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Relative cohomology of groups

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§0. Introduction

If G is a group and A is a G -module, the cohomology groups $H^n(G, A)$ can be interpreted either as the cohomology of the cochain complex $C^*(G, A)$ given by the bar resolution (see [M]) or as equivalence classes of n -fold extensions. This situation has reached perfection and is summarized in an historical note by MacLane in [Ho]. If N is a normal subgroup of G and B is a submodule of A on which N acts trivially (and hence B is a Q -module with $Q = G/N$), one may define the relative cohomology groups $H^n(Q, G; B, A)$ as the cohomology of the quotient complex $C^*(G, A)/C^*(Q, B)$. In this paper we present another cochain complex $L^*(G, N; B, A)$ whose cohomology is the relative cohomology but which is more explicit than the quotient complex and which grew out of certain “crossed” extensions which give an interpretation of the group $H^2(Q, G; B, A)$, analogous to the n -fold extensions mentioned above.

A crossed extension is an exact sequence $1 \rightarrow A \rightarrow C \xrightarrow{\partial} N \rightarrow 1$ together with an action $(g, c) \rightarrow gc$ of G on C such that $\partial(c)d = cdc^{-1}$ for $c, d \in C$ and $\partial(gc) = g\partial(c)g^{-1}$ for $g \in G, c \in C$. It follows that A is in the centre of C and that the action of G induces the structure of a G -module on A . This idea goes back to Whitehead ([W]) and was studied extensively in [H], [L], [O] and [R]. One may define a sum of two crossed extensions and equivalence classes of such form a group. It can be shown that this group is isomorphic to the second relative cohomology group. One way to establish this isomorphism is to give a cocycle description of crossed extensions. More precisely, if $s : N \rightarrow C$ is a section for ∂ , define $\alpha_0 : N \times N \rightarrow A$ and $\alpha_1 : N \times G \rightarrow A$ by

$$\alpha_0(n, m) = s(n)s(m)s(nm)^{-1}$$

$$\alpha_1(n, g) = s(n)(gs(g^{-1}ng))^{-1}$$

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One can easily show (see [R]) the following cocycle relations

- (1) $\alpha_0(m, s) - \alpha_0(nm, s) + \alpha_0(n, ms) - \alpha_0(n, m) = 0$
- (2) $g\alpha_0(g^{-1}ng, g^{-1}mg) - \alpha_0(n, m) = \alpha_1(m, g) - \alpha_1(nm, g) + \alpha_1(n, g)$
- (3) $g\alpha_1(g^{-1}ng, h) - \alpha_1(n, gh) + \alpha_1(n, g) = 0$
- (4) $\alpha_1(n, m) = \alpha_0(n, m) - \alpha_0(m, m^{-1}nm)$

The dependence of α_0 and α_1 on the section s gives natural coboundary relations.

Crossed extensions arise naturally in algebraic topology and in the study of group actions on algebras. In [J] it was shown that the above relations can be interpreted as forming the beginning of a cochain complex derived from the double complex $C^*(G, C^*(N, A))$. In [O], this complex $L^*(G, N; A)$ is defined in all dimensions and even in the case where A is an arbitrary G -module. The pair (α_0, α_1) is then a 2-cocycle. Thus $H^2(L^*(G, N; A))$ classifies crossed extensions when A is a Q -module. It was conjectured in [O] that the cohomology of $L^*(G, N; A)$ is the same as the relative cohomology. The conjecture was proved for H^3 . Also a “crossed module” formalism for arbitrary G -modules was worked out in [O] and [CW]. Another version appears in [H].

In §4 of this paper we will show that $L^*(G, N; B, A)$ has the cohomology of the quotient $C^*(G, A)/C^*(Q, B)$, thus establishing the conjecture of [O]. As an application, we immediately obtain the 8-term exact sequence of [H], [R], [L].

In §3 a spectral sequence converging to $H^*(Q, G; B, A)$ is given. For $B = \{a \mid ga = a \text{ for all } g \in N\}$ this has a small calculational advantage over the spectral sequence of Hochschild–Serre [H–S] in that the bottom line has disappeared.

In §5 we give an example where results are easily obtained using the cocycle relations of L^* which are not obvious using $C^*(G, A)/C^*(Q, B)$.

At this stage there is no “ n -fold crossed extension” theory for the relative cohomology groups although some cases are treated in [O], and the third cohomology relations for the complex L^* do arise naturally in the study of Connes’ invariant $\chi(M)$ for von Neumann algebras (see [C]).

§1. Shuffles and partial shuffles

Let σ be a permutation of $\{1, 2, \dots, n\}$. For a group G we define a map $l_\sigma : G^n \rightarrow G^n$ by $l_\sigma(g_1, \dots, g_n) = (b_1^{-1}a_1b_1, \dots, b_n^{-1}a_nb_n)$ where $a_{\sigma(i)} = g_i$, $b_{\sigma(i)} = g_{j_1}g_{j_2} \cdots g_{j_i}$ where $i < j_1 < \cdots < j_i$ are all the j_k ’s satisfying $\sigma(i) > \sigma(j_k)$. In words, we move the variable g_i into the $\sigma(i)$ th position, and then conjugate g_i by the product of those g_k , $k > i$, in their order, which are now in a position inferior to g_i . (Note that $b_1 = 1$).

