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On Galois descent for Hochschild and cyclic homology

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Abstract. Let G be a finite group acting by automorphisms on an algebra S over some commutative ring k . We show that if the action of G restricted to the center of S is Galois in the sense of [C-H-R], then $HH_*(S^G) \cong HH_*(S)^G$. An analogous result holds for cyclic homology, provided the order of G is invertible in k .

Introduction

Let G be a finite group acting by automorphisms on an algebra S over some commutative ring k . Then G acts on the Hochschild homology $HH_*(S)$ and on the cyclic homology $HC_*(S)$ of S . The relationship between the invariants of this action on the one hand and the cyclic or Hochschild homology of the algebra of invariants S^G on the other is rather opaque. In the special situation where the action of G on S is Galois in the sense of [C-H-R] and the order of G is invertible in k , the obvious “induction” map $HH_*(S^G) \rightarrow HH_*(S)^G$ is at least surjective (see §4 below for a marginally more general formulation). It need however *not* be injective as the explicit computations of $HH_0(A_1(\mathbb{C})^G)$ for certain Galois actions on the Weyl algebra $S = A_1(\mathbb{C})$ in [A-H-V] show. In these examples, $HH_0(A_1(\mathbb{C})^G)$ is nonzero while $HH_0(A_1(\mathbb{C})) = 0$. Our goal in this article is to prove that, if the action of G restricted to the *center* of S is Galois (in which case the action will be called centrally Galois), then induction from S^G to S does in fact yield an isomorphism

$$HH_*(S^G) \cong HH_*(S)^G.$$

This is achieved in §6, and a corresponding result for cyclic homology quickly follows by the usual application of the 5-lemma to the Connes-Gysin sequence,

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provided the order of G is invertible in k . For commutative S , both isomorphisms have been obtained in [W-G] as a consequence of a general result on étale extensions of commutative algebras. Our approach, instead, is to analyze the homology $HH_*(T)$ of the skew group ring $T = S * G$ that is associated with the given action of G on S . Using a description of $HH_*(T)$ in terms of certain hyperhomology groups ([Lo]), we show that restriction from T to S yields an isomorphism $HH_*(T) \cong HH_*(S)^G$. The above isomorphism then follows by means of a Morita isomorphism between $HH_*(S^G)$ and $HH_*(T)$.

Notations and conventions

Our general reference concerning Hochschild and cyclic homology is [L] whose notation we will follow here. All algebras considered in this article are over some commutative base ring k and \otimes denotes \otimes_k . Bimodules are understood to have identical k -operations on both sides. In addition, we will keep the following notations throughout this article.

- S will be a unital k -algebra;
- G denotes a finite group acting by k -algebra automorphisms on S ;
this action will be denoted $s \mapsto s^g$ ($s \in S, g \in G$);
- $R = S^G$ is the subalgebra of G -invariants in S ;
- $T = S * G$ will denote the skew group ring of G over S .

Thus T is an associative algebra which is additively isomorphic to the ordinary group ring $S[G]$ but whose multiplication is determined by the rule $sg = gs^g$ ($s \in S, g \in G$). As S - S -bimodule, T is the direct sum of the subbimodules Sg for $g \in G$. Finally, S can be viewed as R - T -bimodule via $r \cdot s \cdot s'g = (rss')^g$ ($r \in R, s, s' \in S, g \in G$). Similarly, S can be made into a T - R -bimodule.

Proofs

1. Maps on Hochschild homology

Let A and B be k -algebras and let ${}_A P_B$ be an A - B -bimodule such that P_B is finitely generated and projective. Then there is a k -linear map on Hochschild homology

$$HH_*^P : HH_*(A) \rightarrow HH_*(B)$$

which is obtained as follows (see [Lo], §§1.2 and 1.4). Choose dual bases for P , that is, elements $p_i \in P$, $q_i \in P_B^* = \text{Hom}_B(P_B, B)$ ($i = 1, 2, \dots, r$) with $p = \sum_{i=1}^r p_i q_i(p)$ for all $p \in P$. Then the map

$$\Phi^P : C(A) \rightarrow C(B)$$

which on $C_n(A) = A^{\otimes(n+1)}$ is defined by

$$\Phi_n^P(a_0 \otimes a_1 \otimes \cdots \otimes a_n) = \sum_{(i_0, \dots, i_n)} q_{i_0}(a_0 p_{i_1}) \otimes q_{i_1}(a_1 p_{i_2}) \otimes \cdots \otimes q_{i_n}(a_n p_{i_0})$$

