Algebra structure on the Hochschild cohomology of the ring of invariants of a Weyl algebra under a finite group

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Abstract

Let $A_n$ be the $n$-th Weyl algebra, and let $G \subset \text{Sp}_{2n}(\mathbb{C}) \subset \text{Aut}(A_n)$ be a finite group of linear automorphisms of $A_n$. In this paper, we compute the multiplicative structure on the Hochschild cohomology $HH^\bullet(A_n^G)$ of the algebra of invariants of $G$. We prove that, as a graded algebra, $HH^\bullet(A_n^G)$ is isomorphic to the graded algebra associated to the center of the group algebra $\mathbb{C}G$ with respect a filtration defined in terms of the defining representation of $G$.

1. Introduction

1.1. Let us fix an algebraically closed ground field $\mathbb{C}$ of characteristic zero.

1.2. For $n \in \mathbb{N}$, the $n$-th Weyl algebra $A_n$ is the one freely generated by elements $p_i$ and $q_i$, $1 \leq i \leq n$, subject to the commutation relations of Heisenberg:

\[
[p_i, p_j] = [q_i, q_j] = 0, \quad \forall i, j;
\]
\[
[q_i, p_i] = 1, \quad \forall i;
\]
\[
[q_j, p_i] = 0, \quad \forall i, j \text{ such that } i \neq j.
\]

It can be realized either as the algebra of algebraic differential operators on the affine space $\mathbb{A}^n$, or as the Sridharan twisted enveloping algebra $U_qg$ of an abelian Lie algebra $g$ of dimension $2n$ with respect to any non-degenerate Chevalley-Eilenberg 2-cocycle on $g$. It is a simple, left and right Noetherian algebra of Gabriel-Rentschler Krull dimension $n$, Gel’fand-Kirillov dimension $2n$ and global homological dimension $n$.

1.3. Sridharan [13] shows that the Hochschild cohomology $HH^\bullet(A_n) = H^\bullet(A_n, A_n) \cong \mathbb{C}$ and, in fact, that this characterizes the Weyl algebras among the twisted enveloping algebras of abelian Lie algebras. This result can be interpreted as the Poincaré lemma for quantum differential forms. The same methods can be used to show that, dually, $HH_\bullet(A_n) = H_\bullet(A_n, A_n) \cong \mathbb{C}$, concentrated in degree $2n$.

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This work was supported by a grant from UBACYT TW69, the international cooperation project SECyT-ECOS A98E05, and a CONICET scholarship.
1.4. Consider a finite subgroup $G \subset \text{Aut}(A_1)$ and the corresponding algebra of invariants $A_1^G$. As $G$ varies, we obtain in this way a family of algebras, all of which are simple, left and right Noetherian, with Gel’fand-Kirillov dimension 2, Krull dimension 1 and global homological dimension 1; in particular, these numeric invariants do not allow us to separate them.

Alev and Lambre [2] compute the 0-degree Hochschild homology of these algebras: they show that $HH_0(A_1^G)$ is a vector space of dimension $s(G) - 1$, with $s(G)$ the number of irreducible representations of $G$. A theorem of Alev [1] which describes $\text{Aut}(A_1)$ implies that each of its finite groups is conjugate to a subgroup in $\text{SL}_2(\mathbb{C}) \subset \text{Aut}(A_1)$, and the classification up to conjugation of these is classical; with this information one can compute $s(G)$ for each of the possible groups, and conclude that the algebras under consideration are in fact non-isomorphic in pairs, apart from a few exceptions.

1.5. If one considers more generally the algebras $A_n^G$ of invariants of $A_n$ under the action of a finite subgroup $G \subset \text{Sp}_{2n}(\mathbb{C}) \subset \text{Aut}(A_n)$—we restrict our attention to linear automorphisms because we have no description of the whole automorphism group in this case—we again obtain a family of algebras indistinguishable, for fixed $n$, on the basis of the above numerical invariants alone.

Alev, Farinati, Lambre and Solotar [4] obtain a generalization of the above formula for $HH_0(A_1^G)$: they show that $\nu_k = \dim_{\mathbb{C}} HH_k(A_1^G)$ is the number of conjugacy classes of $G$ whose elements have unity as an eigenvalue with multiplicity exactly $k$.

