THE PERIODIC CYCLIC HOMOLOGY OF CROSSED PRODUCTS OF FINITE TYPE ALGEBRAS

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Abstract. We study the periodic cyclic homology groups of the cross-product of a finite type algebra $A$ by a discrete group $\Gamma$. In case $A$ is commutative and $\Gamma$ is finite, our results are complete and given in terms of the singular cohomology of the sets of fixed points. These groups identify our cyclic homology groups with the “orbifold cohomology” of the underlying (algebraic) orbifold. The proof is based on a careful study of localization at fixed points and of the resulting Koszul complexes. This is achieved by extending to our class of noncommutative algebras the concept of an “infinitesimal neighborhood” that plays such an important role in commutative algebra. We provide examples of Azumaya algebras for which this identification is, however, no longer valid. As an example, we discuss some affine Weyl groups.

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Introduction

Let $A$ be an algebra and let $\Gamma$ be a (discrete) group acting on it by a morphism $\alpha : \Gamma \to \text{Aut}(A)$, where $\text{Aut}(A)$ denotes the group of automorphisms of $A$. Then, to this action of $\Gamma$ on $A$, we can associate the crossed product algebra $A \rtimes \Gamma$ consisting of finite sums of elements of the form $a\gamma$, $a \in A$, $\gamma \in \Gamma$, subject to the relations

\[ \gamma a = \alpha_\gamma(a) \gamma. \]

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Crossed products appear often in algebra and analysis and can be used to model several geometric structures. They play a fundamental role in noncommutative geometry \[23\]. For instance, cross-products can be used to recover equivariant $K$-theory \[5, 6, 25, 35, 46\].

Computing $K$-theory is a difficult technical challenge that plays a central role in a number of important conjectures, for instance, in the Baum-Connes conjecture \[23\]. Periodic cyclic homology shares some important formal properties with $K$-theory: there is a six-term exact sequence in periodic cyclic homology \[27, 28\], as in $K$-theory and the basic exact sequences of Pimsner and Voiculescu for cross-products \[69, 70\], see also \[12\]. Also extend to periodic cyclic homology. Periodic cyclic homology, furthermore, has the advantage over $K$-theory that is much easier to compute, in general. For instance, periodic cyclic homology is a homological theory for algebras that can be used to recover the de-Rham cohomology of a smooth, compact manifold $M$ as the periodic cyclic homology of the algebra $C^\infty(M)$ \[22\] (see also \[23, 48, 53, 54, 58, 82\]).

In this paper we study the Hochschild, cyclic, and periodic cyclic homology groups of $A \rtimes \Gamma$ using the additional information provided by the action of $\Gamma$ on $k$. We begin with some general results and then particularize, first, to the case when $A$ is a finite type algebra over $k$ and then, further, to the case when $A = k[X]$, a polynomial ring. Recall \[50\] that $A$ is a finite type algebra over $k$ if $A$ is a $k$-algebra, $k$ is a quotient of a polynomial ring, (which is equivalent to saying that $k$ is finitely generated over the base field) and $A$ is finitely generated as a $k$-module.

For $\gamma \in \Gamma$, let us denote by $\langle \gamma \rangle$ the conjugacy class of $\gamma \in \Gamma$ and by $\langle \Gamma \rangle$ the set of conjugacy classes of $\Gamma$. Our first step is to use the decomposition

\[ HH_q(A \rtimes \Gamma) \simeq \bigoplus_{\langle \gamma \rangle \in \langle \Gamma \rangle} HH_q(A \rtimes \Gamma)_\gamma \]

of the Hochschild homology groups of $A \rtimes \Gamma$ \[5, 6, 15, 35, 48, 64\]. Let $\text{Spec}(k)$ be the maximal ideal spectrum of $k$ and denote by $\text{supp}(A) \subset \text{Spec}(k)$ the support of $A$. A first observation is that, if $\gamma \in \Gamma$ is such $\gamma$ has no fixed points on $\text{supp}(A)$, then the component corresponding to $\gamma$ in the direct sum decomposition of Equation (2) vanishes, that is, $HH_q(A \rtimes \Gamma)_\gamma = 0$ for all $q$. Consequently, we also have $HC_q(A \rtimes \Gamma)_\gamma = HP_q(A \rtimes \Gamma)_\gamma = 0$ for all $q$. More generally, this allows us to show that the groups $HH_q(A \rtimes \Gamma)_\gamma$, $HC_q(A \rtimes \Gamma)_\gamma$, and $HP_q(A \rtimes \Gamma)_\gamma$ are supported at the ideals fixed by $\gamma$. 
We are especially interested in the case $A = \mathcal{O}[V]$, the algebra of regular functions on an affine algebraic variety $V$, in which we obtain complete results, identifying the periodic cyclic homology groups with the corresponding orbifold homology groups [21]. We stress that we do not assume $V$ to be smooth, which is one of the main technical difficulties that we had to deal with. More precisely, we obtain the following main result (see Theorem 2.20 in the main text).

**Theorem 0.1.** Let $A$ be a quotient of the ring of polynomials $\mathbb{C}[X_1, X_2, \ldots, X_n]$ and let $\Gamma$ be a finite group acting on $A$ by automorphisms. Let $\{\gamma_1, \ldots, \gamma_\ell\}$ be a list of representatives of conjugacy classes of $\Gamma$, let $C_j$ be the centralizer of $\gamma_j$ in $\Gamma$, and let $V_j \subset V$ be the set of fixed points of $\gamma_j$ acting on the subset $V \subset \mathbb{C}^n$ corresponding to the set of maximal ideals of $A$. Then

$$\text{HP}_q(A \rtimes \Gamma) \cong \bigoplus_{j=1}^\ell \bigoplus_{k \in \mathbb{Z}} H^{q-2k}(V_j; \mathbb{C})^{C_j}.$$ 

We refer to [4, 30, 60, 68] for the definition of orbifold cohomology groups in the category of smooth manifolds and to its connections with cyclic homology. We are interested in the case $A = \mathcal{O}[V]$ due to its connections with affine Weyl groups.

The proof of our main theorem consists roughly of two parts, analogous to the proof of the corresponding result for affine algebraic varieties by Feigin and Tsygan [35]. Indeed, let us repeat that the main difficulty of both the result of Feigin and Tsygan [35] and of our result is that the underlying variety $V$ (see the statement of Theorem 0.1) is not smooth. In particular, its Hochschild homology is not so well behaved. It is only the periodic cyclic homology of these algebras that is well behaved, and hence computable and having a simple, independent interpretation using singular homology. The two parts of the proof are

(i) Prove the result for a smooth affine algebraic variety $V$,

(ii) Reduce the general result to the smooth case by considering an “infinitesimal” neighborhood $\hat{V}$ of $V$ defined using an equivariant embedding of $V$ into an affine space $\mathbb{A}$.

This strategy works well in the absence of a group action and is based on ideas of Grothendieck. The point is that $\hat{V}$ yields the same homology groups as $V$, whereas for the purpose of actually carrying out the calculations, $\hat{V}$ behaves like a smooth variety. The main challenge addressed in this work is to extend these ideas to a noncommutative algebra. Thus, in a certain sense, we consider an infinitesimal neighborhood of the algebra $\mathcal{O}[V] \rtimes \Gamma$. Extending the idea of an infinitesimal neighborhood to a class of noncommutative algebras is one of the main ideas of this paper and, also, one of the main technical difficulties that we have to resolve. In particular, in order to use completions with respect to ideals (in the sense of commutative algebra), we establish several technical properties of our cross-product algebra $\mathcal{O}[V] \rtimes \Gamma$. To this end, the concept of a finite type algebra is crucial. In particular, we prove that $\mathcal{O}[V] \rtimes \Gamma$ is a finite type algebra. The case $V$ smooth requires us to carefully review the calculations in the simplest case of a smooth variety without a group action, which required a rather lengthy detour through Koszul complexes, their homology and completions with respect to powers of ideals.

For simplicity, we shall consider from now on only complex algebras. Thus $k$ and $A$ are complex vector spaces in a compatible way. The paper is organized as follows. In the first section, we recall the definitions of Hochschild and cyclic homologies...
1.1. Hochschild and cyclic homology. Let $A$ be a complex algebra with unit and denote by $A^{\text{op}}$ the algebra $A$ with the opposite multiplication and $A^e := A \otimes A^{\text{op}}$, so that $A$ becomes a left $A^e$–module with $(a_0 \otimes a_1) \cdot a := a_0 a a_1$.

Let $g$ be an endomorphism of $A$ and define for $x = a_0 \otimes a_1 \otimes \ldots \otimes a_n \in A^{\otimes n+1}$

$$b'_g(x) := a_0 g(a_1) \otimes a_2 \otimes \ldots \otimes a_n + \sum_{i=1}^{n-1} (-1)^i a_0 \otimes \ldots \otimes a_i a_{i+1} \otimes \ldots \otimes a_n$$

and

$$b_g(x) := b'_g(x) + (-1)^n a_0 \otimes a_1 \otimes \ldots \otimes a_{n-1}.$$  \hfill (3)

Let us denote by $B'_q(A) := A \otimes (A/\mathbb{C}1)^{\otimes q} \otimes A$ and $B_q(A) := A \otimes (A/\mathbb{C}1)^{\otimes q}$, $q \geq 0$. Then $b'_g$ and $b_g$ descend to maps $b'_g : B'_q(A) \to B'_{q-1}(A)$ and $b_g : B_q(A) \to B_{q-1}(A)$. As usual, when $g$ is the identity, we write simply $b$ instead of $b_g$ and $b'$ instead of $b'_g$. We then define

**Definition 1.1.** The $q$-twisted Hochschild homology groups $\text{HH}_*(A, g)$ of $A$ are the homology groups of the complex $(B_q(A), b_g) = (B_q(A), b_g)_{q \geq 0}$.

Thus, when $g$ is the identity, and hence $b_g = b$, we obtain that $\text{HH}_*(A, g)$ are simply the usual Hochschild homology groups $\text{HH}_*(A)$ of $A$.

Let $A_g$ be the $A^e$ right-module $a(a_1 \otimes a_2) := a_2 ag(a_1)$. By tensoring the complex $(B'_q(A), b'_g)_{q \geq 1}$ with $A_g$ over $A^e$ we obtain the complex $(B_q(A), b_g)_{q \geq 0}$. Since the complex $(B'_q(A), b')$ is acyclic–and thus provides a projective resolution of $A$ with $A^e := A \otimes A^{\text{op}}$ modules–we obtain [15, 35, 53, 64, 81, 86]

**Proposition 1.2.** For every $q \geq 0$, we have a natural isomorphism

$$\text{HH}_q(A, g) \simeq \text{Tot}^A_{q}(A_g, A).$$ \hfill (4)
See [9, 36] for some generalizations. Let us assume now that $A$ is an algebra over a (commutative) ring $k$. Then we see by a direct calculation that the differential $b_q$ is $k$–linear, and hence each $HH_q(A, g)$ is naturally a $k$–module. Moreover, both $A$ and $A_g$ are $k \otimes k$–modules:

\[(z_1 \otimes z_2) a := g(z_1) z_2 a, \quad \text{for } z_1, z_2 \in k \text{ and } a \in A_g.\]

Consequently, $\text{Tor}_q^k(A, A)$ is naturally a $k \otimes k$–module, with the action of $z_1 \otimes z_2 \in k \otimes k$ on either component of the Tor-group being the same. Examining the proof of Proposition 1.2, we see that the isomorphism $HH_q(A, g) \simeq \text{Tor}_q^k(A, A)$ of that proposition is compatible with these module structures. More related information is contained in the following results. We first need to recall some basic definitions.