is a chain map whose homotopy type is independent of the choice of the dual bases $\{p_i\}$, $\{q_i\}$ for P . Thus the induced map on homology, $HH_*^P = H_*(\Phi^P)$, is well-defined and only depends on the isomorphism type of the A - B -bimodule P . Furthermore, if C is another k -algebra and ${}_BQ_C$ is a B - C bimodule which is finitely generated and projective over C then

$$HH_*^{P \otimes {}_BQ} = HH_*^Q \circ HH_*^P.$$

2. Special cases

The following special cases will be of particular interest for our purposes.

(a) *Action of G on $HH_*(S)$.* Taking $A = B = S$ in §1 and $P = Sg \subseteq T$ for $g \in G$, we obtain maps $HH_*^{Sg} : HH_*(S) \rightarrow HH_*(S)$ which yield a right action of G on $HH_*(S)$. The map HH_*^{Sg} is afforded by the chain map

$$\Phi_g = \Phi^{Sg} : C(S) \rightarrow C(S), \quad s_0 \otimes s_1 \otimes \cdots \otimes s_n \mapsto s_0^g \otimes s_1^g \otimes \cdots \otimes s_n^g.$$

(b) *Induction from R to S and from S to T .* Using $A = R$, $B = S$ and $P = {}_R S_S$ we obtain an induction map

$$\text{Ind}_R^S = H_*^{{}_R S_S} : HH_*(R) \rightarrow HH_*(S).$$

The canonical corresponding chain map $\Phi^{{}_R S_S} : C(R) \rightarrow C(S)$ simply comes from the inclusion $R \hookrightarrow S$, which makes it clear that

$$\text{Im}(\text{Ind}_R^S) \subseteq HH_*(S)^G,$$

where $HH_*(S)^G$ denotes the G -invariants in $HH_*(S)$. (Alternatively, this follows from the fact that ${}_R S_S \otimes_S Sg \cong {}_R S_S$ as R - S -bimodules.) Similarly, the embedding $S \hookrightarrow T$ yields an induction map $\text{Ind}_S^T : HH_*(S) \rightarrow HH_*(T)$ which is easily seen to factor through the canonical epimorphism of $HH_*(S)$ onto the G -coinvariants $HH_*(S)_G$ (cf. [Lo], §2.3). Thus we obtain a map

$$\overline{\text{Ind}_S^T} : HH_*(S)_G \rightarrow HH_*(T).$$

(c) *Restriction from T to S .* With $A = T$, $B = S$, and $P = {}_T T_S$ we obtain a restriction map

$$\text{Res}_S^T = H_*^{T_S} : HH_*(T) \rightarrow HH_*(S).$$

Since the multiplication of T gives a T - S -isomorphism $T \otimes_S Sg \cong Tg = T$, we deduce that $HH_*^{Sg} \circ \text{Res}_S^T = \text{Res}_S^T$. Thus

$$\text{Im}(\text{Res}_S^T) \subseteq HH_*(S)^G.$$

By [Lo], Lemma 2.3(a), one has

$$\text{Res}_S^T \circ \overline{\text{Ind}_S^T} = \overline{\text{tr}} : HH_*(S)_G \rightarrow HH_*(S)^G,$$

where $\overline{\text{tr}}$ is the G -trace map on $HH_*(S)$ (see the Appendix).

We remark that the above inclusion $\text{Im}(\text{Res}_S^T) \subseteq HH_*(S)^G$ can be sharpened to

$$\text{Im}(\text{Res}_S^T) = \text{tr}(HH_*(S)).$$

In fact, using the dual bases $p_g = g$ and $q_g(\sum x s_x) = s_g$ ($g \in G$) of T_S one computes that the chain map Φ^{T_S} maps the element $g_0 s_0 \otimes g_1 s_1 \otimes \cdots \otimes g_n s_n \in C(T)$ to 0 if $g_0 \cdots g_n \neq e$ (so Res_S^T vanishes on the components $HH_*(T)_{[g]}$ with $g \neq e$; cf. [Lo], §2.2) and to

$$\text{tr}(s_0^{g_0^{-1}} \otimes s_1^{g_1^{-1}g_0^{-1}} \otimes \cdots \otimes s_n^{g_n^{-1} \cdots g_0^{-1}})$$

otherwise. This fact will however not be needed in the proofs of our main results.