EXAMPLE. (1) if σ is the permutation (123) then

$$l_\sigma(g_1, g_2, g_3) = (g_3, g_3^{-1}g_1g_3, g_3^{-1}g_2g_3).$$

(2) if σ is (132) then

$$(g_1, g_2, g_3) = (g_2, g_3, g_3^{-1}g_2^{-1}g_1g_2g_3)$$

(3) if σ is (12) then

$$l_\sigma \circ l_\sigma(g, h) = l_\sigma(h, h^{-1}gh) = (h^{-1}gh, h^{-1}g^{-1}hgh)$$

Example (3) above shows that in general $l_\tau \circ l_\sigma \neq l_{\tau\sigma}$. However

PROPOSITION 0. Let σ be a permutation of $\{1, \dots, p+q\}$ fixing the sets $\{1, \dots, p\}$ and $\{p+1, \dots, p+q\}$ and let τ be a permutation satisfying $\tau(i) < \tau(i+1)$ for $i \neq p$. Then $l_\tau \circ l_\sigma = l_{\tau\sigma}$.

Proof. Let $l_\sigma(g_1, \dots, g_p, g_{p+1}, \dots, g_{p+q}) = (x_1, \dots, x_p, x_{p+1}, \dots, x_{p+q})$ $x_i = b_i^{-1}a_i b_i$. For $p+1 \leq i \leq p+q$ we find in both $l_\tau \circ l_\sigma(g_1, \dots, g_{p+q})$ and $l_{\tau\sigma}(g_1, \dots, g_{p+q})$ the variable x_i in the $\tau(i)$ th place. However for $1 \leq i \leq p$ in $l_\tau \circ l_\sigma(g_i)$ we find x_i in the $\tau(i)$ th place conjugated by $x_{p+1} \cdots x_{p+r}$ where r is the maximum j satisfying $\tau(p+j) < \tau(i)$, whereas in $l_{\tau\sigma}(g_i)$ we find x_i in the $\tau(i)$ th place conjugated by the product of the $a_{p+i} = g_{\sigma^{-1}(p+i)}$, $1 \leq i \leq r$, in their original order. From the definition of the b_i , we see, by induction, that these products are identical.

DEFINITION. A permutation σ is a partial shuffle of type (a, b, c, d) , $a + b + c + d = n$ if

$$(1) \sigma(i) = i \text{ for } 1 \leq i \leq a \text{ or } a + b + c + 1 \leq i \leq n$$

$$(2) \sigma(i) < \sigma(i+1) \text{ for } a + 1 \leq i \leq a + b - 1 \text{ or } a + b + 1 \leq i \leq a + b + c - 1$$

(In words, the sets $\{1, \dots, a\}$ and $\{a + b + c + 1, \dots, n\}$ are left fixed, while the sets $\{a + 1, \dots, a + b\}$ and $\{a + b + 1, \dots, a + b + c\}$ are shuffled).

A permutation is a 3-shuffle of type $\langle a, b, c \rangle$, $a + b + c = n$, if $\sigma(i) < \sigma(i+1)$ for $i \neq a, i \neq a + b$.

PROPOSITION 1. (A) If σ is of type $(0, a, b, c)$ and τ of type $(0, a + b, c, 0)$ then $\tau \circ \sigma$ is of type $\langle a, b, c \rangle$. Any η of type $\langle a, b, c \rangle$ has a unique decomposition as above. Furthermore $l_{\tau\sigma} = l_\tau \circ l_\sigma$.

(B) If σ is of type $(a, b, c, 0)$ and τ of type $(0, a, b + c, 0)$ then $\tau \circ \sigma$ is of type $\langle a, b, c \rangle$. Any η of type $\langle a, b, c \rangle$ has a unique decomposition as above. Furthermore $l_{\tau \circ \sigma} = l_{\tau} \circ l_{\sigma}$.

Proof. The formula $l_{\tau \circ \sigma} = l_{\tau} \circ l_{\sigma}$ follows from Proposition 0. The rest is obvious. Q.E.D.

Let G be a group, N a normal subgroup. If we let X, Y, Z denote either G or N then $l_{\sigma}(X^a \times Y^{b+c} \times Z^d) \subset X^a \times Y^{b+c} \times Z^d$ for σ of type (a, b, c, d) . Thus if $\alpha : X^a \times Y^{b+c} \times Z^d \rightarrow A$ is any map, A a \mathbb{Z} -module, we may define $S(a, b, c, d)\alpha : X^a \times Y^{b+c} \times Z^d \rightarrow A$ by

$$S(a, b, c, d)\alpha = \sum_{\substack{\sigma \text{ type} \\ (a,b,c,d)}} (-1)^{|\sigma|} \alpha \circ l_{\sigma} \quad (-1)^{|\sigma|} = \text{signature } \sigma.$$

PROPOSITION 2. Let $\alpha : G^n \rightarrow A$. We have the formula

$$S(a, b, c, 0)S(0, a, b + c, 0)\alpha = S(0, a, b, c)S(0, a + b, c, 0)\alpha$$

Proof. By Proposition 1 both sides are equal to

$$\sum_{\substack{\mu \text{ type} \\ \langle a,b,c \rangle}} (-1)^{|\mu|} \alpha \circ l_{\mu}.$$

§2. Relative cohomology of groups

Let G be a group, N a normal subgroup. We write Q for the quotient G/N . If A is any G -module we denote by A^N the submodule of elements fixed by N . A^N is a Q -module. Let B be a Q -submodule of A^N .

We denote by $C^*(G; A)$ the complex of normalized cochains $\alpha : G^n \rightarrow A$ with coboundary

$$\begin{aligned} d\alpha(g_0, \dots, g_n) &= g_0\alpha(g_1, \dots, g_n) \\ &+ \sum_{i=1}^n (-1)^i \alpha(g_0, \dots, g_{i-1}g_i, \dots, g_n) \\ &+ (-1)^{n+1} \alpha(g_0, \dots, g_{n-1}) \end{aligned}$$

The projection $G \rightarrow Q$ induces an inclusion of complexes $C^*(Q; B) \subset C^*(G; A)$. Let $C^*(Q, G; B, A)$ be the quotient complex.