Let $R$ be a ring (all our rings have units). We assume $\mathbb{C} \subset R$, for simplicity (that’s the only case we need anyway). We denote by $\hat{R}$ the set of maximal ideals $m$ of $R$ with the Jacobson topology. We assume that $R/m \simeq \mathbb{C}$ as $\mathbb{C}$–algebras for any maximal ideal $m$. Recall that if $M$ is a module over a ring $R$ (all our rings have units), then the support of $M$ is the set of maximal ideals $m \in \hat{R}$ such that the localization $M_m := A_m M$ is nonzero. Thus we have that $M_m = 0$ if, and only if, for every $m \in M$, there exists $x \notin m$ such that $xm = 0$.

Returning to our setting, let $m, n \in \text{Spec}(k)$ be maximal ideals and $\chi_m : k/m \to \mathbb{C}$ and $\chi_n : k/n \to \mathbb{C}$ be the canonical isomorphisms. Then $(m, n) \in \text{Spec}(k) \times \text{Spec}(k)$ corresponds to the morphism $\chi_n \otimes \chi_m : k \to k \otimes k \to \mathbb{C}$. This identifies the maximal ideal spectrum of $k \otimes k$ with $\text{Spec}(k) \times \text{Spec}(k)$.

Lemma 1.3. The support of $A_g$ in $\text{Spec}(k) \times \text{Spec}(k)$ is contained in the set

\[\{ (g^{-1}(m), m) : \ m \in \hat{k} \}.\]

Proof. Assume that $(m, n) \in \text{Spec}(k) \times \text{Spec}(k)$ is such that $g^{-1}(n) \neq m$. Since $g^{-1}(n) \neq m$, we have that $\chi_m \neq \chi_n \circ g$. Then there exists $z \in k$ such that $\chi_m(z) \neq \chi_n(g(z))$. Hence $w := z \otimes 1 - 1 \otimes g(z)$ satisfies $\chi_m \otimes \chi_n(w) = \chi_m(z) - \chi_n(g(z)) \neq 0$, and hence is not in $(m, n)$. However, if $a \in A_g$, then $wa = g(z)a - g(z)a = 0$. By definition, this means that the localization of $A_g$ at $(m, n)$ is zero, and hence $(m, n)$ is not in the support of $A_g$. \hfill $\Box$

Recall [16, 50] that if $S \subset k \otimes k$ is a multiplicative subset and $M$ and $N$ are two bimodules (or $A^e$ left-modules), then

\[S^{-1} \text{Tor}_q^k(M, N) \simeq \text{Tor}_q^k(S^{-1}M, S^{-1}N) \simeq \text{Tor}_{q^{-1}A^e}^k(S^{-1}M, S^{-1}N).\]

This shows that the support of $\text{Tor}_q^k(M, N)$ is contained in the intersection of the supports of $M$ and $N$.

Let us assume for the rest of this section that the given endomorphism $g$ of $A$ has a counterpart in an endomorphism of $k$ also denoted $g$–such that $g(za) = g(z)g(a)$, for all $z \in k$ and $a \in A$.

Corollary 1.4. Let $S \subset k$ be a $g$–invariant multiplicative subset. We have

\[HH_q(S^{-1}A, g) \simeq S^{-1} HH_q(A, g).\]

Hence the support of $HH_q(A, g)$ is contained in the set

\[\{ (m, m) : \ m \in \text{Spec}(k), \ g^{-1}(m) = m \}.\]
Proof. The first part of the proof follows from Equation (6) for the multiplicative subset $S \otimes S \subset k \otimes k$. (A direct proof can be obtained as in [50], for example). The support of $A$ is contained in the diagonal \{(m, m), m \in \text{Spec}(k)\}. The support of $A_g$ is contained in the set \{(g^{-1}(m), m), x \in \text{Spec}(k)\}. Since $\text{HH}_q(A, g) \simeq \text{Tor}_q^A(A, A_g)$ and

$$\{(m, m)\} \cap \{(g^{-1}(m), m)\} = \{(m, m), g^{-1}(m) = m\} \subset \text{Spec}(k) \times \text{Spec}(k),$$

the result follows. \qed

Of the two $k$-module structures on $A$ and $A_g$, we shall now retain just the one given by multiplication to the left, that is, the usual $k$-module structure. We also have the following.

**Proposition 1.5.** The support of $\text{HH}_q(A, g)$ as a $k$-module is

$$\{ m \in \text{Spec}(k), \ g^{-1}(m) = m \}.$$

**Proof.** Let $k_1$ and $k_2$ be finitely generated commutative complex algebras with unit and let $M$ be a $k_1 \otimes k_2$-module with support $K \subset \text{Spec}(k_1 \otimes k_2) = \text{Spec}(k_1) \times \text{Spec}(k_2)$. Then the support of $M$ as a $k_1$ module is the projection of $K$ onto the first component. Combining this fact with Corollary 1.4 yields the desired result. \qed

This proposition then gives the following standard consequences

**Corollary 1.6.** If $n \in \text{Spec}(k)$ is such that $g^{-1}(n) \neq n$, then $\text{HH}_q(A, g)_n = 0$. In particular, if $g^{-1}(m) \neq m$ for all maximal ideals $m$ of $k$, then $\text{HH}_q(A, g) = 0$.

**Proof.** Since the support of $\text{HH}_q(A, g)$ is the set \{m \in \text{Spec}(k), g^{-1}(m) = m\}, we obtain that $n$ is not in the support of $\text{HH}_q(A, g)$, that is, $\text{HH}_q(A, g)_n = 0$. This proves the first part. The second part follows from the fact that a $k$-module with empty support is zero. \qed

In order to introduce the closely related cyclic homology groups, let us first recall the following standard operators acting on $A^\otimes n$, $n \geq 0$, [22]

$$s(a_0 \otimes a_1 \otimes \ldots \otimes a_n) := 1 \otimes a_0 \otimes a_1 \otimes \ldots \otimes a_n,
$$

$$t_g(a_0 \otimes a_1 \otimes \ldots \otimes a_n) := (-1)^n g(a_n) \otimes a_0 \otimes \ldots \otimes a_{n-1}, \text{ and}
$$

$$B_g(a_0 \otimes a_1 \otimes \ldots \otimes a_n) := s \sum_{k=0}^n t_g^k(a_0 \otimes a_1 \otimes \ldots \otimes a_n).$$

Let $\gamma$ act diagonally on $B_g(A)$: $g(a_0 \otimes a_1 \otimes \ldots \otimes a_n) = g(a_0) \otimes g(a_1) \otimes \ldots \otimes g(a_n)$. Then $B_g$ descends to differential

$$B_g : X_q(A) := B_q(A)/(g - 1)B_q(A) \to X_{q+1}(A)$$

satisfying $B_g^2 = 0$ and $B_g b_g + b_g B_g = 0$. Therefore $(X_q(A), b_g, B_g)$ is a mixed complex [45], where $b_g$ is the $g$-twisted Hochschild homology boundary map defined in Equation (3). Recall how its cyclic homology are computed. Let

$$C_n(A) := \bigoplus_{q \geq 0} X_{n-2q}(A).$$
Then the $g$-twisted cyclic homology groups of the unital algebra $A$, denoted $\text{HC}_n(A,g)$, are the homology groups of the cyclic complex $(\mathcal{C}_n(A), b_g + B_g)$ [22]. The homology groups of the 2-periodic complex

$$b_g + B_g : \prod_{q \in \mathbb{Z}} X_{i+2q}(A) \to \prod_{q \in \mathbb{Z}} X_{i+1+2q}(A), \quad i \in \mathbb{Z}/2\mathbb{Z},$$

are the $g$-twisted periodic cyclic homology groups of the unital algebra $A$ and are denoted $\text{HP}_n(A,g)$.

1.2. Crossed-products. Let $A$ be an arbitrary complex algebra and $\Gamma$ be a group acting on $A$ by automorphisms: $\alpha : \Gamma \to \text{Aut}(A)$. We do not assume any topology on $\Gamma$, that is, $\Gamma$ is discrete. Then $A \rtimes \Gamma$ is generated by $a\gamma$, $a \in A$, $\gamma \in \Gamma$, subject to the relation $a\gamma b\gamma' = a\alpha_\gamma(b)\gamma\gamma'$.

We want to study the cyclic homology of $A \rtimes \Gamma$. Both the cyclic and Hochschild complexes of $A \rtimes \Gamma$ decompose in direct sums of complexes indexed by the conjugacy classes $(\gamma)$ of $\Gamma$. Explicitly, to $(\gamma) := \{g\gamma g^{-1} \mid g \in \Gamma\}$ there is associated the subcomplex of the Hochschild complex $(\mathcal{B}_q(A \rtimes \Gamma), b)$ generated linearly by tensors of the form $a_{\gamma_0} \otimes a_{\gamma_1} \otimes \cdots \otimes a_{\gamma_k}$ with $\gamma_0 \gamma_1 \cdots \gamma_k \in (\gamma)$. The homology groups of this subcomplex of the Hochschild complex $(\mathcal{B}_q(A \rtimes \Gamma), b)$ associated to $(\gamma)$ will be denoted by $\text{HH}_q(A \rtimes \Gamma)_\gamma$. We similarly define $\text{HC}_q(A \rtimes \Gamma)_\gamma$ and $\text{HP}_q(A \rtimes \Gamma)_\gamma$, see [35, 48, 64] for instance. This yields the decomposition of Equation (2). Similarly,

$$(8) \quad \text{HC}_q(A \rtimes \Gamma) \simeq \bigoplus_{(\gamma) \in (\Gamma)} \text{HC}_q(A \rtimes \Gamma)_\gamma.$$

If $\Gamma$ has finitely many conjugacy classes, a similar relation holds also for periodic cyclic homology. Such decompositions hold more generally for group-graded algebras [55].

Let us assume now that $\Gamma$ is finite. Let, for any $g \in \Gamma$, $C_g$ denote the centralizer of $g$ in $\Gamma$, that is, $C_g = \{\gamma \in \Gamma \mid g\gamma = \gamma g\}$. Then we have the following result [8, 15, 17, 34, 35, 55, 63, 64, 76].

**Proposition 1.7.** Let $\Gamma$ be a finite group acting on $A$ and $\gamma \in \Gamma$. Then we have natural isomorphisms $\text{HH}_q(A \rtimes \Gamma)_\gamma \simeq \text{HH}_q(A, \gamma)^{C_\gamma}$, $\text{HC}_q(A \rtimes \Gamma)_\gamma \simeq \text{HC}_q(A, \gamma)^{C_\gamma}$, and $\text{HP}_q(A \rtimes \Gamma)_\gamma \simeq \text{HP}_q(A, \gamma)^{C_\gamma}$.

An approach to this result (as well as to the spectral sequence for the case when $\Gamma$ is not necessarily finite), using cyclic objects and their generalizations, is contained in [64]. This proposition explains why we are interested in the twisted Hochschild homology groups. The same proof will apply in the case of algebras endowed with filtrations. A proof of this proposition in the more general case of filtered algebras is provided in Proposition 1.13. Algebras with these properties are called *topological algebras* in [43], but this terminology conflicts with the terminology used in other papers in the field.