3. Galois actions

The action of G on S is called *Galois* if $T = TtT$, where $t = \sum_{g \in G} g \in T$. The latter condition is equivalent with the existence of elements $x_i, y_i \in S$ ($i = 1, \dots, n$)

such that

$$\sum_{i=1}^n x_i y_i = 1 \quad \text{and} \quad \sum_{i=1}^n x_i y_i^g = 0 \quad \text{for all } e \neq g \in G. \quad (*)$$

In this case, S is finitely generated and projective as R -module (on either side; e.g., [P], §29, Exercises 3 and 4). Thus from §1 we infer the existence of a map

$$H_*^{T^S_R} : HH_*(T) \rightarrow HH_*(R).$$

LEMMA. *Suppose that the action of G on S is Galois.*

- (a) $\text{Ind}_R^S \circ H_*^{T^S_R} = \text{Res}_S^T$.
- (b) *If there exists an $z \in S$ with $\text{tr}(z) = 1$ then $H_*^{T^S_R}$ is an isomorphism.*

Proof. (a) The map $S \otimes_R S \rightarrow T$, $s \otimes s' \mapsto sts'$ is a T - T -bimodule isomorphism (see [Co]). Thus the left hand side in (a) is equal to $H_*^{R^S_S} \circ H_*^{T^S_R} = H_*^{T^S \otimes_R S} = H_*^{T^T_S}$, which proves (a).

(b) In this case, the bimodules ${}_T S_R$ and ${}_R S_T$ yield a Morita equivalence between R and T . Specifically, the map $S \otimes_T S \rightarrow R$, $s \otimes s' \mapsto \text{tr}(ss')$ is an R - R -bimodule isomorphism (see [Co]). Therefore, $H_*^{R^S_T}$ is inverse to $H_*^{T^S_R}$. \square

In view of §2, part (a) of the lemma implies the following inclusions for Galois actions:

$$\text{tr}(HH_*(S)) = \text{Im}(\text{Res}_S^T) \subseteq \text{Im}(\text{Ind}_R^S) \subseteq HH_*(S)^G.$$

4. Module structures

Let M be an S - S -bimodule. Then the Hochschild homology of S with coefficients in M , $H(S, M)$, becomes a module over the center $Z(S)$ of S by means of the action of $Z(S)$ on the chain complex $C(S, M)$ which, for a given $z \in Z(S)$ is defined by (cf. [L], 1.1.5)

$$\lambda_z(m \otimes s_1 \otimes \cdots \otimes s_n) = (zm) \otimes s_1 \otimes \cdots \otimes s_n.$$

This yields the structure map

$$\phi : Z(S) \rightarrow \text{End}_k(H_*(S, M)), \quad \phi(z) = H_*(\lambda_z).$$

Similarly, one can consider the right action of $Z(S)$ on $C(S, M)$ that is given by

$$\rho_z(m \otimes s_1 \otimes \cdots \otimes s_n) = (mz) \otimes s_1 \otimes \cdots \otimes s_n.$$

However, by [L], E.1.1.2, λ_z and ρ_z are homotopic and, consequently, they yield the same map on homology:

$$\phi(z) = H_*(\rho_z).$$

In the special case where $M = S$, the actions of G (as in §2(a)) and $Z(S)$ on $HH_*(S)$ combine to give a right $Z(S) * G$ -module structure on $HH_*(S)$. Indeed, the chain maps ρ_z and Φ_g satisfy $\rho_{zg} = \Phi_g \circ \rho_z \circ \Phi_{g^{-1}}$ for all $g \in G, z \in Z(S)$. Therefore, the Lemma in the Appendix has the following immediate consequence.

LEMMA. *Assume that there exists $z \in Z(S)$ with $\text{tr}(z) = 1$. Then the trace map $\bar{\text{tr}} : HH_*(S)_G \rightarrow HH_*(S)^G$ is an isomorphism and $H_n(G, HH_*(S)) = 0$ holds for all $n > 0$.*

We remark that the Lemma implies in particular that, if the action of G on S is Galois and there exists $z \in Z(S)$ with $\text{tr}(z) = 1$, then all inclusions at the end of §3 are equalities.