DEFINITION. The group $H^*(Q, G; B, A) = H^*(C^*(Q, G; B, A))$ is called the relative cohomology group. The associated long exact sequence

$$\cdots \rightarrow H^*(Q, B) \rightarrow H^*(G, A) \rightarrow H^*(Q, G; B, A) \rightarrow \cdots$$

is called the fundamental long exact sequence.

Remark. We justify our use of the term “relative”.

If A is a trivial G module, and $B = A$, then $H^n(Q, G; B, A) = H^{n+1}(M_p, BG; A)$ where M_p is the mapping cylinder of the fibration $p: BG \rightarrow BQ$.

Proof. If $C_*(X, A)(C^*(X, A))$ denotes singular (co)chains then $C^*(G, A) \simeq C^*(BG, A)$, $C^*(Q, A) \simeq C^*(BQ, A)$ so

$$\frac{C^*(G, A)}{C^*(Q, A)} \simeq \frac{\text{Hom}_{\mathbb{Z}}(C_*(BG), A)}{\text{Hom}_{\mathbb{Z}}(C_*(BQ), A)} = \text{Hom}_{\mathbb{Z}}(\ker p_*, A)$$

where $1 \rightarrow \ker p_* \rightarrow C_*(BG) \xrightarrow{p_*} C_*(BQ) \rightarrow 1$ is exact. Finally, the suspension of $\ker p_*$ is isomorphic to $\text{coker } i_*$, where

$$1 \rightarrow C_*(BG) \xrightarrow{i_*} C_*(M_p) \rightarrow \text{coker } i_* \rightarrow 1 \text{ is exact.}$$

§3. A spectral sequence for relative cohomology

We review briefly parts of the fundamental paper of Hochschild and Serre [1]:

Regard $C^*(N, A)$ as a G -module by $(g\beta)(n_1, \dots, n_s) = g\beta(g^{-1}n_1g, \dots, g^{-1}n_sg)$. Then $C^*(G, C^*(N, A))$ is a double complex with coboundaries

$$\begin{aligned} d_N\alpha(g_1, \dots, g_r)(n_0, \dots, n_s) &= n_0\alpha(g_1, \dots, g_r)(n_1, \dots, n_s) \\ &+ \sum_{i=1}^s (-1)^i \alpha(g_1, \dots, g_r)(n_0, \dots, n_{i-1}n_i, \dots, n_s) \\ &+ (-1)^{s+1} \alpha(g_1, \dots, g_r)(n_0, \dots, n_{s-1}) \end{aligned}$$

and

$$\begin{aligned} d_G\alpha(g_0, \dots, g_r)(n_1, \dots, n_s) &= g_0\alpha(g_1, \dots, g_r)(g_0^{-1}n_1g_0, \dots, g_0^{-1}n_sg_0) \\ &+ \sum_{i=1}^r (-1)^i \alpha(g_0, \dots, g_{i-1}g_i, \dots, g_r)(n_1, \dots, n_s) \\ &+ (-1)^{r+1} \alpha(g_0, \dots, g_{r-1})(n_1, \dots, n_s) \end{aligned}$$

For reasons of convenience we will write $\alpha(n_1, \dots, n_s, g_1, \dots, g_r)$ in place of $\alpha(g_1, \dots, g_r)(n_1, \dots, n_s)$.

Let $T^*(G, N; A) = \bigoplus_{p+q=n} C^p(G, C^q(N, A))$ be the total complex associated to the double complex with total differential $d_G + (-1)^{i+1}d_N$ on $C^*(G, C^i(N, A))$.

We define a map $l: C^*(G, A) \rightarrow T^*(G, N; A)$ by

$$l(\alpha) = (\alpha_0, \dots, \alpha_n), \quad \boxed{\alpha_p = S(0, q, p, 0)\alpha|_{N^q \times G^p}} \quad p+q=n.$$

Note in particular that $\alpha_n = \alpha$ and $\alpha_0 = \alpha|_{N^n}$.

PROPOSITION 3. $l: C^*(G, A) \rightarrow T^*(G, N; A)$ is a map of complexes.

Proof. This is the “general identity” of [H-S]. Q.E.D.

Define a filtration R_p of $C^*(G, A)$ where $\alpha \in R_p$ if $\alpha(h_1, \dots, h_q, g_1, \dots, g_p)$ depends only on the h_i and the classes mod N of the g_j . Also $R_p \cap C^n(G, A) = 0$ if $p > n$.

Define a filtration S_p of $T^*(G, N; A)$ by $S_p = \bigoplus_{i \leq p} C^i(G, C^*(N, A))$. If $\alpha \in R_p$ and $l(\alpha) = (\alpha_0, \dots, \alpha_n)$, then $\alpha_j = 0$, $j < p$, so $l(\alpha) \in S_p$. Thus l is a map of filtered complexes.

THEOREM 4 (Hochschild–Serre).

$$l^*: E_{p,q}^1(R) \rightarrow E_{p,q}^1(S) = C^p(G, H^q(N, A))$$

is an injection and image $l^* = C^p(Q, H^q(N, A))$.

COROLLARY 5. $E_{p,q}^2(R) = H^p(Q, H^q(N, A))$

We now study the quotient complex $C^*(Q, G; B, A)$. Define a filtration of $C^*(Q, G; B, A)$ by $\bar{R}_j = \text{image of } R_j$.