1.3. Finite type algebras and completions. We continue to assume that $A$ is a $k$-algebra with unit, for some commutative ring $k$, $\mathbb{C} \subset k$. We shall need the following definition from [50]

**Definition 1.8.** A $k$-algebra $A$ is called a *finite type $k$-algebra* if $k$ is a finitely generated ring (over $\mathbb{C}$) and $A$ is a finitely generated $k$-module.
We shall need to consider completions of our algebras and of our complexes with respect to the topology defined by the powers of an ideal. Let us consider then a vector space $V$ endowed with a decreasing filtration

$$V = F_0V \supset F_1V \supset \ldots \supset F_nV \supset \ldots .$$

Then its completion is defined by

$$(9) \quad \hat{V} = \lim_{\leftarrow} (V/F_jV).$$

If the natural map $V \to \hat{V}$ is an isomorphism, we shall say that $V$ is complete. A linear map $\phi : V \to W$ between two filtered vector spaces is called continuous if for every integer $n \geq 0$ there is an integer $k \geq 0$ such that $\phi(F_nV) \subset F_{n+k}W$. It is called bounded if there is an integer $k \geq 0$ such that $\phi(F_{n+k}V) \subset F_nW$ for all $n \geq 0$. Clearly, every bounded map is continuous. A bounded map $\phi : V \to W$ of filtered vector spaces extends to a linear map $\hat{\phi} : \hat{V} \to \hat{W}$ between their completions. If $V$ and $W$ are filtered vector spaces, the completed tensor product is defined as

$$(10) \quad V\hat{\otimes}W := \lim_{\leftarrow} (V/F_jV \otimes W/F_jW).$$

Recall that a morphism of complexes is called a quasi-isomorphism if it induces an isomorphism of the corresponding homology groups. We shall need the following standard lemma.

**Lemma 1.9.** Let $f_* : (V_*, d) \to (W_*, d), \ast \geq 0$, be a morphism of filtered complexes with $f_q(F_nV_q) \subset F_qW_q$ for all $n, q \geq 0$. We assume that all groups $V_q$ and $W_q, q \geq 0$, are complete and that $f_*$ induces isomorphisms $H_q(F_nV/F_{n+1}V) \to H_q(F_nW/F_{n+1}W)$ for all $n \geq 0$ and $q \geq 0$. Then $f$ is a quasi-isomorphism.

**Proof.** A spectral sequence argument (really, just the “Five Lemma”) shows that $f_*$ defines a quasi-isomorphism $(V_*/F_nV_*, d) \to (W_*/F_nW_*, d)$, for all $n \geq 0$. The assumption that the modules $V_q$ and $W_q$ are complete and an application of the lim$^1$-exact sequence for the homology of a projective limit of complexes then give the result. 

Typically, the filtered vector spaces $V$ that we will consider will come from $A$-modules endowed with the $I$-adic filtration corresponding to a two-sided ideal $I$ of $A$. More precisely, $F_nV := I^nV$, for some fixed two-sided ideal $I$ of $A$. Most of the time, the ideal $I$ will be of the form $I = I_0A$, where $I_0 \subset k$ is an ideal. Consequently, if $M$ and $N$ are a right, respectively a left, $A$-module endowed with the $I$-adic filtration, then we define

$$(11) \quad M\hat{\otimes}_A N := \lim_{\leftarrow} (M/I^nM \otimes_A N/I^nN).$$

Basic results of homological algebra extend to $A$-modules endowed with filtrations if one is careful to use only admissible resolutions, that is resolutions that have bounded $\mathbb{C}$-linear contractions, in the spirit of relative homological algebra. The completion of every admissible resolution by finitely generated free modules is admissible, and this is essential for our argument.

Let $A$ be a filtered algebra with filtration $F_qA \subset A$, where $F_qAF_pA \subset F_{q+p}A$. We then define $A\hat{\otimes} := \lim_{\leftarrow} (A/F_nA)\hat{\otimes}$ be the topological tensor product in the category of complete modules. In the case of the $I$-adic filtration, we have $F_pA := I^pA$ and $A\hat{\otimes} := \lim_{\leftarrow} (A/I^nA)\hat{\otimes}$. Let $g$ be an endomorphism $g : A \to A$ as before, and...
assume also that $g$ preserves the filtration and that it induces an endomorphism of $k$ as well. (So $g$ is an endomorphism of $A$ as a $\mathbb{C}$-algebra, not as a $k$-algebra.)

Then the topological, twisted Hochschild complex [75] of $A$ is denoted $(\tilde{B}_s(\hat{A}), b_g)$ and is the completion of the usual Hochschild complex $(B_s(A), b_g)$ with respect to the filtration topology topology. See also [43]. Explicitly,

$$
\hat{A} \xleftarrow{b_g} A \otimes A \xleftarrow{b_g} A \otimes A \otimes A \xleftarrow{b_g} \ldots
$$

We shall denote by $\text{HH}^{\text{top}}_s(\hat{A}, g)$ the homology of the topological, twisted Hochschild complex. Note that $\text{HH}^s(A, g)$ is naturally a $k$-module, since $b_g$ is $k$-linear. When $I = 0$, we recover, of course, the usual Hochschild homology groups $\text{HH}^s(A, g)$ and we have natural, $k$-linear maps $\text{HH}^s(A, g) \rightarrow \text{HH}^{\text{top}}_s(\hat{A}, g)$. The topological, $b'$-complex $(\tilde{B}_s(\hat{A}), b')$ is defined analogously. We then see that $s$ is a bounded contraction for $(\tilde{B}_s(\hat{A}), b')$, where we recall $s(a_0 \otimes a_1 \otimes \ldots \otimes a_n) = 1 \otimes a_0 \otimes a_1 \otimes \ldots \otimes a_n$.

In particular, the complex so $(\tilde{B}_s(\hat{A}), b')$ is still acyclic.

From now on, we shall fix an ideal $I$ of $A$ and consider only the $I$-adic filtration given by $F_p A = I^p A$. We will see then that both the Hochschild homology and the periodic cyclic homology groups behave very well under completions for the $I$-adic topologies. We need however to introduce some notation and auxiliary material for the following theorem.

Let $I = I_0 A$, where $I_0$ is an ideal of $k$. We denote by $\hat{k}$ the completion of $k$ with respect to the topology defined by the powers of $I_0$, that is, $\hat{k} := \varprojlim k/I_0^n$. Then $\hat{A} \simeq A \otimes_k \hat{k}$, by standard homological algebra [2, 10]. Similarly, we shall denote by $\hat{A}^c := \hat{A} \otimes \hat{A}^{\text{top}}$, the completion of $A^c$ with respect to the topology defined by the ideal $J_2 := I_0 \otimes k + k \otimes I_0$. Let $g$ be a $k$-algebra endomorphism of $A$ and let $A_g$ be the $A^c$ right-module with the action $a(a' \otimes a'') = a'' a g(a')$.

The following result was proved for $g = 1$ (identity automorphism) in [50].

**Theorem 1.10.** Let $A$ be a finite-type $k$-algebra. Using the notation just introduced, we have that $\text{HH}^q_s(A, g)$ is a finitely generated $k$-module for each $q$. If we endow $A$ with the filtration defined by the powers of $I$, then the natural map $\text{HH}^s_s(A, g) \rightarrow \text{HH}^{\text{top}}_s(\hat{A}, g)$ and the $k$-module structure on $\text{HH}^s_s(A, g)$ define a $k$-module isomorphism

$$
\text{HH}^s_s(A, g) \otimes_k \hat{k} \simeq \text{HH}^{\text{top}}_s(\hat{A}, g) \simeq \text{Tor}^{A^c}_q(\hat{A}_g, \hat{A}).
$$

**Proof.** We consider a resolution of $A$ by finitely-generated, free, left $A^c$ modules say $(A^c \otimes V_i, d_i)$, which always exist since $A^c$ is Noetherian. By tensoring this resolution with $A_g$ over $A^c$, we obtain that the homology groups $\text{HH}^q_s(A, g) \simeq \text{Tor}^{A^c}_q(A_g, A)$ are all finitely generated $k$-modules. Since completion over Noetherian rings is exact in the category of finitely generated $k$-modules, the above complex completed by $I_2 := I_0 \otimes k + k \otimes I_0$ provides an admissible resolution of $\hat{A}$ namely $(\hat{A}^c \otimes V_i, d_i)$.

(Recall a complex is admissible if it has a bounded contraction; this property in this case is ensured by [50].) Now $\text{Tor}^{A^c}_q(\hat{A}_g, \hat{A})$ is the homology of the complex,

$$
\hat{A}_g \otimes_{\hat{A}^c} (\hat{A}^c \otimes V_i, d_i) = (\hat{A}_g \otimes V_i, 1 \otimes d_i).
$$

The right-hand side is the completion with respect to the ideal $I$ of the complex $(A_g \otimes V_i, 1 \otimes d_i)$, a complex whose homology is $\text{HH}^s_s(A, g)$. Hence

$$
\text{Tor}^{A^c}_q(\hat{A}_g, \hat{A}) = \text{HH}^s_s(A, g) \otimes_k \hat{k},
$$

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Since \( \text{HH}_s(A, g) \) is a finitely generated \( k \)-module. On the hand, since the \( I \)-adic bar-complex \( \widehat{\mathcal{B}}_s(\widehat{A}, b') \) has an obvious contraction that makes it admissible, there exist morphisms
\[
(\widehat{A}^e \otimes V_i, \widehat{d}_i) \overset{\phi}{\to} (\widehat{\mathcal{B}}_s(\widehat{A}, b'), \widehat{d}_i) \overset{\psi}{\to} (\widehat{A}^e \otimes V_i, \widehat{d}_i),
\]
with \( \phi \circ \psi \), respectively \( \psi \circ \phi \), homotopic to identity on \( (\widehat{\mathcal{B}}_s(\widehat{A}, b')) \), respectively \( (\widehat{A}^e \otimes V_i, \widehat{d}_i) \), thus after tensoring with \( \widehat{A}_g \) over \( A^e \), we obtain that \( \text{Tor}_{\widehat{A}_g}^1(\widehat{A}_g, \widehat{A}) = \text{HH}^\text{top}_{\widehat{A}_g}(\widehat{A}_g, \widehat{A}) \).

In the particular case \( g = \text{id} \), our isomorphism becomes \( \text{HH}^\text{top}_{\widehat{A}_g}(\widehat{A}, \text{id}) \simeq \text{Tor}_{\widehat{A}_g}^1(\widehat{A}_g, \widehat{A}) \) and was first proved by Hübl [43]. We now recall some properties of periodic cyclic homology with repect to completions. We have the following result of Goodwille [38].

**Theorem 1.11** (Goodwillie). If \( J \subset B \) is a nilpotent ideal of an algebra \( B \), then the quotient morphism \( B \to B/J \) induces an isomorphism \( \text{HP}_* (B) \to \text{HP}_* (B/J) \).

This gives the following result of [75] (Application 1.15(2)).

**Theorem 1.12** (Seibt). Let \( J \) be a two-sided ideal of an algebra \( B \). Then the quotient morphism \( B \to B/J \) induces an isomorphism \( \text{HP}^\text{top}_* (\widehat{B}) \to \text{HP}_* (B/J) \), where the completion is with respect to the powers of \( J \).

Let us assume that \( I \subset A \) is a two-sided ideal invariant for the action of the finite group \( \Gamma \), so that \( \widehat{A} \rtimes \Gamma \) is defined. Then the Hochschild, cyclic, and periodic cyclic complexes of the completion of \( \widehat{A} \rtimes \Gamma \) still decompose according to the conjugacy classes of \( \Gamma \). Recall that \( C_\gamma \) denotes the centralizer of \( \gamma \in \Gamma \) (that is, the set of elements in \( \Gamma \) commuting with \( \gamma \)) and denote \( J := I \rtimes \Gamma = I \otimes \mathbb{C}[\Gamma] \).