5. Centrally Galois actions

We will call the action of G on S *centrally Galois* if the restricted action on the center $Z(S)$ of S is Galois or, equivalently, if the elements x_i, y_i in §3 can be chosen to belong to $Z(S)$. In this case, by [C-H-R], Lemma 1.6, there also exists an element $z \in Z(S)$ with $\text{tr}(z) = 1$. In particular, the Lemmas in §§3 and 4 apply. Furthermore, we have the following vanishing result for the Hochschild homology of S with coefficients in the bimodules $Sg \subseteq T$.

LEMMA. *Suppose that the action of G on S is centrally Galois. Then $H_*(S, Sg) = 0$ holds for all $e \neq g \in G$.*

Proof. We use the maps λ_z and ρ_z of §4 in the special case where $M = Sg$. It follows from $sgz^g = zsg$ that $\rho_{zg} = \lambda_z$, and hence the structure map $\phi : Z(S) \rightarrow \text{End}_k(H_*(S, Sg))$ satisfies $\phi(z) = \phi(z^g)$ for all $z \in Z(S)$. Applying ϕ to the equations (*) in §3, we deduce that $1 = 0$ holds in $\text{End}_k(H_*(S, Sg))$ if $g \neq e$ which proves the lemma. \square

6. THEOREM. *Suppose that the action of G on S is centrally Galois. Then the maps $\text{Res}_S^T : \text{HH}_*(T) \rightarrow \text{HH}_*(S)^G$ and $\text{Ind}_S^T : \text{HH}_*(S) \rightarrow \text{HH}_*(S)^G$ are isomorphisms.*

Proof. In view of the Lemma in §3, it suffices to prove the assertion for Res_S^T . To this end, we use the following description of $\text{HH}_*(T)$ (cf. [Lo], §2.6):

$$\text{HH}_*(T) \cong \bigoplus_g \text{H}_*(\mathbf{C}_G(g), C(S, Sg)),$$

where g runs over a complete representative set of the conjugacy classes of G and $\text{H}_*(\mathbf{C}_G(g), C(S, Sg))$ denotes the hyperhomology of the centralizer $\mathbf{C}_G(g)$ of g in G with coefficients in the complex $C(S, Sg)$. By [B], (5.10) on p. 169, there exists a spectral sequence

$$E_{p,q}^2 = H_0(\mathbf{C}_G(g), H_q(S, Sg)) \xrightarrow{p} H_{p+q}(\mathbf{C}_G(g), C(S, Sg)).$$

Therefore, the Lemma in §5 implies that $H_*(\mathbf{C}_G(g), C(S, Sg)) = 0$ holds for $g \neq e$, and hence $\text{HH}_*(T)$ is isomorphic with the $(g = e)$ -component of the above direct sum. For $g = e$, the spectral sequence becomes

$$E_{p,q}^2 = H_p(G, \text{HH}_q(S)) \xrightarrow{p} H_{p+q}(G, C(S)).$$

The Lemma in §4 implies that $E_{p,q}^2 = 0$ holds for all $p > 0$ and, consequently, the edge homomorphism $E_{0,*}^2 = H_0(G, \text{HH}_*(S)) \rightarrow H_*(G, C(S))$ is an isomorphism. The composite of this edge map with the isomorphism $H_*(G, C(S)) \cong \text{HH}_*(T)$ is just the map $\overline{\text{Ind}_S^T}$ of §2(b). Thus we conclude that $\overline{\text{Ind}_S^T}$ yields an isomorphism

$$\overline{\text{Ind}_S^T} : \text{HH}_*(S)_G \xrightarrow{\cong} \text{HH}_*(T).$$

Finally, by §2(c) and the Lemma in §4, the composite

$$\text{Res}_S^T \circ \overline{\text{Ind}_S^T} = \overline{\text{tr}} : \text{HH}_*(S)_G \rightarrow \text{HH}_*(S)^G$$

is an isomorphism, whence Res_S^T is an isomorphism as well, and the theorem is proved. \square