THEOREM 6 (Spectral sequence for relative cohomology).

$$E_2^{p,q}(\bar{R}) = \begin{cases} H^p(Q, H^q(N, A)) & q > 0 \\ H^p\left(Q, \frac{A^N}{B}\right) & q = 0 \end{cases} \\ \Rightarrow H^*(Q, G; B, A)$$

Remark. If $B = A^N$, the E_2 term of this spectral sequence is identical to the Hochschild–Serre E_2 term except that the bottom line has disappeared.

Proof. Considering $B \subset A \subset C^0(N, A)$ we have an inclusion $C^*(G, B) \rightarrow T^*(G, N; A)$ of complexes since $d_N(C^*(G, B)) = 0$. Since $l(C^n(Q, B)) \subset C^n(G, B)$, we get

$$\bar{l}: C^n(Q, G; B, A) \rightarrow \frac{T^N(G, N; A)}{C^n(G, B)}.$$

If we let $\bar{S}_j = \text{image of } S_j \text{ in } T^n(G, N; A)/C^n(G, B)$ then \bar{l} is a map of filtered complexes. Theorem 6 is then a corollary of the following analog of Theorem 4.

PROPOSITION 7. $\bar{l}_*: E_{p,q}^1(\bar{R}) \rightarrow E_{p,q}^1(\bar{S})$ is an inclusion with image

$$\begin{cases} C^p(Q, H^q(N, A)) & q > 0 \\ C^n\left(Q, \frac{A^N}{B}\right) & q = 0 \end{cases}$$

Proof. $C^n(Q, B) \subset R_n \subset R_p$, if $p \leq n$, so $E_{p,q}^0(\bar{R}) \simeq E_{p,q}^0(R)$ if $q > 0$ and

$$E_{n,0}^0(\bar{R}) \simeq \frac{E_{n,0}^0(R)}{C^n(Q, B)}.$$

Since $d(C^n(Q, B)) \subset C^{n+1}(Q, B) \subset R_{n+1}$, it follows that

$$\begin{aligned} 0 \rightarrow C^n(Q, B) \rightarrow 0 & \rightarrow \dots \text{ is a subcomplex of} \\ 0 \rightarrow E_{n,0}^0(R) \rightarrow E_{n,1}^0(R) \rightarrow \dots & \text{ with quotient} \\ 0 \rightarrow E_{n,0}^0(\bar{R}) \rightarrow E_{n,1}^0(\bar{R}) \rightarrow \dots & \end{aligned}$$

From the associated long exact sequence, we get

$$0 \rightarrow C^n(Q, B) \rightarrow E_{n,0}^1(R) \rightarrow E_{n,0}^1(\bar{R}) \rightarrow 0$$

is exact and $E_{p,q}^1(R) = E_{p,q}^1(\bar{R})$, $q > 0$.

Similarly $0 \rightarrow C^n(G, B) \rightarrow E_{n,0}^1(S) \rightarrow E_{n,0}^1(\bar{S}) \rightarrow 0$ is exact and $E_{p,q}^1(S) \simeq$

$E_{p,q}^1(\bar{S}), q > 0$. A look at the commutative diagrams

$$\begin{array}{ccc} E_{p,q}^1(R) \cong C^p(Q, H^q(N, A)) \subset E_{p,q}^1(S) & & q > 0 \\ \downarrow \wr & & \downarrow \wr \\ E_{p,q}^1(\bar{R}) & \longrightarrow & E_{p,q}^1(\bar{S}) \end{array}$$

and

$$\begin{array}{ccccccc} 0 \rightarrow C^n(Q, B) & \rightarrow & E_{n,0}^1(R) & \rightarrow & E_{n,0}^1(\bar{R}) & \rightarrow & 0 \\ & & \downarrow & & \downarrow & & \\ & & C^n(Q, A^N) & & & & \\ & & \cap & & & & \\ & & C^n(G, A^N) & & & & \\ & & \downarrow & & \downarrow & & \\ 0 \rightarrow C^n(G, B) & \rightarrow & E_{n,0}^1(S) & \rightarrow & E_{n,0}^1(\bar{S}) & \rightarrow & 0 \end{array}$$

establishes the proposition.

§4. The complex $L^*(G, N; A, B)$

We write an element of $T^n(G, N; A)/C^n(G, B)$ as $(\alpha_0, \dots, \alpha_{n-1}, \bar{\alpha}_n)$ where

$$\bar{\alpha}_n \in \frac{C^n(G, A)}{C^n(G, B)} \cong C^n(G, A/B).$$

DEFINITION

$$L^n(G, N; A, B) = \left\{ (\alpha_0, \dots, \alpha_{n-1}, \bar{\alpha}_n) \in \frac{T^n(G, N; A)}{C^n(G, B)} \right.$$

such that $\alpha_k \equiv S(0, n-k, k, 0)\bar{\alpha}_n|_{N^{n-k} \times G^k} \pmod B$

and $S(0, n-m, m-k, k)\alpha_k = S(n-m, m-k, k, 0)\alpha_m|_{N^{n-k} \times G^k}$ }

Remark. If $A = A^N = B$ we make abbreviations such as $L^n(G, N; A, A)$ to $L^n(G, N; A)$. Note that in this case

$$\bar{\alpha}_n \in \frac{C^n(G, A)}{C^n(G, A)} = 0$$

so we abbreviate $(\alpha_0, \dots, \alpha_{n-1}, \bar{\alpha}_n)$ to $(\alpha_0, \dots, \alpha_{n-1})$. The reader may check that if $A = A^N = B$, then (α_0, α_1) is in $L^2(G, N; A)$ if and only if the relation (4) of the introduction is satisfied and a cocycle iff (1) (2) and (3) are satisfied.