**Proposition 1.13.** Let \( \Gamma \) be a finite group, then \( \widehat{A} \rtimes \Gamma \) is naturally isomorphic to the \( J := I \rtimes \Gamma \)-adic completion of \( A \rtimes \Gamma \) and we have natural isomorphisms \( \text{HH}^\text{top}_q(\widehat{A} \rtimes \Gamma)_\gamma \simeq \text{HH}^\text{top}_q(\widehat{A}_\gamma \rtimes \Gamma)^{C_\gamma} \), \( \text{HC}^\text{top}_q(\widehat{A} \rtimes \Gamma)_\gamma \simeq \text{HC}^\text{top}_q(\widehat{A}_\gamma \rtimes \Gamma)^{C_\gamma} \), and, similarly, \( \text{HP}^\text{top}_q(\widehat{A} \rtimes \Gamma)_\gamma \simeq \text{HP}^\text{top}_q(\widehat{A}_\gamma \rtimes \Gamma)^{C_\gamma} \).

**Proof.** The first statement is a direct consequence of the definitions. Observe that \( \widehat{\mathcal{B}}_\gamma(\widehat{A} \rtimes \Gamma)^{\gamma} = \widehat{A} \rtimes \Gamma \) \( \times \Gamma \) is the same as \( \widehat{A} \rtimes \Gamma \times \Gamma \) and this space admits a known decomposition into conjugacy classes with respect to the action of \( \Gamma \), namely,
\[
\widehat{\mathcal{B}}_\gamma(\widehat{A} \rtimes \Gamma) = \bigoplus_{(\gamma) \in \langle \Gamma \rangle} \widehat{\mathcal{B}}_\gamma(\widehat{A} \rtimes \Gamma)_\gamma,
\]
where \( (a_0, a_1, \ldots, a_n) (g_0, g_1, \ldots, g_n) \in \widehat{\mathcal{B}}_\gamma(\widehat{A} \rtimes \Gamma)_\gamma \) exactly when \( g_0 g_1 \ldots g_n \in \langle \gamma \rangle \).

As in Proposition 1.7, the chain map,
\[
(a_0, a_1, \ldots, a_n) (g_0, g_1, \ldots, g_n) \mapsto \frac{1}{|C_\gamma|} \sum_{h \in C_\gamma} (\gamma h g_0^{-1}(a_0), h(a_1), \ldots, h g_1 g_2 \ldots g_{n-1}(a_n))
\]
now provides an quasi-isomorphism between \( \widehat{\mathcal{B}}_\gamma(\widehat{A} \rtimes \Gamma)_\gamma \) and \( \widehat{\mathcal{B}}_\gamma(\widehat{A}, b_\gamma)^{C_\gamma} \). \( \square \)

We have the following corollary.

**Corollary 1.14.** In the framework of Proposition 1.13, let us assume that \( \gamma \in \Gamma \) acts freely on \( \text{Spec}(k) \). Then
\[
\text{HH}^\text{top}_q(\widehat{A} \rtimes \Gamma)_\gamma = \text{HC}^\text{top}_q(\widehat{A} \rtimes \Gamma)_\gamma = \text{HP}^\text{top}_q(\widehat{A} \rtimes \Gamma)_\gamma = 0.
\]
Proof. Corollary 1.6 gives that $\text{HH}_q(A, \gamma) = 0$ for all $q$. Proposition 1.7 then gives that $\text{HH}_q(A \rtimes \Gamma, \gamma) = 0$ for all $q$. Connes’ SBI-long exact sequence relating the cyclic and Hochschild homologies then gives that $\text{HC}_q(A \rtimes \Gamma, \gamma) = 0$ for all $q$. This in turn implies the vanishing of the periodic cyclic homology. □

2. Crossed products of regular functions

Our focus from now on will be on the case when $A$ is a finitely generated commutative algebra and $\Gamma$ is finite. Goodwillie’s theorem then allows us to reduce to the case when $A = \mathcal{O}[V]$, where $V$ is a complex, affine algebraic variety and where $\mathcal{O}[V]$ is the ring of regular functions on $V$. We will thus concentrate on crossed products of the form $\mathcal{O}[V] \rtimes \Gamma$, where $\Gamma$ is a discrete group acting by automorphisms on $\mathcal{O}[V]$. We begin with a discussion of the case when there is, in fact, no group.

2.1. The commutative case. In this section we recall some known constructions and results, see [4, 15, 33, 34, 35, 47, 53, 54] and the references therein. We mostly follow (and expand) the method in [17], where rather the case of $\mathcal{C}^\infty$-functions was considered. We begin by fixing some notation. As usual, we shall denote by $\Omega^q(X)$ the space of algebraic $q$-forms on a smooth, algebraic variety $X$. If $Y \subset X$ is a smooth subvariety, we denote by $\omega_Y \in \Omega^q(Y)$ the restriction of $\omega \in \Omega^q(X)$ to $Y$.

In this subsection, we will consider affine, complex algebraic varieties $X$ and $V$, where $X$ is assumed to be smooth, $V \subset X$, and $I \subset \mathcal{O}[X]$ is the ideal defining $V$ in $X$. Recall that $\mathcal{O}[X]$ denotes the ring of regular functions on $X$, it is the quotient of a polynomial ring by the ideal defining $X$. Let $g : \mathcal{O}[X] \to \mathcal{O}[X]$ be an endomorphism such that $g^{-1}(I) = I$. We shall denote by $X^g$ the set of fixed points of $g : X \to X$ and assume that it is also a smooth variety. We then let $\chi_g$ be the twisted Connes-Hochschild-Kostant-Rosenberg map $\chi_g : \mathcal{O}[X] \otimes_{n+1} \to \Omega^n(X^g)$,

$$\chi_g(a_0 \otimes \ldots \otimes a_n) \to \frac{1}{n!} a_0 da_1 \ldots da_n |_{X^g},$$

where the restriction to $X^g$ is defined because $X^g$ is smooth. The map $\chi_g$ descends to a map

$$\chi_g : \text{HH}_n(\mathcal{O}[X], g) \to \Omega^n(X^g), \quad n \geq 0,$$

for any fixed $n$. When $g = 1$, the identity automorphism, the map $\chi_g$ is known to be an isomorphism for each $n$ [54]. This fundamental result has been proved in the smooth, compact manifold case in [22]. See also [42, 43, 49, 53].

We want to identify the groups $\text{HH}_n(A, g)$, $A = \mathcal{O}[X]$, and their completions with respect to the powers of $I^n$. The idea is to first use localization to reduce to the case when $X$ is a vector space, $X = \mathbb{C}^N$, and $g$ acts linearly on $\mathbb{C}^N$. In that case, the calculation is achieved by constructing a more appropriate free resolution of the module $A_g$ with free $A^e$ modules using Koszul complexes (here $A = \mathcal{O}[X]$).

While the proof is rather lengthy, it is standard and follows a well understood path in algebraic geometry and commutative algebra. However, this path is not so well known and understood when it comes to cyclic homology calculations, so we include all the details for the benefit of the reader. The reader with more experience (or less patience), can skip directly to Proposition 2.16. Our first step is to construct the relevant Koszul complex.

Definition 2.1. Let $R$ be a commutative complex algebra, $M$ be an $R$-module, $E$ be a finite dimensional complex vector space, and $f : E \to R$ be a linear map.
Then to this data we associate the Koszul complex \((K_\ast, \partial) = (K_\ast(M, E, f), \partial)\), with differential \(\partial : K_j \to K_{j-1}\), defined by

\[
K_j = K_j(M, E, f) := M \otimes \wedge^j E \quad \text{and}
\]

\[
\partial(m \otimes e_{i_1} \wedge \ldots \wedge e_{i_j}) = \sum_{k=1}^{j} (-1)^{k-1} f(e_{i_k}) m \otimes e_{i_1} \wedge \ldots \wedge \widehat{e}_{i_k} \wedge \ldots \wedge e_{i_j},
\]

where \(m \in M\) and \(e_1, \ldots, e_n\) is an arbitrary basis of \(E\).

In the rest of this subsection, by \(E\) and \(F\), sometimes decorated with indices, we shall denote finite-dimensional, complex vector spaces. The definition above is correct as explained in the following remark.

**Remark 2.2.** The definition of the differential in the Koszul complex is, in fact, independent of the choice of a basis of \(E\). Indeed, if we denote by \(i_\xi : \wedge^j E \to \wedge^{j-1} E\) the contraction with \(\xi \in E^*\), then \(\partial = \sum_j f(e_j) \otimes i_{e_j^*}\), where \(e_j^*\) is the dual basis of \(e_j\), and this definition is immediately seen to be independent of the choice of the basis \((e_j)\) of \(E\).

We need to look first at the simplest instances of Koszul complexes.

**Example 2.3.** Let \(E = \mathbb{C}\). Then \(f : E \to R\) is completely determined by \(r := f(1) \in R\). Then, up to an isomorphism, \(K_\ast(R, \mathbb{C}, f)\) is the complex

\[
0 \leftarrow M \leftarrow 0 \leftarrow 0 \leftarrow \ldots
\]

that has only two non-zero modules: \(K_0 \simeq K_1 \simeq M\). We are, in fact most interested in the case \(M = R = 0[\mathbb{C}] \simeq \mathbb{C}[x]\) (we identify the ring of polynomial functions on \(\mathbb{C}\) with the ring of polynomials in one indeterminate \(x\)) and \(r = f(1) = x\), in which case the Koszul complex \(K_\ast(\mathbb{C}[x], \mathbb{C}, x)\) provides a free resolution of the \(\mathbb{C}[x]\)-module \(\mathbb{C} \simeq \mathbb{C}[x]/x\mathbb{C}[x]\) (thus on \(\mathbb{C}\) we consider the \(\mathbb{C}[x]\)-module structure given by “evaluation at 0”, that is, \(P \cdot \lambda = P(0)\lambda\) for \(P \in \mathbb{C}[x]\) and \(\lambda \in \mathbb{C}\). This identifies the homology of \(K_\ast(\mathbb{C}[x], \mathbb{C}, 0)\) as being \(\mathbb{C}\), concentrated in degree zero, and the isomorphism is given by evaluation at zero. The other case in which we are interested is the complex \(K_\ast(\mathbb{C}[x], \mathbb{C}, 0)\), in which case, its homology coincides with \(K_\ast(\mathbb{C}[x], \mathbb{C}, x)\) itself, because the differential is zero.

We treat the other Koszul complexes that we need by combining the two basic examples considered in Example 2.3 above, using also the functoriality of the Koszul complex. In all our applications, we will have \(M = R\), so we assume from now on that this is the case. The next remark deals with functoriality.

**Remark 2.4.** First, a ring morphism \(\phi : R \to R_1\) induces a morphism of complexes

\[
\phi_* : K_\ast(R, E, f) \to K_\ast(R_1, E, \phi \circ f)
\]

given by the formula \(\phi_*(r \otimes e_{i_1} \wedge \ldots \wedge e_{i_j}) = \phi(r) \otimes e_{i_1} \wedge \ldots \wedge e_{i_j}\). Then we notice also that a linear map \(g : E_1 \to E\) induces a natural morphism of complexes

\[
g_* : K_\ast(R, E_1, f \circ g) \to K_\ast(R, E, f)
\]

given by the formula \(g_*(r \otimes e_{i_1} \wedge \ldots \wedge e_{i_j}) = r \otimes g(e_{i_1}) \wedge \ldots \wedge g(e_{i_j})\). If \(g\) is an isomorphism, then \(g_*\) is an isomorphism as well.