We thus see that in general homology is not enough to separate this algebras, at least without further analysis: one can easily show that these numbers $\nu_k$ can be computed in terms of the character of the defining representation and the power maps of the group $G$, and it is known [8] that there are pairs of non-isomorphic finite groups for which these data coincide.

1.6. In part, the interest of these computations comes from the wish to understand the Poisson structures underlying the objects under consideration.

The algebra $A_n$ has a natural filtration, that of Bernstein, such that the associated graded object $\text{gr} A_n$ is a polynomial algebra on $2n$ variables, canonically endowed with a Poisson bracket deduced from the commutator of $A_n$. The action of $\text{Sp}_{2n}(\mathbb{C})$ on $\text{gr} A_n$ respects this structure, so that $(\text{gr} A_n)^G$, for $G \subset \text{Sp}_{2n}(\mathbb{C})$, is naturally a Poisson algebra. Moreover, one can show that if $G \subset \text{Sp}_{2n}(\mathbb{C})$ is a finite subgroup, the graded algebra associated to $A_n^G$ with respect to the restricted Bernstein filtration is exactly $(\text{gr} A_n)^G$, with the same Poisson structure.

In particular, this means that we can regard the algebras $A_n^G$ as quantizations of the Poisson algebras $(\text{gr} A_n)^G$. This is the point of view of [3], where the authors show that, in a precise sense, the 0-degree Hochschild homology of $A_1^G$ approximates the 0-degree Poisson homology of $(\text{gr} A_1)^G$. This idea cannot be transferred to the general case because we have no good definition of Poisson homology for non-smooth algebras and $(\text{gr} A_n)^G$ is non-smooth for most finite subgroups $\text{Sp}_{2n}(\mathbb{C})$.

1.7. It is a result of [4] that there is a duality between the homology and the cohomology of the algebras at hand. In particular, we have $\dim_{\mathbb{C}} HH_k(A_n^G) = \nu_{2n-k}$ for each finite subgroup $G \subset \text{Sp}_{2n}(\mathbb{C})$. In this paper we complete the computation of Hochschild cohomology making the algebra structure on $HH^\bullet(A_n^G)$ explicit. The final result is the following:

1.8. Theorem. Let $G \subset \text{Sp}_{2n}(\mathbb{C})$ be a finite subgroup. Let $G$ act naturally on the $n$-th Weyl algebra $A_n$. The subspace $V \subset A_n$ spanned by the standard generators is $G$-invariant for this action. Define $d : G \to \mathbb{N}_0$ by $d(g) = 2n - \dim_{\mathbb{C}} V^g$. For each $p \geq 0$, write $F_p \mathbb{C} G$ the subspace of the group algebra $\mathbb{C} G$ spanned by the elements $g \in G$ such that $d(g) \leq p$. 
1.9. It is very easy to construct examples of the situation considered in the theorem. If \( G \) is a finite group and \( V \) is a faithful \( G \)-module of degree \( n \), \( G \) acts faithfully on the algebra of algebraic differential operators on \( V \), which is isomorphic to \( A_n \), so we can regard \( G \subset \text{Aut}(A_n) \). One sees that—using the notation of the theorem—\( d(g) \) is simply two times the codimension of the subspace of \( V \) fixed by \( g \).

One particularly nice instance of this arises when we consider the canonical action of the Weyl group corresponding to a Cartan subalgebra \( h \) of a semi-simple Lie algebra \( g \) on the algebra of regular differential operators on \( h \)∗, the dual space of \( h \).

1.10. In the next section, we recall the construction of the multiplicative structure on the Hochschild theory, and indicate the reductions leading to its determination in our particular case. In section 3 we carry out the various explicit computations needed for the proof of the theorem.

2. The multiplicative structure on \( HH^\bullet(A_n^G) \)

2.1. Let us fix from now on \( n \in \mathbb{N} \) and a finite subgroup \( G \subset \text{Sp}_{2n}(\mathbb{C}) \). We consider the natural action of \( G \) on the \( n \)-th Weyl algebra \( A_n \) by linear automorphisms.