7. Cyclic homology

In the situation of §1, there is an analogous map for cyclic homology

$$HC_*^p : HC_*(A) \rightarrow HC_*(B).$$

In particular, one has a G -action and restriction and induction maps for cyclic homology as in §2. Furthermore, the maps H_*^P and HC_*^P yield a commutative diagram of Connes-Gysin sequences (see [Lo], §1.3)

$$\begin{array}{ccccccc} \cdots & \longrightarrow & HH_n(A) & \longrightarrow & HC_n(A) & \longrightarrow & HC_{n-2}(A) \longrightarrow HH_{n-1}(A) \longrightarrow \cdots \\ & & \downarrow H_n^P & & \downarrow HC_n^P & & \downarrow HC_{n-2}^P & & \downarrow H_{n-1}^P \\ \cdots & \longrightarrow & HH_n(B) & \longrightarrow & HC_n(B) & \longrightarrow & HC_{n-2}(B) \longrightarrow HH_{n-1}(B) \longrightarrow \cdots \end{array}$$

Thus the above Theorem has the following consequence.

COROLLARY. *Suppose that the action of G on S is centrally Galois and that $|G|^{-1} \in k$. Then the maps $\text{Res}_S^T : HC_*(T) \rightarrow HC_*(S)^G$ and $\text{Ind}_R^S : HC_*(R) \rightarrow HC_*(S)^G$ are isomorphisms.*

Proof. We concentrate on Ind_R^S . By assumption on $|G|$, the G -fixed point functor is exact on k -modules and so the above commutative diagram yields the following commutative diagram with exact rows and with all vertical maps equal to Ind_R^S .

$$\begin{array}{ccccccc} HC_{n-1}(R) & \longrightarrow & HH_n(R) & \longrightarrow & HC_n(R) & \longrightarrow & HC_{n-2}(R) \longrightarrow HH_{n-1}(R) \\ \downarrow & & \downarrow \cong & & \downarrow & & \downarrow \\ HC_{n-1}(S)^G & \longrightarrow & HH_n(S)^G & \longrightarrow & HC_n(S)^G & \longrightarrow & HC_{n-2}(S)^G \longrightarrow HH_{n-1}(S)^G \end{array}$$

The assertion thus follows from the 5-lemma by induction on n . (Note that all homologies under consideration are zero in negative degrees.) \square

Appendix: The G -trace map

In this Appendix we collect some well-known facts concerning the G -trace map. Let A be any k -algebra on which G acts by automorphisms. Then, for any right module V over the skew group ring $A * G$, we can consider $V^G = H^0(G, V)$, the G -invariants in V . The G -trace map is defined by

$$\text{tr} : V \rightarrow V^G, \quad v \mapsto \sum_{g \in G} vg = vt,$$

where we have put $t = \sum_{g \in G} g \in T$. In particular, one has the usual G -trace $\text{tr} : A \rightarrow A^G$. Letting $V_G = H_0(G, V) = V/(v(g-1) \mid v \in V, g \in G)$ denote the G -

coinvariants of V , one observes that the G -trace factors through the canonical epimorphism $V \rightarrow V_G$. Thus we obtain a map

$$\overline{\text{tr}} : V_G \rightarrow V^G.$$

LEMMA. *Suppose that $\text{tr}(z) = 1$ for some $z \in A$. Then, for every right $A * G$ -module V , the trace map $\overline{\text{tr}} : V_G \rightarrow V^G$ is an isomorphism and $H_n(G, V) = 0$ holds for all $n > 0$.*

Proof. Recall that the Tate cohomology $\hat{H}^*(G, V)$ satisfies $\hat{H}^0(G, V) = \text{Coker}(\overline{\text{tr}})$, $\hat{H}^{-1}(G, V) = \text{Ker}(\overline{\text{tr}})$, and $\hat{H}^{-n-1}(G, V) = H_n(G, V)$ for all $n > 0$ (see [B], §V1.4). Thus it suffices to show that $\hat{H}^*(G, V)$ vanishes. To this end, let $\phi : A * G \rightarrow \text{End}_k(V)^{op}$ denote the structure map of the $A * G$ -module V . Then, in $\text{End}_k(V)^{op}$, we have $\text{Id} = \text{tr}(\phi(z))$. Since $\hat{H}^*(G, \text{Id})$ is the identity on $\hat{H}^*(G, V)$ and $\hat{H}^*(G, \text{tr}(\phi(z)))$ is zero (cf. [Ba], 15.3), we conclude that $\hat{H}^*(G, V) = 0$, as required. \square

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