Let us denote by \(\otimes\) the graded tensor product of complexes. Koszul complexes can be simplified using the following well known lemma whose proof is a direct calculation.
**Lemma 2.5.** Assume that $R = R_1 \otimes R_2$, that $E = E_1 \oplus E_2$, that $f_i : E_i \to R_i$ are linear $i = 1, 2$, and that $f = f_1 \otimes 1 + 1 \otimes f_2 := (f_1 \otimes 1, 1 \otimes f_2)$. Then

$$K_* (R, E, f) \simeq K_* (R_1, E_1, f_1) \otimes K_* (R_2, E_2, f_2).$$

Let $E$ be a vector space and let $E^*$ be its dual. We denote by $\mathcal{O}[E]$ the ring of regular functions on $E$, as usual. In this case, $\mathcal{O}[E]$ is isomorphic to the ring of polynomial functions in $\dim(E)$ variables. Then there is a natural inclusion

$$i : E^* \to \mathcal{O}[E].$$

Although we shall not use that, let us mention, in order to provide some intuition, that the differential of the resulting Koszul complex $K_* (\mathcal{O}[E], E^*, i)$ is the Fourier transform of the standard de Rham differential. Its homology is given by the following lemma. (Recall that in this subsection $E$ and $F$, decorated sometimes with indices, denote finite-dimensional, complex vector spaces.)

**Lemma 2.6.** Let $i : E^* \to \mathcal{O}[E]$ be the canonical inclusion. Then the resulting complex $K_* (\mathcal{O}[E], E^*, i)$ has homology

$$H_q K_* (\mathcal{O}[E], E^*, i) \simeq \begin{cases} 0 & \text{if } q > 0 \\ \mathbb{C} & \text{if } q = 0 \end{cases},$$

with the isomorphism for $q = 0$ being given by the evaluation at $0 \in E$ morphism, namely, by $K_0 (\mathcal{O}[E], E^*, i) \mathcal{O}[E] \to \mathbb{C}$.

**Proof.** We can assume that $E = \mathbb{C}^n$, by the functoriality of the Koszul complexes (Remark 2.4). If $n = 1$, we may identify $\mathcal{O}[E] = \mathbb{C} [x]$, in which case the result has already been proved (see Example 2.3). In general, we can proceed by induction by writting $\mathbb{C}^n = \mathbb{C}^{n-1} \oplus \mathbb{C}$ and using the fact that the Koszul complex associated to $E = \mathbb{C}^n$ is the tensor product of the Koszul complexes associated to $\mathbb{C}^{n-1}$ and $\mathbb{C}$ and then invoquing Lemma 2.5. The calculation of the homology groups is completed using the Künneth formula, which gives that the homology of a tensor product of complexes (over $\mathbb{C}$) is the tensor product of the individual homologies $[56, 37]$. $\square$

It is useful to state explicitly the following direct consequence of the above lemma and of the functoriality of the Koszul complexes (Remark 2.4).

**Corollary 2.7.** Let $R = \mathcal{O}[F]$ and let $g : E \to F^*$ be an isomorphism. Let $R_1$ be a commutative complex algebra. Denote by $f := i \circ g : E \to \mathcal{O}[F]$, then

$$H_q K_* (R \otimes R_1, E, f) \simeq \begin{cases} 0 & \text{if } q > 0 \\ R_1 & \text{if } q = 0 \end{cases},$$

with the isomorphism for $q = 0$ being induced by the the evaluation at $0 \in F$ morphism $K_0 (R \otimes R_1, E, f) = R \otimes R_1 = \mathcal{O}[F] \otimes R_1 \to \mathbb{C} \otimes R_1 = R_1$.

Most of the time, the above corollary will be used for $R_1 = \mathbb{C}$. We now prove the result that we need for Künneth complexes.

**Proposition 2.8.** Let $h : E_1 \to E^*$ be a linear map and $f := i \circ h : E_1 \to \mathcal{O}[E]$, where $i : E^* \to \mathcal{O}[E]$ is the canonical inclusion. Denote by $F \subset E$ the annihilator of $h(E_1) \subset E^*$ and by $F_1 \subset E_1$ the kernel of $h$. Then the restriction morphism $\mathcal{O}[E] \to \mathcal{O}[F]$ and the choice of a projection $E_1 \to F_1$ define isomorphisms

$$\text{res} : H_q K_* (\mathcal{O}[E], E_1, f) \simeq H_q K_* (\mathcal{O}[F], F_1, 0) = \mathcal{O}[F] \otimes \wedge^q F_1.$$

These isomorphisms are independent of the choice of the projection $E_1 \to F_1$. 
Proof. Let \( F'_1 \) be the kernel of the chosen projection \( E_1 \to F_1 \), which thus gives a direct sum decomposition \( E_1 = F_1 \oplus F'_1 \). Similarly, let us chose a complement \( F' \) to \( F \) in \( E \), which also gives a direct sum decomposition \( E = F \oplus F' \). Then we obtain that \( \mathcal{O}[E] = \mathcal{O}[F] \otimes \mathcal{O}[F'] \) and that the map \( f \) splits as \( f_1 \otimes 1 + 1 \otimes f_2 \), \( f_1 : F_1 \to \mathcal{O}[F] \), \( f_2 : F'_1 \to \mathcal{O}[F'] \), with \( f_1 = 0 \) and with \( f_2 \) obtained from a linear isomorphism \( F'_1 \to (F')^* \). Then Lemma 2.5 gives that \( \mathcal{K}_*(\mathcal{O}[E], E_1, f) \simeq \mathcal{K}_*(\mathcal{O}[F], F_1, 0) \otimes \mathcal{K}_*(\mathcal{O}[F'], F'_1, f_2) \). The homology of the last complex is given by Corollary 2.7 with \( R_1 = \mathbb{C} \) and is seen to be \( \mathbb{C} \) in dimension zero and zero in the other dimensions. This gives the desired result since \( \mathcal{K}_*(\mathcal{O}[F], F_1, 0) \) has vanishing differentials. \( \square \)

**Corollary 2.9.** Let \( h : E^* \to E^* \) be a linear map that induces an injective map \( E^*/\ker(h) \to E^*/\ker(h) \). Let \( f := i \circ h : E^* \to \mathcal{O}[E] \), where \( i : E^* \to \mathcal{O}[E] \) is the inclusion. Denote by \( \mathcal{F} \) the restriction morphisms \( \mathcal{O}[E] \to \mathcal{O}[F] \) and \( E^* \to F^* \) define isomorphisms

\[
\text{res}_g : H_q \mathcal{K}_*(\mathcal{O}[E], E^*, f) \simeq H_q \mathcal{K}_*(\mathcal{O}[F], F^*, 0) = \mathcal{O}[F] \otimes \wedge^q F^* = \mathcal{O}^q[F].
\]

Proof. This follows from Proposition 2.8 for \( E_1 = E^* \) as follows. First of all, by assumption, we have that \( F_1 := \ker(h : E^* \to E^*) \) has \( h(E^*) \) as complement. We shall therefore choose the projection \( E^* \to F_1 \) to vanish on \( h(E^*) \). But \( E^*/h(E^*) \simeq F^* \) naturally, by restricting linear forms on \( E \) to \( F \), since \( F \) was defined as the annihilator of \( h(E^*) \). Thus \( F_1 \cong F^* \) and the projection \( E^* \to F_1 \) becomes simply the restriction \( E^* \to F^* \). \( \square \)

Koszul complexes are relevant for Hochschild homology through the following lemma that is also well known [54]. We denote as usual by \( S_q \) the group of permutations of the set \( \{1, \ldots, q\} \), \( q \geq 1 \).

**Lemma 2.10.** Let \( i : E^* \to \mathcal{O}[E] \) be the canonical inclusion and \( \delta : E^* \to R^e := R \otimes R \) be given by the formula \( \delta(\xi) = i(\xi) \otimes 1 - 1 \otimes i(\xi) \). Then the Koszul complex \( \mathcal{K}_*(R^e, E^*, \delta) \) is a resolution of \( R \) by projective \( R^e \)-modules. Fix a basis \( e_1, \ldots, e_n \) of \( E^* \) and define \( \kappa_0 : \mathcal{K}_*(R^e, E^*, \delta) \to (\mathcal{B}_e(R), b') \) by the formula

\[
\kappa_0(a_1 \otimes a_2 \otimes e_{j_1} \wedge \ldots \wedge e_{j_p}) := \sum_{\sigma \in S_p} \text{sign}(\sigma) a_1 \otimes i(e_{j_{\sigma(1)}}) \otimes \ldots \otimes i(e_{j_{\sigma(p)}}) \otimes a_2.
\]

Then \( \kappa_0 \) is a chain map, that is, \( \kappa_0 \partial = b' \kappa_0 \).

We provide a proof in our setting, for the benefit of the reader.

Proof. Recall that \( R \) is commutative, so \( R^{op} = R \), and hence the notation \( R^e = R \otimes R \) is justified. The Koszul complex \( \mathcal{K}_*(R^e, E^*, \delta) \) is a resolution of \( R \) by projective \( R^e \)-modules by Corollary 2.7 applied to \( R_1 = \mathcal{O}[E] \) and the decomposition \( R^e \simeq R_2 \otimes R_1 \), where \( R_2 \) is the polynomial ring generated by the image of \( \delta \). \( R_1 \) is the polynomial ring generated by vectors of the form \( i(\xi) \otimes 1 + 1 \otimes i(\xi) \), \( \xi \in E \), and \( R_1 \simeq R_2 \simeq R \). The fact that \( \kappa_0 \) is a chain map is a direct calculation. \( \square \)

We then obtain

**Corollary 2.11.** Let \( g : E \to E \) be linear and \( f := i \circ (g^* - 1) : E^* \to E^* \subset \mathcal{O}[E] \). Let us denote also by \( g \) the endomorphism of \( \mathcal{O}[E] \) induced by \( g \). Using the notation
of Lemma 2.10, we have that \( \kappa_E : (K_*(R, E^*, f), \partial) \to (B_*(R), b_g) \)

\[
\kappa_E(a \otimes e_{j_1} \wedge \ldots \wedge e_{j_p}) := \sum_{\sigma \in S_p} \text{sign}(\sigma) a \otimes i(e_{j_{\sigma(1)}}) \otimes i(e_{j_{\sigma(2)}}) \otimes \ldots \otimes i(e_{j_{\sigma(p)}})
\]

is a quasi-isomorphism (that is, \( \kappa_E \partial = b_g \kappa_E \), and it induces an isomorphism of homology groups).

**Proof.** Denote \( R := \mathcal{O}[E] \), as above. The groups \( \text{HH}_q(R, g) \) can be obtained from any projective resolution of \( R \) as a \( R^e \) module by tensoring this projective resolution with \( R_g \) over \( R_e \), by Proposition 1.2. We shall use to this end the resolution of Lemma 2.10. Thus \( \text{HH}_q(R, g) \) are the homology groups of the complex

\[
(K_*(R^e, E^*, \delta) \otimes_{R \otimes_R R_g} \mathcal{O}_g, \partial \otimes 1).
\]

By the functoriality of the Koszul complex (Remark 2.4), this tensor product is nothing else but the Koszul complex \( K_* \). Let \( \kappa_0 \) be as in the statement of Lemma 2.10. We have then that \( \kappa_0 \otimes_{R \otimes_R R_g} \mathcal{O}_g = \kappa_E \). Since \( \kappa_0 \) is a morphism of projective resolutions by Lemma 2.10, it follows that \( \kappa_E \) is a quasi-isomorphism by standard homological algebra. \( \square \)

We shall need the following lemma, which is a particular case of Proposition 2.16. Some closely related results with a Hopf algebra flavor can be found in [34] and some applications of it to deformation of algebras are given in [76].