2.2. The computation of \( HH^\bullet(A_n^G) \) presented in [4] is based on the fact that \( A_n^G \) and the crossed product \( A_n \rtimes G \) are Morita equivalent; since Hochschild cohomology groups are invariant under this kind of equivalence, in order to determine \( HH^\bullet(A_n^G) \), one can instead choose to compute \( HH^\bullet(A_n \rtimes G) \). Now, the algebra structure on \( HH^\bullet(A_n^G) \) can be defined in terms of the composition of iterated self-extensions of \( A_n^G \) in the category of \( A_n^G \)-bimodules; since this procedure is clearly invariant under equivalences, the algebras \( HH^\bullet(A_n^G) \) and \( HH^\bullet(A_n \rtimes G) \) coincide.

2.3. The next reduction depends on results of Stefan [12] and others, which show that, in our situation, for each \( A_n \rtimes G \)-bimodule \( M \) there is a natural spectral sequence with initial term \( E_2^{p,q} \cong H^p(G, H^q(A_n, M)) \) converging to \( H^\bullet(A_n \rtimes G, M) \). Since our ground field has characteristic zero, group cohomology is trivial in positive degrees, and this spectral sequence immediately degenerates, giving us natural isomorphisms \( H^\bullet(A_n \rtimes G, M) \cong H^\bullet(A_n, M)^G \).

We set \( M = A_n \rtimes G \). It is easy to see that Stefan’s spectral sequence is a spectral sequence of algebras in this case—for example, by using the resolutions given by the bar construction in order to compute the cohomologies of \( G \) and of \( A_n \). The distribution of zeros in its initial term implies that there are no extension problems, neither in order to compute the cohomology groups nor to compute the product maps. We thus conclude that the isomorphism between \( HH^\bullet(A_n \rtimes G) \) and \( H^\bullet(A_n, A_n \rtimes G)^G \) is multiplicative; we will determine this last algebra.

2.4. Let us recall the construction of the multiplicative structure on the functor \( H^\bullet(A_n, -) = \text{Ext}^\bullet_{A_n}(A_n, -) \). We fix a projective resolution \( X^\bullet \to A_n \) of \( A_n \) as a \( A_n^e \)-module. Since plainly \( \text{Tor}_p^{A_n}(A_n, A_n) = 0 \) for \( p \geq 0 \), \( X^\bullet \otimes_{A_n} X^\bullet \) is an acyclic complex over \( A_n \otimes_{A_n} A_n \cong A_n \). It follows from [5], proposition IX.2.6, that it is a projective resolution of \( A_n \) as an \( A_n^e \)-module.

In particular, there is a morphism \( \Delta : X^\bullet \to X^\bullet \otimes_{A_n} X^\bullet \) of resolutions lifting the identity map of \( A_n \). If \( M \) and \( N \) are \( A_n^e \)-modules, the product

\[
\cup : \text{Ext}^\bullet_{A_n}(A_n, M) \otimes \text{Ext}^\bullet_{A_n}(A_n, N) \to \text{Ext}^\bullet_{A_n}(A_n, M \otimes_{A_n} N)
\]
is induced by the composition
\[
\begin{align*}
&\text{hom}_{A_n}(X^\bullet, M) \otimes \text{hom}_{A_n}(X^\bullet, N) \\
&\quad \downarrow \psi \\
&\text{hom}_{A_n}(X^\bullet \otimes_{A_n} X^\bullet, M \otimes_{A_n} N) \\
&\quad \downarrow \Delta \\
&\text{hom}_{A_n}(X^\bullet, M \otimes_{A_n} N)
\end{align*}
\]
with $\psi$ standing for the evident $\text{hom} \otimes$ "interchange map", up to the canonical isomorphisms
\[
H(\text{hom}_{A_n}(X^\bullet, M)) \otimes H(\text{hom}_{A_n}(X^\bullet, N)) \cong H(\text{hom}_{A_n}(X^\bullet, M) \otimes \text{hom}_{A_n}(X^\bullet, N)).
\]

2.5. When $M = N = A_n \rtimes G$, we can compose the map (1) with the morphism induced by the product $\mu : (A_n \rtimes G) \otimes_{A_n} (A_n \rtimes G) \to A_n \rtimes G$. We obtain in this way the internal product of $H^\bullet(A_n, A_n \rtimes G)$.