It is a direct consequence of Proposition 2 that the map

$$\bar{l}: \frac{C^n(G, A)}{C^n(Q, B)} \rightarrow \frac{T^n(G, N; A)}{C^n(G, B)}$$

of §3 (given by $\bar{l}(\bar{\alpha}) = (\alpha_0, \dots, \alpha_{n-1}, \bar{\alpha}_n)$, $\alpha_k = S(0, n-k, k, 0)\alpha|_{N^{n-k} \times G^k}$) has image contained in $L^n(G, N; A, B)$. In fact

PROPOSITION 8.

Image $\bar{l} = L^n(G, N; A, B)$

COROLLARY 9. $L^*(G, N; A, B)$ is a subcomplex of $T^*(G, N; A)/C^*(G, B)$.

DEFINITION. $\Lambda^*(G, N; A, B) = H^*(L^*(G, N; A, B))$

THEOREM 10. $\bar{l}^*: H^*(Q, G; B, A) \rightarrow \Lambda^*(G, N; A, B)$ is an isomorphism.

Proof of Proposition 8 and Theorem 10. Consider the following diagram of complexes

$$\begin{array}{ccccccc} 0 & \rightarrow & \frac{C^*(G, B)}{C^*(Q, B)} & \longrightarrow & \frac{C^*(G, A)}{C^*(Q, B)} & \longrightarrow & \frac{C^*(G, A)}{C^*(G, B)} \rightarrow 0 \\ & & \downarrow \bar{l}_1 & & \downarrow \bar{l}_2 & & \parallel \\ 0 & \rightarrow & L^*(G, N; B, B) & \rightarrow & L^*(G, N; A, B) & \xrightarrow{\pi} & \frac{C^*(G, A)}{C^*(G, B)} \rightarrow 0 \end{array}$$

where $\pi(\alpha_0, \dots, \bar{\alpha}_n) = \bar{\alpha}_n$. The top row obviously is exact and the first square commutative. Commutativity of the second square follows from the identity $S(0, 0, n, 0)\alpha = \alpha$, so that if $l(\alpha) = (\alpha_0, \dots, \alpha_n)$, then $\alpha_n = \alpha$. Hence π is surjective since $\pi \circ \bar{l}_2$ is.

Furthermore, since $\alpha_k \equiv S(0, n-k, k, 0)\bar{\alpha}_n|_{N^{n-k} \times G^k} \pmod{B}$, it follows that if $\bar{\alpha}_n = 0$ then α_k takes values in B . This proves exactness of the bottom line.

From the diagram it follows that \bar{l}_1 is surjective if and only if \bar{l}_2 is. The five lemma applied to the long exact sequences in homology shows that \bar{l}_1 induces an isomorphism on homology if and only if \bar{l}_2 does.

So it suffices to prove 8 and 10 in case $A = A^N = B$. Then

$$\frac{T^n(G, N; A)}{C^n(G, A)} = \bigoplus_{\substack{p+q=n \\ q>0}} C^p(G, C^q(N, A))$$

and

$$L^n(G, N; A) = \left\{ (\alpha_0, \dots, \alpha_{n-1}) \in \frac{T^n(G, N; A)}{C^n(G, A)} \text{ such that for } \right. \\ \left. k < m \leq n-1, S(n-m, m-k, k, 0)\alpha_m|_{N^{n-k} \times G^k} = S(0, n-m, m-k, k)\alpha_k \right\}$$

We begin with the following

LEMMA 11. *Let $a = (\alpha_0, \dots, \alpha_{n-1})$, $b = (\beta_0, \dots, \beta_{n-1})$ be elements of $L^n(G, N; A)$. Then $a = b$ if and only if $\alpha_0 = \beta_0$ and $\alpha_k(m_1, \dots, m_{n-k}, g_1, \dots, g_k) = \beta_k(m_1, \dots, m_{n-k}, g_1, \dots, g_k)$ whenever $g_1 \notin N$.*

Proof of Lemma 11. Since $\alpha_k|_{N^n} = S(0, n-k, k, 0)\alpha_0 = S(0, n-k, k, 0)\beta_0 = \beta_k|_{N^n}$ we may assume some $g_i \notin N$. Suppose we have shown that $\alpha_i = \beta_i$ for $i < k$, and that $\alpha_k = \beta_k$ whenever the first l for which $g_l \notin N$ satisfies $l \leq j < k$. We show $\alpha_k(m_1, \dots, m_{n-k}, h_1, \dots, h_j, g_{j+1}, \dots, g_k) = \beta_k(m_1, \dots, m_{n-k}, h_1, \dots, h_j, g_{j+1}, \dots, g_k)$ whenever $h_1, \dots, h_j \in N$ but $g_{j+1} \notin N$.

For simplicity, write (m, h, g) for $(m_1, \dots, m_{n-k}, h_1, \dots, h_j, g_{j+1}, \dots, g_k)$. Since $\alpha_{k-j} = \beta_{k-j}$ we have

$$S(n-k, j, k-j, 0)\alpha_k(m, h, g) = S(0, n-k, j, k-j)\alpha_{k-j}(m, h, g) \\ = S(0, n-k, j, k-j)\beta_{k-j}(m, h, g) = S(n-k, j, k-j, 0)\beta_k(m, h, g).$$

Furthermore, for σ of type $(n-k, j, k-j, 0)$, $\sigma \neq id$, we have by our induction hypothesis that $\alpha_k \circ l_\sigma(m, h, g) = \beta_k \circ l_\sigma(m, h, g)$ since in $l_\sigma(m, h, g)$ the value $g_{l+1} \notin N$ will occur earlier. Thus

$$\alpha_k(m, h, g) = S(n-k, j, k-j, 0)\alpha_k(m, h, g) - \sum_{\substack{\sigma \text{ type}(n-k, j, k-j, 0) \\ \sigma \neq id}} (-1)^{|\sigma|} \alpha_k \circ l_\sigma(m, h, g) \\ = S(n-k, j, k-j, 0)\beta_k(m, h, g) - \sum_{\substack{\sigma \text{ type}(n-k, j, k-j, 0) \\ \sigma \neq id}} (-1)^{|\sigma|} \beta_k \circ l_\sigma(m, h, g) \\ = \beta_k(m, h, g).$$

