n denote the n -ball with boundary S^{n-1} . Choose a relative homeomorphism $(B^n, S^{n-1}) \rightarrow (S^n, x_0)$ and lift this to a map $k: (B^n, S^{n-1}) \rightarrow (P, G)$. The homotopy class $\theta \in \pi_{n-1}(G)$ of $l = k|_{S^{n-1}}$ classifies the bundle according to clutching theory.

Let $c \in G$ be central and let $\lambda: I \rightarrow G$ be a path such that $\lambda(0) = e$, $\lambda(1) = c$. Consider the map $A: B^n \times I \rightarrow Q$ which is given by

$$A(y, t) = \{ \lambda(t), k(y) \} \quad (y \in B^n, t \in I).$$

The boundary of $B^n \times I$ is the sphere

$$B^n \times 0 \cup S^{n-1} \times I \cup B^n \times 1,$$

and A maps $S^{n-1} \times I$ into $G \subset Q$ by

$$A(y, t) = (ly) \cdot (\lambda t) \cdot (ly)^{-1},$$

using (7.1). Let us compare this with the map A' of the boundary which agrees with A on $B^n \times I$ but is given on $S^{n-1} \times I$ by $A'(y, t) = \lambda t$. Now λ can be regarded as a vertical homotopy of $e'_{\#}$ into $c'_{\#}$ over $\{x_0\}$ and A represents the obstruction

$$\delta = \delta(e'_{\#}, c'_{\#}; \lambda) \in \pi_n(G)$$

to extending this vertical homotopy over S^n . Since $A|_{(B^n \times I)}$ is null-homotopic, however, it follows that δ is also represented by $d: \tilde{\Sigma}S^{n-1} \rightarrow G$, where

$$d(y, t) = (ly) \cdot (\lambda t) \cdot (ly)^{-1}.$$

For example, take $G = SO(m)$, with m even. Take $c = -e$ and

$$\lambda(t) = e \cos \pi t + b \sin \pi t \quad (0 \leq t \leq 1),$$

where b denotes the matrix

$$\left(\begin{array}{cc} 0 & 1 \\ -1 & 0 \end{array} \right) \oplus \dots \oplus \left(\begin{array}{cc} 0 & 1 \\ -1 & 0 \end{array} \right) \quad (m/2 \text{ summands}).$$

Then $\delta = F\theta$, by definition, where

$$F: \pi_{n-1} SO(m) \rightarrow \pi_n SO(m)$$

denotes the Bott suspension, as in [6].

Now let $A_i (i=1, 2)$ be a locally compact pointed G -space and write $E_i = P_{\#}A_i$. Recall that $N = N(A_1, A_2)$ denotes the function-space of pointed maps $A_1 \rightarrow A_2$. Given a pointed G -map $f: A_1 \rightarrow A_2$ we can construct an ex-map $P_{\#}f: E_1 \rightarrow E_2$ and a pointed G -map $\bar{f}: G \rightarrow N$, where $\bar{f}(g) = g_{\#} \circ f = f \circ g_{\#}$. I assert

PROPOSITION (7.2). *The ex-maps*

$$P_{\#}f, P_{\#}f \circ P_{\#}c: E_1 \rightarrow E_2$$

are ex-homotopic if and only if

$$\bar{f}^* \delta \in D\pi_1(N) \subset \pi_n(N),$$

where δ is as above.

Here D is the operator which occurs in the modified exact sequence of the evaluation fibration derived from the function-space bundle, as in §6. The proof of (7.2) is by naturality, as follows.

First observe that \bar{f} extends to a fibre-preserving map $\hat{f}: Q \rightarrow M$, where $M = M_X(E_1, E_2)$ denotes the function-space bundle. To see this we note that f determines a pointed G -map $F: A_1 \times G \rightarrow A_2$, where

$$F(x, g) = f(xg) \quad (x \in A_1, g \in G).$$

Hence $P_{\#}f: E_1 \times Q \rightarrow E_2$ is defined and we take \hat{f} to be the adjoint.

We have $X = S^n$ so that the evaluation fibrations can be modified as in §6. Clearly

$$(7.3) \quad \Gamma_0(\hat{f}) \circ k \simeq l \circ \Omega^n(\bar{f})$$

as shown below, where k is defined by subtracting the cross-section $e'_{\#}$ and l by subtracting $\hat{f} \circ e'_{\#}$.

$$\begin{array}{ccc} \Omega^n(G) & \xrightarrow{k} & \Gamma_0(Q) \\ \Omega^n(\bar{f}) \downarrow & & \downarrow \Gamma_0(\hat{f}) \\ \Omega^n(N) & \xrightarrow{l} & \Gamma_0(M) \end{array}$$

Hence we obtain a commutative diagram as follows, relating the modified exact sequences for Q and M .

$$\begin{array}{ccc} \pi_n(G) & \xrightarrow{u_*} & \pi(\Gamma(Q)) \\ \bar{f}_* \downarrow & & \downarrow (\Gamma(\hat{f}))_* \\ \pi_n(N) & \xrightarrow{v_*} & \pi(\Gamma(M)) \end{array}$$

Recall that δ is the obstruction to extending λ to a vertical homotopy of $e'_{\#}$ into $c'_{\#}$. Hence $\bar{f}_* \delta$ is the obstruction to extending $\bar{f} \circ \lambda$ to a vertical homotopy of $\hat{f} \circ e'_{\#}$ into $\hat{f} \circ c'_{\#}$. Hence it follows, as explained in the previous section, that $\hat{f} \circ e'_{\#}$ and $\hat{f} \circ c'_{\#}$ are vertically homotopic if and only if $\delta \in D\pi_1(N)$. Finally we use the correspondence between ex-maps and cross-sections to obtain (7.2) as stated.

8. EXAMPLES

Let X be a finite simply-connected complex and let P be a principal $SO(m)$ -bundle over X . Consider the antipodal self-map a of S^{m-1} . The unreduced suspension \hat{a} is a pointed $SO(m)$ -map of S^m into itself. Hence $P_{\#} \hat{a}$ is an ex-map of $E = P_{\#} S^m$ into itself; let $\sigma \in \pi_X(E, E)$ denote the ex-homotopy class. Since \hat{a} is of degree $(-1)^m$ we can apply (5.3) and obtain that

$$(8.1) \quad 2^r \Sigma_* \sigma = 2^r \quad (m \text{ even}),$$

where $r = \text{reg}(X)$. It follows at once that

$$(8.2) \quad 2^{r+1} [l_{\Sigma E}, l_{\Sigma E}] = 0 \quad (m \text{ even}),$$

by (2.1) and (3.1), and hence from (3.3) that

$$(8.3) \quad [l_{\Sigma E}, [l_{\Sigma E}, l_{\Sigma E}]] = 0 \quad (m \text{ even}).$$

Here $l_{\Sigma E}$ denotes the ex-homotopy class of the identity on ΣE . Similar results, but under more restrictive conditions, have been obtained by Eggar [4]. It can also be shown that the quadruple Whitehead products

$$[[l_{\Sigma E}, l_{\Sigma E}], [l_{\Sigma E}, l_{\Sigma E}]], [l_{\Sigma E}, [l_{\Sigma E}, [l_{\Sigma E}, l_{\Sigma E}]]]$$

are trivial, whether m is even or odd.