The additivity of the functors involved and the decomposition $A_n \rtimes G \cong \bigoplus_{g \in G} A_ng$ of $A_n \rtimes G$ as an $A_n^e$-module—here and elsewhere $A_n g$ is the $A_n^e$-module obtained from $A_n$ by twisting the right action by the automorphism $g$—have the consequence that this product is determined by its restrictions
\[
\cup : \text{Ext}^\bullet_{A_n}(A_n, A_n g) \otimes \text{Ext}^\bullet_{A_n}(A_n, A_n h) \to \text{Ext}^\bullet_{A_n}(A_n, A_n gh),
\]
which we will compute in the next section.

3. Explicit computations

3.1. First of all, let us consider a filtered $\mathbb{C}$-algebra $A$ with a positive ascending filtration such that the associated graded algebra $\text{gr} A$ has no zero divisors. For each $x \in A$, we denote $s(x)$ the principal symbol of $x$ in $\text{gr} A$.

Consider commuting elements $x_1, \ldots, x_n \in A$, and write, for each $k$ such that $0 \leq k \leq n$, $I_k$ and $I_k'$ the left ideals generated by $x_1, \ldots, x_k$ and $s(x_1), \ldots, s(x_k)$ in $A$ and $\text{gr} A$, respectively; in particular, $I_0 = I_0' = 0$. Let us suppose that we have, for $1 \leq k \leq n$,
\[
a \in \text{gr} A, as(x_k) \in I_{k-1}' \Rightarrow a \in I_{k-1}'.
\]

Let $k$ be such that $1 \leq k \leq n$, $a \in F_n A$ and suppose $ax_k \in I_{k-1}$, so that there are $a_i \in A$ for $i = 1, \ldots, k - 1$ with $ax_k = \sum_{i=1}^{k-1} a_i x_i$. Then $s(ax_k) = s(\sum_{i=1}^{k-1} a_i x_i) \in I_{k-1}'$, and, as $s(ax_k) = s(a)s(x_k)$ because $\text{gr} A$ is a domain, we see from (2) that $s(a) \in I_{k-1}'$. We conclude that there exist $b_i \in A$, for each $i = 1, \ldots, k - 1$, and $a' \in F_{n-1} A$ such that $a = \sum_{i=1}^{k-1} b_i x_i + a'$. We have
\[
a' x_k = ax_k - \sum_{i=1}^{k-1} b_i x_i x_k = ax_k - \sum_{i=1}^{k-1} b_i x_k x_i \in I_{k-1};
\]
by induction, this tells us that $a' \in I_{k-1}'$, and, consequently, that $a \in I_{k-1}$.

We have shown that
\[
a \in A, ax_k \in I_{k-1} \Rightarrow a \in I_{k-1},
\]
for each $k$ such that $1 \leq k \leq n$, and we see that this is a condition that can be tested up to an appropriate filtration.
3.2. Let $A_n$ be the $n$-th Weyl algebra over $\mathbb{C}$, with generators $p_i$, $q_i$, for $i = 1, \ldots, n$. Let $\mu : A_n^e \to A_n$ be the canonical augmentation, and put $I = \ker \mu$. If $x \in A$, we’ll write $\partial x = 1 \otimes x - x \otimes 1$; plainly, $\partial x \in I$. A trivial computation shows that if $x, y \in A_n$ are such that $[x, y] \in \mathbb{C}1$, $[\partial x, \partial y] = 0$. In particular, the elements $\partial p_i$ and $\partial q_i$, $i = 1, \ldots, n$, which generate $I$ as a left $A_n^e$-module, commute.