**Lemma 2.12.** We use the notation of Corollary 2.11 and assume that \( g - 1 : E/\ker(g - 1) \to E/\ker(g - 1) \) injective. Let \( E^g := \ker(g - 1) \). Then the restriction \( \mathcal{O}[E] \to \mathcal{O}[E^g] \) defines isomorphisms

\[
\text{res}_{\text{HH}} : \text{HH}_q(\mathcal{O}[E], g) \to \text{HH}_q(\mathcal{O}[E^g]),
\]

and hence the twisted Connes-Hochschild-Kostant-Rosenberg map \( \chi_g \) of Equation (13) gives isomorphisms

\[
\chi_g : \text{HH}_q(\mathcal{O}[E], g) \cong \Omega^q(E^g).
\]

**Proof.** Let \( R = \mathcal{O}[E] \), as before and \( f := g^* - 1 \). Corollary 2.11 gives that the groups \( \text{HH}_q(\mathcal{O}[E], g) \) are isomorphic to the homology groups of the Koszul complex \( (K_*(R, E^*, f), \partial) \). Since the annihilator of \( (g^* - 1)(E^*) \) is \( \ker(g - 1) =: E^g \), we have by Corollary 2.11 that the homology groups of this Koszul complex are the same as those of the Koszul complex \( (K_*(\mathcal{O}[E^g], (E^g)^*, 0) \), with the isomorphism being given by restriction from \( E \) to \( E^g \), a map that we will denote \( \text{res}_K : K_*(\mathcal{O}[E], E^*, f) \to K_*(\mathcal{O}[E^g], (E^g)^*) \).

Let us denote by \( \text{res}_B : (B(\mathcal{O}[E]), b_g) \to (B(\mathcal{O}[E^g]), b_g) \) the natural map given by restriction. Then we have that the restriction maps \( \text{res}_B \) and the restriction map \( \text{res}_K \) just defined satisfy \( \text{res}_B \circ \kappa_E = \kappa_{E^g} \circ \text{res}_K \), with the maps \( \kappa \) as in Corollary 2.11. That same corollary gives that \( \kappa_E \) are \( \kappa_{E^g} \) quasi-isomorphisms. Since \( \text{res}_K \) is also a quasi-isomorphisms, we obtain that \( \text{res}_B \) is a quasi-isomorphism as well. Recall that \( \text{res}_{\text{HH}} \) is the map induced at the level of homology by \( \text{res}_B \). That means that \( \text{res}_{\text{HH}} \) is an isomorphism and hence proves the first half of our statement.

To prove the last part of our statement, we first notice that the Connes-Hochschild-Kostant-Rosenberg map is an isomorphism \( \chi : \text{HH}_q(\mathcal{O}[E^g]) \to \Omega^q(E^g) \). Hence so is \( \chi_g \), as the composition \( \chi_g := \chi \circ \text{res}_B \). \( \square \)
2.2. Completion at a maximal ideal. For the rest of this paper, we shall use completions extensively. Let us fix a maximal ideal \( m \) of our base ring \( k \). We denote by \( \hat{k}_m \) the completion of \( k \) with respect to \( m \): \( \hat{k}_m := \lim_{\leftarrow} k/m^n k \). For the rest of this subsection, all completions will be with respect to \( m \), and this will be stressed by including \( m \) as an index. Thus, for any \( k \)-module \( M \), we shall denote by
\[
\hat{M}_m := \lim_{\leftarrow} M/m^n M
\]
the completion of \( M \) with respect to the topology defined by the ideal \( m \subset k \). We notice that the completion \( \hat{M}_m \) is naturally a \( \hat{k}_m \)-module, and hence we obtain a natural map \( \text{comp} : M \otimes_k \hat{k}_m \to \hat{M}_m \). In case \( M \) is finitely generated as a \( k \)-module (always the case in what follows), then \( \text{comp} : M \otimes_k \hat{k}_m \to \hat{M}_m \) is an isomorphism [2, 10], which will be used as an identification from now on. Thus, in order not to overburden the notation, we shall drop \( \text{comp} \) from the notation and simply identify \( \hat{M}_m \) and \( M \otimes_k \hat{k}_m \).

**Remark 2.13.** We know that every element \( x \in k \setminus m \) is invertible in \( \hat{k}_m \) by writing a convergent Neumann series for its inverse. Therefore, for every \( k \)-module \( M \), the canonical map \( M \to \hat{M}_m \) factors through \( M_m := (k \setminus m)^{-1}M \), that is, it is the composition of the canonical maps \( M \to M_m \to \hat{M}_m \). In particular, if \( M_m = 0 \), then \( \hat{M}_m = 0 \), since the image of \( M_m \) in \( \hat{M}_m \) is dense. Moreover, we see that completion with respect to \( m \) and localization at \( m \) commute, so there is no danger of confusion in the notation \( \hat{M}_m \); that is, \( (\hat{M})_m = (\hat{M}_m) \).

**Remark 2.14.** If \( f : M \to N \) is a morphism of \( k \)-modules, we shall denote by \( \hat{f}_m : \hat{M}_m \to \hat{N}_m \) the induced morphism of the corresponding completions with respect to the topology defined by the powers of \( m \). If \( M \) and \( N \) are finitely generated, we shall make no difference between \( \hat{f}_m : \hat{M}_m \to \hat{N}_m \) and \( f \otimes_k 1 : M \otimes_k \hat{k}_m \to N \otimes_k \hat{k}_m \).

Assume \( M \) and \( N \) are finitely generated \( k \)-modules. Then it is a standard result in commutative algebra that \( f \) is an isomorphism if, and only if, \( \hat{f}_m \) is an isomorphism for all maximal ideals \( m \) of \( A \) [2, 10].

Let \( A \) be a finite type \( k \) algebra. We let
\[
\text{can} : \text{HH}_\ast(A, g) \otimes_k \hat{k}_m \cong \text{HH}_\ast^{\text{top}}(\hat{A}_m, g)
\]
denote the canonical isomorphism of Theorem 1.10. It is obtained from the fact that \( \text{HH}_\ast^{\text{top}}(\hat{A}_m, g) \) is a \( \hat{k}_m \)-module using also the natural map \( \text{HH}_\ast(A, g) \to \text{HH}_\ast^{\text{top}}(\hat{A}_m, g) \) induced by the inclusion \( A \to \hat{A}_m \). We shall use the map \( \text{can} \) in the following corollary in the following setting: \( E \) will be a finite dimensional, complex vector space, \( k := \mathcal{O}[E] \), and \( m \) will be the maximal ideal of \( k := \mathcal{O}[E] \) corresponding to functions vanishing at \( 0 \). Then we shall consider, as explained, the filtrations defined by \( m \) and in the completions of \( \mathcal{O}[E] \) and \( \mathcal{O}[E^g] \) with respect to the filtrations defined by the powers of \( m \).

The following corollary is an analog of Lemma 2.12 for completed algebras.

**Corollary 2.15.** We use the notation and assumptions of Lemma 2.12, in particular, \( g \) is a linear endomorphism of \( E \) such that \( g - 1 : E / \ker(g - 1) \to E / \ker(g - 1) \) is injective. Let \( m \) be the maximal ideal of \( k := \mathcal{O}[E] \) corresponding to functions vanishing at \( 0 \). Then the restriction \( \hat{\mathcal{O}}[E]_m \to \hat{\mathcal{O}}[E^g]_m \) defines an isomorphism
\[
\hat{\text{res}}_{\text{HH}} : \text{HH}_q^{\text{top}}(\hat{\mathcal{O}}[E]_m, g) \to \text{HH}_q^{\text{top}}(\hat{\mathcal{O}}[E^g]_m)
\]
Define $\hat{\chi}_g$ by $\chi_g \circ \text{can} = \chi_g \otimes_k 1$. Then we have an isomorphism

$$\hat{\chi}_g : \text{HH}^{\text{top}}_q(\widehat{\mathcal{O}[E]}_m, g) \cong \widehat{\Omega^q(E^g)}_m := \lim_{\longrightarrow} \Omega^q(E^g)/m^n\Omega^q(E^g).$$

As the notation suggests, $\hat{\chi}_g$ is, up to canonical identifications, nothing but the extension by continuity (or completion) of the usual Connes-Hochschild-Kostant-Rosenberg map.

Proof. For the first part of the proof, let us denote for any $k$-algebra $A$ by $\text{nat}$ the natural map $\text{HH}_q(A, g) \to \text{HH}^{\text{top}}_q(\widehat{A}, g)$. Hence $\text{can} = \text{nat} \otimes_k 1$, see Equation (18).

Let us consider then the diagram

$$\begin{array}{ccc}
\text{HH}_q(\mathcal{O}[E], g) & \xrightarrow{\text{res}_{\text{HH}}} & \text{HH}_q(\mathcal{O}[E^g]) \\
\text{nat} & & \text{nat} \\
\text{HH}^{\text{top}}_q(\mathcal{O}[E], g) & \xrightarrow{\text{res}_{\text{HH}}} & \text{HH}^{\text{top}}_q(\mathcal{O}[E^g]) \\
\end{array}$$

whose arrows are given by the natural morphisms of the corresponding algebras and hence is commutative. That is, we have the relation $\text{nat} \circ \text{res}_{\text{HH}} = \text{res}_{\text{HH}} \circ \text{nat}$, which gives then the relation $\text{can} \circ (\text{res}_{\text{HH}} \otimes_k 1) = \text{res}_{\text{HH}} \circ \text{can}$, that is, that the diagram

$$\begin{array}{ccc}
\text{HH}_q(\mathcal{O}[E], g) \otimes_k \hat{k}_m & \xrightarrow{\text{res}_{\text{HH}} \otimes_k 1} & \text{HH}_q(\mathcal{O}[E^g]) \otimes_k \hat{k}_m \\
\text{can} & & \text{can} \\
\text{HH}^{\text{top}}_q(\mathcal{O}[E], g) \otimes_k \hat{k}_m & \xrightarrow{\text{res}_{\text{HH}}} & \text{HH}^{\text{top}}_q(\mathcal{O}[E^g]) \otimes_k \hat{k}_m
\end{array}$$

is commutative. The map $\text{res}_{\text{HH}} : \text{HH}_q(\mathcal{O}[E], g) \to \text{HH}_q(\mathcal{O}[E^g])$ is an isomorphism by Lemma 2.12. Therefore $\text{res}_{\text{HH}} \otimes_k 1 : \text{HH}_q(\mathcal{O}[E], g) \otimes_k \hat{k}_m \to \text{HH}_q(\mathcal{O}[E^g]) \otimes_k \hat{k}_m$ is an isomorphism as well. Since the vertical arrows (that is, the maps $\text{can}$) are isomorphisms, we obtain that $\text{res}_{\text{HH}}$ is an isomorphism as well.

The fact that $\hat{\chi}_g$ is an isomorphism follows from the commutative diagram

$$\begin{array}{ccc}
\text{HH}_q(\mathcal{O}[E], g) \otimes_k \hat{k}_m & \xrightarrow{\chi_g \otimes_k 1} & \Omega^q(E^g) \otimes_k \hat{k}_m \\
\text{can} & & \text{can} \\
\text{HH}^{\text{top}}_q(\mathcal{O}[E], g) \otimes_k \hat{k}_m & \xrightarrow{\hat{\chi}_g} & \widehat{\Omega^q(E^g)}_m
\end{array}$$

(that is, $\hat{\chi}_g \circ \text{can} = \chi_g \otimes_k 1$) and the fact that $\text{can}$ and $\chi_g$ are isomorphisms.