End of proof of Proposition 8. Let $(\alpha_0, \dots, \alpha_{n-1}) \in L(G, N; A)$. We will define $\beta \in C^n(G, A)$ so that if $\bar{l}(\bar{\beta}) = (\beta_0, \dots, \beta_{n-1})$, then $\beta_0 = \alpha_0$ and $\beta_i(m_1, \dots, m_{n-i}, g_1, \dots, g_i) = \alpha_i(m_1, \dots, m_{n-i}, g_1, \dots, g_i)$ whenever $m_1, \dots, m_{n-i} \in N$ and

$g_1 \notin N$. By Lemma 11, it will follow that $\beta_i = \alpha_i$, all i , i.e. $\bar{l}(\bar{\beta}) = (\alpha_0, \dots, \alpha_{n-1})$.

Set $\beta \mid N^n = \alpha_0$. Then $\beta_0 = \alpha_0$. Set $\beta(g_1, \dots, g_n) = 0$ if $g_1 \notin N$. Suppose β is defined on $N^{n-i} \times (G-N) \times G^{i-1}$, for $i > j > 0$. Define

$$\begin{aligned} & \beta(m_1, \dots, m_{n-j}, g_1, \dots, g_j) \\ &= - \sum_{\substack{\sigma \text{ type}(0, n-j, j, 0) \\ \sigma \neq id}} (-1)^{|\sigma|} \beta \circ l_\sigma(m_1, \dots, m_{n-j}, g_1, \dots, g_j) \\ & \quad + \alpha_j(m_1, \dots, m_{n-j}, g_1, \dots, g_j), \end{aligned}$$

for $m_i \in N$ and $g_1 \notin N$. (Note that $\beta \circ l_\sigma(m_1, \dots, m_{n-j}, g_1, \dots, g_j)$ has already been defined). It follows that

$$\begin{aligned} \beta_j(m_1, \dots, m_{n-j}, g_1, \dots, g_j) &= \sum_{\sigma \text{ type}(0, n-j, j, 0)} (-1)^{|\sigma|} \beta \circ l_\sigma(m_1, \dots, m_{n-j}, g_1, \dots, g_j) \\ &= \alpha_j(m_1, \dots, m_{n-j}, g_1, \dots, g_j). \end{aligned}$$

Proof of Theorem 10 ($A = A^N = B$). It suffices to show the following:
Let K^* be the kernel of the composite

$$C^*(G, A) \rightarrow \frac{C^*(G, A)}{C^*(Q, A)} \xrightarrow{\bar{l}} L^*(G, N; A).$$

Then the inclusion $C^*(Q, A) \subset K^*$ induces an isomorphism on homology.

Let B_i be the filtration of $C^*(G, A)$ where $\alpha \in B_i \cap C^n(G, A)$ if α is unchanged whenever any of the last i values is multiplied by an element of N , $B_i \cap C^n(G, A) = C^n(Q, A)$ if $i \geq n$. For $i < p \leq n$, let $B_{i,p} = \{\alpha \in B_i \mid \alpha(g_1, \dots, g_n) = 0 \text{ if } g_{p-i}, \dots, g_n \text{ are all in } N\}$, $B_{i,i} = B_i$, and $B_{i,p} \cap C^n(G, A) = B_{i+1} \cap C^n(G, A)$ if $p > n$. Set $K_i = K \cap B_i$, $K_{i,p} = K \cap B_{i,p}$.

We will show the following

- (a) $K_i = K_{i,i+1}$
- (b) $H^n\left(\frac{K_{i,n}}{K_{i,n+1}}\right) = 0 \quad i < n$
- (c) $H^n\left(\frac{K_{i,p}}{K_{i,p+1}}\right) = 0 \quad i < p < n.$

It follows that

$$H^n\left(\frac{K_i}{K_{i+1}}\right) = H^n\left(\frac{K_{i,i+1}}{K_{i,n+2}}\right) = 0$$

and hence that

$$H^n\left(\frac{K}{C^*(Q, A)}\right) = H^n\left(\frac{K_0}{K_{n+1}}\right) = 0.$$

Proof of (a). Let σ be of type $(0, n-i, i, 0)$. If $\sigma \neq id$ and $\alpha \in B_i$, then $\alpha \circ l_\sigma|_{N^{n-i} \times G^i} = 0$. Hence the formula, valid for $\alpha \in B_i : \alpha_i = \alpha|_{N^{n-i} \times G^i}$. In particular if $\alpha \in K_i$, $0 = \alpha_i = \alpha|_{N^{n-i} \times G^i}$, i.e. $\alpha \in K_{i,i+1}$.

Proof of (b). For $\alpha \in B_{i,n} \cap C^n(G, A)$, $d\alpha \in B_{i,n+1}$ we have for $m \in N$

$$\begin{aligned} 0 &= d\alpha(g_1, \dots, g_{n-i-1}, g, m, h_1, \dots, h_i) \\ &= (-1)^{n-i}(\alpha(g_1, \dots, g_{n-i-1}, gm, h_1, \dots, h_i) - \alpha(g_1, \dots, g_{n-i-1}, g, h_1, \dots, h_i)) \end{aligned}$$

i.e. $\alpha \in B_{i+1} \cap C^n(G, A) = B_{i,n+1} \cap C^n(G, A)$. It follows that if $\alpha \in K_{i,n} \cap C^n(G, A)$, $d\alpha \in K_{i,n+1}$, then $\alpha \in K_{i,n+1}$.