There is an isomorphism of algebras $\phi : A_n^e \to A_{2n}$, uniquely determined by the conditions

$$\phi(p_i \otimes 1) = p_i, \quad \phi(q_i \otimes 1) = q_i, \quad \phi(1 \otimes p_i) = q_{i+n}, \quad \text{and} \quad \phi(1 \otimes q_i) = p_{i+n},$$

for each $i = 1, \ldots, n$. One has $\phi(\partial p_i) = -p_i + q_{i+n}$ and $\phi(\partial q_i) = -q_i + p_{i+n}$, and these elements obviously commute. When we consider the Bernstein filtration on $A_{2n}$, gr $A_{2n}$ turns out to be a polynomial algebra on variables $x_i = s(p_i)$ and $y_i = s(q_i)$ for $i = 1,\ldots, 2n$; moreover, if $i = 1,\ldots, n$,$$

s(\phi(\partial p_i)) = -x_i + y_{i+n}, \quad s(\phi(\partial q_i)) = -y_i + x_{i+n}.

$$It is clear that in this case (2) is satisfied, so that in turn the elements $\partial p_1, \ldots, \partial p_n$ and $\partial q_1, \ldots, \partial q_n$ satisfy (3).

We see that the left augmented algebra $\mu : A_n^e \to A_n$ satisfies the hypotheses of theorem VIII.4.2 of [5]; in particular, if we let $V = \bigoplus_{i=1}^n \mathbb{C} p_i \oplus \bigoplus_{i=1}^n \mathbb{C} q_i$, we have a projective resolution of $A_n$ as a left $A_n^e$-module of the form $A_n^e \otimes \Lambda^* V \to A_n$ with differentials $d : A_n^e \otimes \Lambda^p V \to A_n^e \otimes \Lambda^{p-1} V$ given by

$$d(a \otimes v_1 \wedge \cdots \wedge v_p) = \sum_{i=1}^p (-1)^{i+1} a \partial v_i \otimes v_1 \wedge \cdots \wedge \hat{v}_i \wedge \cdots \wedge v_p.$$

There are, accordingly, natural isomorphisms

$$\operatorname{Ext}^*_{A_n^e}(A_n, M) \cong H(\operatorname{hom}_{A_n^e}(A_n^e \otimes \Lambda^* V, M)) \cong H(\operatorname{hom}(\Lambda^* V, M))$$

for each left $A_n^e$-module $M$, where, in the last term, homology is computed with respect to differentials $d : \operatorname{hom}(\Lambda^d V, M) \to \operatorname{hom}(\Lambda^{d+1} V, M)$ such that

$$df(v_1 \wedge \cdots \wedge v_{p+1}) = \sum_{i=1}^{p+1} (-1)^i \partial v_i f(v_1 \wedge \cdots \wedge \hat{v}_i \wedge \cdots \wedge v_{p+1})$$

$$= \sum_{i=1}^{p+1} (-1)^i [v_i, f(v_1 \wedge \cdots \wedge \hat{v}_i \wedge \cdots \wedge v_{p+1})]$$

for each $f : \Lambda^d V \to M$.

3.3. Keeping the notations introduced in the previous paragraph, let $g \in \operatorname{Sp}(V)$, where we view $V$ as a symplectic space in the usual way; there is a unique decomposition $V = V_1^g \oplus V_2^g$, preserved by $g$ and such that $g|_{V_1^g} = Id_{V_1^g}$ and $Id_{V_2^g} - g|_{V_2^g} \in \operatorname{GL}(V_2^g)$. Let $d(g) = \dim V_2^g$. Whenever possible, we will suppress reference to the automorphism $g$ in our notation.

Let $\omega \in (\Lambda^d V_2)^* \setminus 0$. The decomposition $V = V_1 \oplus V_2$ induces a decomposition

$$\Lambda^d V = \bigoplus_{p+q=d} \Lambda^p V_1 \otimes \Lambda^q V_2;$$

5
in particular, we see that $\Lambda^dV_2$ can be identified with a subspace of $\Lambda^dV$, and, in this identification, admits a natural complement; we extend $\omega$ to the whole of $\Lambda^dV$ prescribing it to be zero on this complement.