In plain terms, one has that $\hat{\chi}_g$ is an isomorphism since it is the completion of an isomorphism.

We now come back to the case of a general smooth, complex algebraic variety $X$. We obtain the following result (due to Brylinski in the case of the algebra of smooth functions [15]). See also [30].

**Proposition 2.16.** Let $X$ be a smooth, complex, affine algebraic variety and $g$ an endomorphism of $\mathcal{O}[X]$ such that $X^g$ is also a smooth algebraic variety and such that, for any fixed point $x \in X^g$, $T_xX^g$ is the kernel of $g_x - 1$ acting on $T_xX$ and $g_x - 1$ induces an injective endomorphism of $T_xX/T_xX^g$. Then the twisted Connes-Hochschild-Kostant-Rosenberg map $\chi_g$ induces isomorphisms

$$\chi_g : \text{HH}_q(\mathcal{O}[X], g) \cong \Omega^q(X^g).$$
Proof. Recall that we agreed to identify \( \hat{M}_m \) with \( M \otimes_k \hat{k}_m \), provided that \( M \) is finitely generated. However, in this proof, it will be convenient to work with the tensor product \( M \otimes_k \hat{k}_m \) rather than with the completion \( \hat{M}_m \), for notational simplicity. Denote \( k = \mathcal{O}[X] \) and let \( m \) be an arbitrary maximal ideal of \( k \). For the clarity of the presentation, we shall write in this proof \( \chi^X_g \) instead of simply \( \chi_g \). As explained in Remark 2.14, it is enough to check that the map

\[
\chi^X_g \otimes_k 1 : \mathrm{HH}_q(\mathcal{O}[X], g) \otimes_k \hat{k}_m \to \Omega^q(X^g) \otimes_k \hat{k}_m.
\]

is an isomorphism (since the maximal ideal \( m \) of \( A \) was chosen arbitrarily). We shall now check that this property is satisfied.

Indeed, if \( m \) is not fixed by \( g \) (recall that the maximal ideals \( m \) of \( \mathcal{O}[X] \) and the points of \( X \) are in one-to-one correspondence), then \( \chi^X_g \otimes_k 1 \) is an isomorphism since both groups in Equation (22) are zero, by Corollary 1.6 and Remark 2.13.

Let us therefore assume that \( m \) is fixed by \( g \) and denote by \( E := (m/m^2)^* \) the tangent space to \( X \) at \( m \). The assumption that \( X \) is smooth at \( m \) means, by definition [40], that we have a natural isomorphism \( \tan : \mathcal{O}[X]_m \simeq \mathcal{O}[E]_m \). Similarly, we have a natural isomorphism

\[
\Omega^q(X^g) \otimes_k \hat{k}_m \simeq \hat{\Omega}^q(X^g)_m \simeq \hat{\Omega}^q(E^g)_m \simeq \Omega^q(E^g) \otimes_k \hat{k}_m,
\]

which we shall also denote by \( \tan \).

Recall that the canonical map \( \text{can} : \mathrm{HH}_q(\mathcal{O}[X], g) \otimes_k \hat{k}_m \to \mathrm{HH}_q^{\text{top}}(\hat{\mathcal{O}}[X]_m, g) \) is an isomorphism (by Theorem 1.10) and consider then the commutative diagram

\[
\begin{array}{ccc}
\mathrm{HH}_q(\mathcal{O}[X], g) \otimes_k \hat{k}_m & \xrightarrow{\chi^X_g \otimes_k 1} & \Omega^q(X^g) \otimes_k \hat{k}_m \\
\downarrow \text{can} & & \uparrow \text{id} \\
\mathrm{HH}_q^{\text{top}}(\hat{\mathcal{O}}[X]_m, g) & \xrightarrow{\hat{\chi}^X_g} & \hat{\Omega}^q(X^g)_m \\
\downarrow \text{tan} & & \downarrow \text{tan} \\
\mathrm{HH}_q^{\text{top}}(\hat{\mathcal{O}}[E]_m, g) & \xrightarrow{\hat{\chi}^E_g} & \hat{\Omega}^q(E^g)_m
\end{array}
\]

in which the vertical arrows are isomorphisms as explained.

In order to complete the proof, it is enough to check that the bottom horizontal arrow is also an isomorphism. The problem is that \( g \) is not a linear map. Let us denote by \( D_g : T_m E \to T_m E \) the differential of the map \( g \) at \( m \) and consider the chain maps

\[
\chi^E_g : (B_*(\mathcal{O}[E]), b_g) \to (\Omega^*(E^g), 0) \quad \text{and} \quad \chi^E_{Dg} : (B_*(\mathcal{O}[E]), b_{Dg}) \to (\Omega^*(E^g), 0)
\]

of filtered complexes (with the filtration defined by the powers of \( m \)). The second map is a quasi-isomorphism by Corollary 2.15. Recall that each of the three filtered complexes in Equation (24) gives rise to a spectral sequence with \( E^1 \) term given as the homology of the subquotient complexes. We have that the corresponding \( E^1 \)-terms and maps between these \( E^1 \)-terms depend only on \( Tg \). Since \( \chi^E_{Dg} \) induces a quasi-isomorphism, the result follows from Lemma 1.9.

We note that the assumptions of our proposition are satisfied for \( g \) a finite order automorphism.
We have the following analog of a result of [43] (see also [11] Theorem 4.8), where from now on the completions are with respect to an ideal \( I \), and hence the subscript \( m \) will be dropped from the notation.

**Theorem 2.17.** Let \( A = \mathcal{O}[X] \) with \( X \) a complex, smooth, affine algebraic variety, \( V \subset X \) a subvariety with ideal \( I \) and \( g \) finite order automorphism of \( \mathcal{O}[X] \) that leaves \( V \) invariant. Then the twisted Connes-Hochschild-Kostant-Rosenberg map \( \chi_g \) induces an isomorphism

\[
\chi_g : \text{HH}^\text{top}_q(\widehat{\mathcal{O}[X]}, g) \cong \widehat{\Omega}^q(V^g) := \lim_{\rightarrow} \Omega^q(X^g)/I^n\Omega^q(X^g),
\]

where the completions are taken with respect to the powers of \( I \).

*Proof.* This follows by taking the \( I \)-adic completion of the map \( \chi_g \) of Proposition 2.16 and then using Theorem 1.10. \( \square \)

### 2.3. Crossed products

We now return to crossed products. The cyclic homology of crossed products was extensively studied due to its connections with noncommutative geometry [23]. See [1, 20, 44, 57, 65, 83, 85, 88] for a few recent results. The homology of cross-product algebras was studied recently by Dave in relation to residues [29] and by Manin and Marcolli in relation to arithmetic geometry [59]. In this section, we compute the homology of \( \mathcal{O}[X] \times_\Gamma \) for \( X \) an algebraic variety (not necessarily smooth) and \( \Gamma \) a finite group. The idea is to reduce to the case when \( V \) is the affine space \( \mathbb{C}^n \) acted upon linearly by \( \Gamma \). In this case the Hochschild and cyclic homology groups of \( \mathcal{O}[V] \times_\Gamma \) were computed in [34, 76], but we need a slight enhancement of those results, which are provided by the results of the previous subsection.

Let us therefore fix an affine, complex algebraic variety \( V \) and let \( \Gamma \) be a finite group acting by automorphisms on \( \mathcal{O}[V] \). Let us choose a \( \Gamma \)-equivariant embedding \( V \to X \), where \( X \) is a smooth, affine algebraic variety on which \( \Gamma \) acts by regular maps. Propositions 1.7 and 2.16 then give the following result (see also [30, 34, 76]).

**Proposition 2.18.** Let \( \Gamma \) be a finite group acting on a smooth, complex, affine algebraic variety \( X \) and \( \{\gamma_1, \ldots, \gamma_\ell\} \) be a list of representatives of its conjugacy classes. We denote by \( C_j \) the centralizer of \( \gamma_j \), and by \( X_j \) be the set of fixed points of \( \gamma_j \). Then

\[
\text{HH}^q(\mathcal{O}[X] \times_\Gamma) \cong \bigoplus_{j=1}^\ell \Omega^q(X_j)^{C_j},
\]

\[
\text{HC}^q(\mathcal{O}[X] \times_\Gamma) \cong \left( \bigoplus_{j=1}^\ell \Omega^q(X_j)^{C_j}/d\Omega^{q-1}(X_j)^{C_j} \oplus \bigoplus_{k \geq 1} H^{q-2k}(X_j)^{C_j} \right),
\]

and

\[
\text{HP}^q(\mathcal{O}[X] \times_\Gamma) \cong \bigoplus_{j=1}^\ell \bigoplus_{k \in \mathbb{Z}} H^{q-2k}(X_j)^{C_j}.
\]

*Proof.* The result for Hochschild homology follows from Propositions 1.7 and 2.16. Let \( g = \gamma_j \), for some \( j \). The result for Hochschild homology, together with the equation \( \chi_g B_g = d\chi_g \), with \( d \) the de Rham differential, then gives the other isomorphisms using a standard argument based on mixed complexes. Mixed complexes were introduced in [45]. They are also reviewed in [50, 74].
Let us recall now this standard argument based on mixed complexes. For any \( \gamma \in \Gamma \) with centralizer \( C_\gamma \), the twisted Connes-Hochschild-Kostant-Rosenberg map \( \chi_\gamma \) defines a map of mixed complexes
\[
\chi_\gamma : (B_\gamma (O[X])^{C_\gamma}, b_\gamma, B_\gamma) \to (\Omega^*(X)^{C_\gamma}, 0, d),
\]
which is an isomorphism in Hochschild homology by Proposition 2.16. It follows that \( \chi_\gamma \) induces an isomorphism of the corresponding cyclic and periodic cyclic homology groups. Since the cohomology groups of the de Rham complex \( \Omega^*(X) \) identify with \( H^*(X; \mathbb{C}) \), the singular cohomology groups of \( X \) with complex coefficients, [32, 33, 39, 43] and these groups vanish for \( * \) large, the result follows. \( \square \)

Similarly, we obtain

**Theorem 2.19.** Let \( \Gamma \) be a finite group acting on a smooth, complex, affine algebraic variety \( X \) and \( V \subset X \) be a \( \Gamma \)-invariant subvariety. Let \( \{\gamma_1, \ldots, \gamma_\ell\} \) be a list of representatives of conjugacy classes of \( \Gamma \), let \( C_j \) be the centralizer of \( \gamma_j \), and let \( X_j \) and \( V_j \) be the set of fixed points of \( \gamma_j \). We complete with respect to the powers of the ideal \( I \subset O[X] \) defining \( V \) in \( X \). Then we have
\[
\text{HH}_q^{\text{top}}(O[X] \rtimes \Gamma) \cong \bigoplus_{j=1}^\ell \hat{\Omega}^q(X_j)^{C_j},
\]
\[
\text{HC}_q^{\text{top}}(O[X] \rtimes \Gamma) \cong \bigoplus_{j=1}^\ell \left( \hat{\Omega}^q(X_j)^{C_j}/d\hat{\Omega}^{q-1}(X_j)^{C_j} \oplus \bigoplus_{k \geq 1} H^{q-2k}(V_j; \mathbb{C})^{C_j} \right),
\]
and \( \text{HP}_q^{\text{top}}(O[X] \rtimes \Gamma) \cong \bigoplus_{j=1}^\ell \bigoplus_{k \in \mathbb{Z}} H^{q-2k}(V_j; \mathbb{C})^{C_j} \).