Proof of (c). Choose a section $*$: $Q \rightarrow G$ of the quotient map $\pi : G \rightarrow Q$ such that $1^* = 1$.

We first show (c) in the special case $i = 0$.

Suppose $\alpha \in K_{0,p} \cap C^n(G, A)$, $d\alpha \in K_{0,p+1}$. Define for

$$\begin{aligned} \sigma, m_{p+2}, \dots, m_n \in N, \beta(g_1, \dots, g_{p-1}, q^*\sigma, m_{p+2}, \dots, m_n) \\ = \alpha(g_1, \dots, g_{p-1}, q^*, \sigma, m_{p+2}, \dots, m_n). \end{aligned}$$

If $\tilde{\beta}$ is any extension of β to all G^{n-1} , then $\tilde{\beta} \in B_{0,p}$. Moreover

$$\begin{aligned} d\tilde{\beta}(g_1, \dots, g_{p-1}, q^*\sigma, m_{p+1}, \dots, m_n) \\ &= (-1)^p \beta(g_1, \dots, g_{p-1}, q^*\sigma m_{p+1}, m_{p+2}, \dots, m_n) + \dots \\ &\quad + (-1)^p \beta(g_1, \dots, g_{p-1}, q^*\sigma, m_{p+1}, \dots, m_n) \\ &= (-1)^p \alpha(g_1, \dots, g_{p-1}, q^*, \sigma m_{p+1}, m_{p+2}, \dots, m_n) + \dots \\ &\quad + (-1)^n \alpha(g_1, \dots, g_{p-1}, q^*, \sigma, m_{p+1}, \dots, m_{m-1}) \\ &= -d\alpha(g_1, \dots, g_{p-1}, q^*, \sigma, m_{p+1}, \dots, m_n) \\ &\quad + (-1)^p \alpha(g_1, \dots, g_{p-1}, q^*\sigma, m_{p+1}, \dots, m_n) \\ &= (-1)^p \alpha(g_1, \dots, g_{p-1}, q^*\sigma, m_{p+1}, \dots, m_n) \end{aligned}$$

since $d\alpha \in K_{0,p+1}$, i.e. $\alpha - (-1)^p d\tilde{\beta} \in B_{0,p+1}$.

Thus it suffices to show that β can be extended to a $\tilde{\beta} \in K$. Now β is already defined on $G^p \times N^{n-p-1}$. Extend β as follows:

Let $\beta(g_1, \dots, g_{n-1}) = 0$ if $g_1 \notin N$ and some $g_i \notin N$, $p < i \leq n-1$. Assume now that β is defined if some $g_i \notin N$, $i \leq k < n-1$. Then if $g_{k+1} \notin N$ but $m_1, \dots, m_k \in N$ (and if $k < p$ some $g_i \notin N$, $p < i \leq n-1$) define

$$\begin{aligned} & \beta(m_1, \dots, m_k, g_{k+1}, \dots, g_{n-1}) \\ = & - \sum_{\substack{\sigma \text{ type}(0, k, n-k-1, 0) \\ \sigma \neq \text{id}}} (-1)^{|\sigma|} \beta \circ l_{\sigma}(m_1, \dots, m_k, g_{k+1}, \dots, g_{n-1}) \end{aligned}$$

the right side already having been defined. It follows that $\beta_{n-k-1}(m_1, \dots, m_k, g_{k+1}, \dots, g_{n-1}) = 0$ for $g_{k+1} \notin N$ (and provided some $g_i \notin N$, $p < i \leq n-1$, if $k < p$). Thus, by Lemma 11, it will follow that $\beta \in K$ if we can show

$$\beta_{n-k-1}(m_1, \dots, m_k, g_{k+1}, \dots, g_p, m_{p+1}, \dots, m_{n-1}) = 0 \quad \text{for } m_{p+1}, \dots, m_{n-1} \in N.$$

But since $\beta \in B_{0,p}$ and $\alpha \in K_{0,p}$, a calculation shows

$$\begin{aligned} & \beta_{n-k-1}(m_1, \dots, m_k, g_{k+1}, \dots, g_{p-1}, q^* \sigma, m_{p+1}, \dots, m_{n-1}) \\ & = \alpha_{n-k}(m_1, \dots, m_k, g_{k+1}, \dots, g_{p-1}, q^*, \sigma, m_{p+1}, \dots, m_{n-1}) = 0. \end{aligned}$$

Now suppose $\alpha \in K_{i,p}$, $d\alpha \in K_{i,p+1}$, $i > 0$. Define $\alpha'(q_1, \dots, q_i)(g_1, \dots, g_{n-i}) = \alpha(g_1, \dots, g_{n-i}, q_1^*, \dots, q_i^*)$. Then $\alpha'(q_1, \dots, q_i) \in B_{0,p-i}$ and a calculation shows

$$\begin{aligned} & \alpha'(q_1, \dots, q_i)_k(m_1, \dots, m_{n-i-k}, g_1, \dots, g_k) \\ & = \alpha_{k+i}(m_1, \dots, m_{n-i-k}, g_1, \dots, g_k, q_1^*, \dots, q_i^*) = 0 \end{aligned}$$

so $\alpha'(q_1, \dots, q_i) \in K_{0,p-i}$. Moreover $d\alpha'(q_1, \dots, q_i) \in K_{0,p-i+1}$ since

$$d\alpha'(q_1, \dots, q_i)(g_1, \dots, g_{n-i}, m) = d\alpha(g_1, \dots, g_{n-i}, m, q_1^*, \dots, q_i^*) \quad \text{for } m \in N.$$

Thus there is a $\beta'(q_1, \dots, q_i) \in K_{0,p-i}$ such that $\alpha'(q_1, \dots, q_i) - d\beta'(q_1, \dots, q_i) \in K_{0,p-i+1}$.