We define $\tilde{\omega} : \Lambda^dV \to A_n g$ by setting $\tilde{\omega}(v) = \omega(v)g$. We will show that $\tilde{\omega}$ represents a non-zero homology class of degree $d$ in the complex $\text{hom}(\Lambda^\bullet V, A_g)$ considered above.

Let us fix a basis $v_1, \ldots, v_{2n}$ of $V$ and, for each $i$, $d_i = \dim v_i$. Suppose now that there is an $h \in \text{hom}(\Lambda^{d-1} V, A)$ such that $d(hg) = \tilde{\omega}$. Then, writing $h_i = h(v_1 \wedge \cdots \wedge v_i) \in A_n$, we have

$$d\tilde{\omega}(v_1 \wedge \cdots \wedge v_{d+1}) = (\sum_{j=1}^{d+1} (-1)^{d+1+j} [v_i, h_j] g) \in \mathbb{C}.$$ (4)

In particular, $[V_2, A_n]_g \cap \mathbb{C} \neq 0$.

For each $i = 1, \ldots, n$, let $V^i$ be the subspace of $V$ spanned by $p_i$ and $q_i$, and let $A^i$ be the subalgebra of $A_n$ generated by $p_i$ and $q_i$. Abusing a little of our notation, we see that $V = \bigoplus_{i=1}^n V^i$ and $A_n = \bigotimes_{i=1}^n A^i$. Suppose, without any loss of generality, that $V_2$ and $V_1$ are generated by $p_i$, $q_i$ for $i = 1, \ldots, d$ and for $i = d + 1, \ldots, n$ respectively, and that each $V^i$ is preserved by $g$; let us write $g_i = g|_{V^i}$. We have

$$[V_2, A_n]_g = \sum_{i=1}^d \bigoplus_{i=1}^d A^1 \otimes \cdots \otimes A^n.$$ (5)

Theorem 4 in [2] states, among other things, that, for $g$ an automorphism of $A_1$ different from the identity, $A_1 = \mathbb{C}1 \oplus [A_2, A_1]_g$. This implies that $A^i = \mathbb{C}1 \oplus [A^1, A^i]_g$, and, using (5), that $\mathbb{C}1$ and $[V_2, A_n]_g$ are transversal subspaces in $A_n$. This contradicts (4); we have thus proved that $\tilde{\omega}$ cannot be a coboundary in our complex.

3.4. In fact, this construction produces all $d$-cocycles with values in $\mathbb{C}g \subset A_n g$. To see this, let $\eta : \Lambda^d V \to A_n g$ be one such cocycle, let $v_1, \ldots, v_{2n}$ be a basis of $V$ as above with respect to which $g$
acts diagonally; for each $1 \leq i \leq 2n$, let $\lambda_i \in \mathbb{C}$ be such that $g v_i = \lambda_i v_i$. If $1 \leq i_1 < \cdots < i_{d+1} \leq 2n$ and $s$ satisfies $i_s \leq d < i_{s+1}$, we have that

$$0 = d \eta(v_{i_1} \wedge \cdots \wedge v_{i_{d+1}})$$

$$= \sum_{j=1}^{d+1} (-1)^{j+1} [v_{i_j}, \eta(v_{i_1} \wedge \cdots \wedge \hat{v}_{i_j} \wedge \cdots \wedge v_{i_{d+1}})]_g$$

$$= \sum_{j=1}^{d+1} (-1)^{j+1} [v_{i_j}, \eta(v_{i_1} \wedge \cdots \wedge \hat{v}_{i_j} \wedge \cdots \wedge v_{i_{d+1}})]$$

$$+ \sum_{j=1}^{s} (-1)^{j+1}(1 - \lambda_{i_j}) \eta(v_{i_1} \wedge \cdots \wedge \hat{v}_{i_j} \wedge \cdots \wedge v_{i_{d+1}}) v_{i_j};$$

since the first sum in the last member is zero, we see that, for $1 \leq j \leq s$,

$$\eta(v_{i_1} \wedge \cdots \wedge \hat{v}_{i_j} \wedge \cdots \wedge v_{i_{d+1}}) = 0.$$