**Proof.** The result for Hochschild homology follows from Proposition 1.13 and Theorem 2.17. The rest for is very similar, except that one has to use also the fact that the de Rham complex \( \hat{\Omega}^*(V) := \lim \Omega(X)/\mathcal{H}^*(X) \) endowed with the de Rham differential has cohomology \( H^*_\text{inf}(V) \simeq H^*(V; \mathbb{C}) \) [32, 33, 35, 39, 43]. \( \square \)

This result was obtained in the case of smooth functions in [17]. We now come to our main result. Note that in the following theorem we do not assume the variety \( V \) to be smooth and that we recover the orbifold homology groups. The case when \( \Gamma \) is trivial is due to Feigin and Tsygan [35] (see also Emmanouil’s papers [32, 33] and the references therein) for the case when \( V \) is smooth. See also the paper by Dolgushev and Etinghof [30] and [41]. We do not assume \( V \) to be smooth in the next result.

**Theorem 2.20.** Let \( \Gamma \) be a finite group acting on a complex, affine algebraic variety \( V \). Let \( \{\gamma_1, \ldots, \gamma_\ell\} \) be a list of representatives of conjugacy classes of \( \Gamma \), let \( C_j \) be the centralizer of \( \gamma_j \), and let \( V_j \subset V \) be the set of fixed points of \( \gamma_j \). Then
\[
\text{HP}_q(O[V] \rtimes \Gamma) \cong \bigoplus_{j=1}^\ell \bigoplus_{k \in \mathbb{Z}} H^{q-2k}(V_j; \mathbb{C})^{C_j}.
\]

**Proof.** Let us choose a \( \Gamma \)-equivariant embedding \( V \subset E \) into an affine space. This can be done by first choosing a finite system of generators \( I := \{a_i\} \) of \( O[V] \) and
then replacing it with \( I_{\Gamma} := \{ \gamma a_i \} \), for all \( \gamma \in \Gamma \). We let \( E \) to be the vector space with basis \( \{ \gamma a_i \} \). Let \( I \subset \mathcal{O}[E] \) be the ideal defining \( V \) in \( E \).

We let \( k = \mathcal{O}[E]^I = \mathcal{O}[E/\Gamma] \), then \( k \) is a finitely generated complex algebra by Hilbert’s finiteness theorem \([51]\). Moreover, \( \mathcal{O}[E] \) is a finitely generated \( k \)-module, and hence \( \mathcal{O}[E] \times \Gamma \) is also a finite type \( k \)-algebra. Let \( I_0 := k \cap I \). We also notice that there exists \( j \) such that \( I^j \subset I_0 \mathcal{O}[E] \subset I \). Indeed, this is due to the fact that if a character \( \phi : \mathcal{O}[E] \to \mathbb{C} \) vanishes on \( I_0 \), then it vanishes on \( I \) as well, so \( I \) and \( I_0 \mathcal{O}[E] \) have the same nilradical. To prove this, let us consider \( \phi : \mathcal{O}[E] \to \mathbb{C} \) that vanishes on \( I_0 \) and let \( a \in I \). Since \( a \in I \) and \( I \) is \( \Gamma \)-invariant, the polynomial \( P(X) := \prod_{\gamma \in \Gamma} (X - \gamma(a)) \) has coefficients in \( I \) that are invariant with respect to \( \gamma \), so they are in \( I_0 \). This gives \( \phi(P(X)) = X^n = \prod_{\gamma \in \Gamma} (X - \phi(\gamma(a))), \) with \( n \) the number of elements in \( \Gamma \). Therefore \( \phi(\gamma(a)) = 0 \) for all \( \gamma \). In particular, \( \phi(a) = 0 \).

The fact that there exists \( j \) such that \( I^j \subset I_0 \mathcal{O}[E] \subset I \) gives that completing with respect to \( I \times \Gamma \) or with respect to \( I_0 \) has the same effect. Then \( \mathcal{O}[E] \times \Gamma/\Gamma \times \Gamma \simeq \mathcal{O}[V] \times \Gamma \). Therefore \( HP^q_{\text{per}}(\mathcal{O}[E] \times \Gamma) \simeq HP^q(\mathcal{O}[V] \times \Gamma) \), by Seibert’s theorem (Theorem 1.12). The result then follows from Theorem 2.19. \( \square \)

This theorem extends the calculations for the cross-products of the form \( C^\infty(X) \times \Gamma \), see \([8, 17, 15, 31, 35, 62, 64, 73]\). A similar result exists for orbifolds in the \( C^\infty \)-setting (often the resulting groups are called “orbifold cohomology” groups). It would be interesting to extend our result to “algebraic orbifolds”. Theorem 0.1 now follows right away. Since for a finite type algebra \( A \) and \( \Gamma \) finite, \( A \times \Gamma \) is again a finite type algebra, it would be interesting to compare the result of Theorem 2.20 with the spectral sequence of \([50]\), which are based on the excision exact sequence in cyclic homology \([27, 28, 61]\). Cyclic cohomology for various algebras (among which cross-products play a central role) has played a role in index theory \([6, 23, 25, 24, 52, 67, 71, 72]\).

We can now complete the proof of our main theorems, Theorem 0.1.

**Proof.** (of Theorem 0.1). Let \( I \) be the nilradical of \( A \). Then \( A/I \simeq \mathcal{O}[V] \) and \( I \) is nilpotent. The result then follows from Goodwill’s result, Theorem 1.11 and Theorem 2.20. \( \square \)

**Remark 2.21.** The above result is no longer true if we replace \( A = \mathcal{O}[V] \) with an Azumaya algebra. Indeed, let \( A = M_2(\mathbb{C}) \) and let \( \Gamma := (\mathbb{Z}/2\mathbb{Z})^2 \) act on \( A \) by the inner automorphisms induced by the matrices

\[
\begin{bmatrix}
0 & 1 \\
1 & 0 
\end{bmatrix}
\quad \text{and} \quad
\begin{bmatrix}
1 & 0 \\
0 & -1 
\end{bmatrix}.
\]

Then \( A \rtimes \Gamma \simeq M_4(\mathbb{C}) \) by the morphism defined by

\[
M_2(\mathbb{C}) \ni a \to a \otimes 1 \in M_2(\mathbb{C}) \otimes M_2(\mathbb{C}) \simeq M_4(\mathbb{C})
\]

and by \( u_i \to u_i \otimes u_i \). Therefore the periodic cyclic homology of \( A \rtimes \Gamma \) is concentrated at the identity.

This remark is related to a result of P. Green. See the beginning of the introduction to \([84]\) for a statement of this result in the form we need it (but with \( \mathbb{Z}_2 \) replaced by the unit circle group \( S^1 = T \)).
3. Affine Weyl groups

We now use the general results developed in previous sections to determine the periodic cyclic cohomology of the group algebras of (extended) affine Weyl groups. These results continue the results in [7], where the corresponding Hecke algebras were studied. In fact, cyclic and Hochschild homologies behave remarkably well for the algebras associated to reductive $p$-adic groups [3, 7, 26, 50, 77, 78, 79, 80]. Some connections with the Langlands program were pointed out in [66].

An (extended) affine Weyl group is the crossed product $W = X \rtimes W_0$, where $W_0$ is a finite Weyl groups and $X$ is a sublattice of the lattice of weights of a complex algebraic group with Weyl group $W_0$. Then $\mathbb{C}[W]$, the group algebra of $W$, satisfies $\mathbb{C}[W] \cong \mathcal{O}(X^*) \rtimes W_0$, that is, it is isomorphic to the crossed product algebra of the ring of regular functions on $X^* := \text{Hom}(X, \mathbb{C}^*)$, the dual torus of $X$, by the action of $W_0$. The cyclic homology groups of $\mathbb{C}[W] \cong \mathcal{O}(X^*) \rtimes W_0$ thus can be computed in two, dual ways, either using the results of [18, 22, 49] on the periodic cyclic homology of group algebras or using our determination in Theorem 2.20.

As a concrete example, let us compute the periodic cyclic cohomology of the group algebra $\mathbb{C}[W]$ of the extended Weyl group $W := \mathbb{Z}^n \rtimes S_n$, the symmetric Weyl group $S_n$ acting by permutation on the components of $\mathbb{Z}^n$. Denote by

$$\Pi(n) := \{(\lambda_1, \lambda_2, \ldots, \lambda_r), \lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_r > 0, \sum \lambda_j = n, \lambda_i \in \mathbb{Z}\}$$

the set of partitions of $n$. The set $\Pi(n)$ is in bijective correspondence with the set of conjugacy classes of $S_n$. If $S_\lambda = S_{\lambda_1} \times S_{\lambda_2} \times \ldots \times S_{\lambda_r}$ denotes the Young (or parabolic) subgroup of $S_n$ consisting of permutations leaving the first $\sum_{j=1}^k \lambda_j$ elements invariant, for all $k$, then to the partition $\lambda$ there corresponds a conjugacy class in $S_n$ represented by a permutation $\sigma_\lambda \in S_\lambda$, which in each factor is the cyclic permutation $(l, l+1, \ldots, m)$ of maximum length, for suitable integers $l < m$ (more precisely $l = \lambda_1 + \lambda_2 + \ldots + \lambda_k + 1$ and $m = \lambda_1 + \lambda_2 + \ldots + \lambda_{k+1}$, for a suitable $k$). Let $\sigma_\lambda$ be that element. Then the set of fixed points of $\sigma_\lambda$ acting on $(\mathbb{C}^*)^n$ is a torus naturally identified with $(\mathbb{C}^*)^r$.

The centralizer $(S_n)_{\sigma_\lambda}$ is isomorphic to a semi-direct product of a permutation group, denoted $Q_\lambda$, which permutes the equal length cycles of $\sigma_\lambda$, and the commutative group generated by the cycles of $\sigma_\lambda$. The action of the centralizer $(S_n)_{\sigma_\lambda}$ on the set $(X^*)^{\sigma_\lambda} \simeq (\mathbb{C}^*)^r$ of fixed points of $\sigma_\lambda$ descends to an action of $Q_\lambda$ on that set. The group $Q_\lambda$ permutes the equal-length cycles of $\sigma_\lambda$, and acts accordingly by permutations on $(\mathbb{C}^*)^r$. Let $t(\lambda)$ be the number of permutation subgroups appearing as factors of $Q_\lambda$. Thus, $t(\lambda)$ is the set of distinct values in the sequence $\{\lambda_1, \lambda_2, \ldots, \lambda_r\}$. Then $(\mathbb{C}^*)^r/Q_\lambda$ is the product of $(\mathbb{C}^*)^{t(\lambda)}$ and a euclidean space, so $H^*((\mathbb{C}^*)^r/Q_\lambda) \cong H^*((\mathbb{C}^*)^{t(\lambda)}) \cong H^*(\mathbb{T}^{t(\lambda)})$, with $\mathbb{T} \simeq S^1$ the unit circle.

**Theorem 3.1.** Let $A = \mathbb{C}[W]$ be the group algebra of the extended affine Weyl group $W = \mathbb{Z}^n \rtimes S_n$. Then

$$\text{HP}_q(A) \cong \bigoplus_{\lambda \in \Pi(n)} \bigoplus_{k=0}^{t(\lambda)/2} H^{2k+q}(\mathbb{T}^{t(\lambda)}), \quad q = 0, 1.$$

See also [13, 14] for some related results. Theorem 3.1 and Lemma 3.2 in [14] extends some of these results to Hecke algebras.
References


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