Define β by $\beta(g_1, \dots, g_n) = \beta'(\pi(g_{n-i}), \dots, \pi(g_n))(g_1, \dots, g_{n-i-1})$. We have $\beta \in B_{i,p}$ (so $\beta_j = 0$ for $j < i$). Moreover

$$\begin{aligned} & \beta_{i+k}(m_1, \dots, m_{n-i-k-1}, g_1, \dots, g_k, h_1, \dots, h_i) \\ & = \beta'(\pi(h_1), \dots, \pi(h_i))_k(m_1, \dots, m_{n-i-k-1}, g_1, \dots, g_k) = 0. \end{aligned}$$

So $\beta \in K$. Since

$$\begin{aligned} (\alpha - d\beta)(g_1, \dots, g_{n-i-1}, m, h_1, \dots, h_i) \\ = (\alpha' - d\beta')(\pi(h_1), \dots, \pi(h_i))(g_1, \dots, g_{n-i-1}, m) \quad \text{for } m \in N, \end{aligned}$$

it follows that $\alpha - d\beta \in K_{i,p+1}$.

§5. A calculation using $L^*(G, N; A)$

PROPOSITION 12. *Let A be a divisible abelian group. Let N be a central subgroup of a perfect group G . Then $H^3(G/N; A) \rightarrow H^3(G, A)$ is injective and $H^2(G/N; A) \rightarrow H^2(G, A)$ is surjective (trivial coefficients).*

Proof. It is equivalent to show $H^2(G/N, G; A) = 0$. By Theorem 10, it is equivalent to show $\Lambda^2(G, N; A) = 0$. So let $a = (\alpha_0, \alpha_1)$ be a cocycle of $L^*(G, N; A)$. We must show $a = db$, where $b = (\beta)$ and $db = (d_N\beta, d_G\beta)$. Now

$$\begin{aligned} 0 &= d_G\alpha_1(n, g, h) = g\alpha_1(g^{-1}ng, h) - \alpha_1(n, gh) + \alpha_1(n, g) \\ &= \alpha_1(n, h) - \alpha_1(n, gh) + \alpha_1(n, g) \quad (\text{since } A \text{ is a trivial } G \text{ module and } N \text{ is} \\ &\quad \text{central}) \end{aligned}$$

so $\alpha_1(n, \cdot): G \rightarrow A$ is a homomorphism. Since G is perfect this shows $\alpha_1 = 0$.

Now $0 = \alpha_1(n, m) = \alpha_0(n, m) - \alpha_0(n, m^{-1}nm) = \alpha_0(n, m) - \alpha_0(m, n)$ so $\alpha_0: N^2 \rightarrow A$ is a symmetric cocycle. The corresponding extension $1 \rightarrow A \rightarrow C \rightarrow N \rightarrow 1$ is thus abelian and represents an element in $\text{Ext}_Z^1(N, A) = 0$, since A is divisible (hence injective, c.f. [M2] p. 93). So this extension is split, i.e. $0 = [\alpha_0] \in H^2(N, A)$, i.e., $\alpha_0 = d_N\beta$ for $\beta: N \rightarrow A$. Now

$$d_G\beta(n, g) = g\beta(g^{-1}ng) - \beta(n) = \beta(n) - \beta(n) = 0$$

so

$$db = (d_N\beta, d_G\beta) = (d_N\beta, 0) = (\alpha_0, 0) = (\alpha_0, \alpha_1) = a.$$

The case N central, A trivial

Let $1 \rightarrow N \rightarrow G \rightarrow Q \rightarrow 1$ be a central extension and A a trivial G module. Then equations 2–4 become

- (2) $0 = \alpha_1(m, g) - \alpha_1(mn, g) + \alpha_1(n, g)$ i.e. α_1 is bilinear
- (3) $0 = \alpha_1(n, h) - \alpha_1(n, gh) + \alpha_1(n, g)$
- (4) $\alpha_1(n, m) = \alpha_0(n, m) - \alpha_0(m, n)$

It follows easily that

PROPOSITION 13. *For a central extension with trivial coefficients we have an exact sequence*

$$0 \rightarrow \Lambda^2(G, N; A) \xrightarrow{i} H^2(N, A) \times \text{Bilin}(N \times G, A) \xrightarrow{t} \text{Bilin}(N \times N, A)$$

(where $i(\alpha_0, \alpha_1) = ([\alpha_0], \alpha_1)$ and

$$t([\alpha_0], \alpha_1) = \alpha_1|_{N \times N} - (\alpha_0 - T\alpha_0), \quad T\alpha_0(n, m) = \alpha_0(m, n).)$$

COROLLARY 14. (1) $\text{Ext}^1(N, A) \times \text{Bilin}(N \times Q; A) \subset \Lambda^2(G, N; A)$

(2) If $\text{Bilin}(N \times G; A) = 0$, $\Lambda^2(G, N; A) = \text{Ext}^1(N, A)$

(3) If $H^2(N, A) = 0$, $\Lambda^2(G, N; A) = \text{Bilin}(N \times Q; A)$

COROLLARY 15. *If G is perfect, $\Lambda^2(G, N; A) \cong \text{Ext}^1(N, A)$*

Remark. The results in this section may also be derived from known results from the homology theory of groups. [K] [EHS] [GS].

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