If now $1 \leq r_1 < \cdots < r_d \leq 2n$ and $r_d > d$, there exists $t \in \{1, \ldots, d\} \setminus \{r_1, \ldots, r_d\}$; let $1 \leq i_1 < \cdots < i_{d+1} \leq 2n$ be such that $\{i_1, \ldots, i_{d+1}\} = \{r_1, \ldots, r_d\} \cup \{t\}$ and suppose $i_f = t$. Our previous observation implies that

$$\eta(v_{i_1} \wedge \cdots \wedge v_{r_d}) = \eta(v_{i_1} \wedge \cdots \wedge \hat{v}_{i_f} \wedge \cdots \wedge v_{i_{d+1}}) = 0.$$

We see that $\eta(v_{r_1} \wedge \cdots \wedge v_{i_d})$ vanishes unless $r_d \leq d$, and in this case $v_{r_j} = v_j$ if $1 \leq j \leq d$. It is clear now that $\eta$ is one of the cocycles constructed the previous paragraph.

3.5. In our situation, and using the notations of the end of 3.3, we have an iterated product, c.f. [5] XI.1,

$$\forall : \bigotimes_{i=1}^{n} \text{Ext}^i_{A_n}(A^i, A^i g_i) \to \text{Ext}^i_{A_n}(A_n, A_n g)$$

which is an isomorphism in view of theorem XI.3.1, loc.cit. On the other hand, we know from [4] that, for an algebra automorphism $g$ of $A_1$,

$$\dim_{\mathbb{C}} \text{Ext}^i_{A_1}(A_1, A_1 g) = \begin{cases} 1, & \text{if } g = Id_{A_1} \text{ and } \bullet = 0 \text{ or if } g \neq Id_{A_1} \text{ and } \bullet = 2; \\ 0, & \text{in any other case.} \end{cases}$$

From these two facts, we easily deduce that $\text{Ext}^i_{A_n}(A_n, A_n g)$ is trivial except in degree $d$, where it is one-dimensional. Comparing dimensions, we see that the map $\omega \mapsto \hat{\omega}$ is an isomorphism

$$\Lambda^d(V_2)^*[-d] \cong \text{Ext}^i_{A_n}(A_n, A_n g). \quad (6)$$

Here $M[-d]$ denotes the $d$-th suspension of a graded space $M$.

3.6. Let $G \subset \text{Sp}(V)$ be a finite subgroup. The natural action of $G$ on $V$ extends to an homogeneous action on the exterior algebra $\Lambda^* V$, on one side, and, on the other, to an action by algebra automorphisms on $A_n$, and, thence, on $A_n^e$. With respect to these actions, each module in the resolution $A_n^e \otimes \Lambda^* V \to A_n$ is a $G$-module, and the differentials are $G$-equivariant.
If $M$ is a left $A_n^e \times G$-module, there is an homogeneous action of $G$ on $\text{hom}_{A_n^e}(\Lambda_n^e \otimes \Lambda^* V, M)$, which is natural with respect to morphisms $M \to M'$ of $A_n^e \times G$-modules, and, under the isomorphism of $\mathbb{C}$-spaces $\text{hom}_{A_n^e}(\Lambda_n^e \otimes \Lambda^* V, M) \cong \text{hom}(\Lambda^* V, M)$, corresponds to the usual diagonal action of $G$. Passing to homology, we obtain an action of $G$ on $\text{Ext}_{A_n^e}(A_n, M) \cong H(\text{hom}(\Lambda^* V, M))$.

In particular, $\text{Ext}_{A_n^e}(A_n, A_n \times G)$ is, in a natural way, a graded $G$-module. In view of the decomposition $A_n \times G \cong \oplus_{g \in G} A_n \otimes G$ of $A_n \times G$ as a left $A_n^e$-module and the considerations of the previous paragraph, we have an isomorphism

$$\text{Ext}_{A_n^e}(A_n, A_n \times G) \cong \bigoplus_{g \in G} (\Lambda^d(g)\Lambda_V^g)^* g[-d(g)],$$

With respect to this isomorphism, the action of $G$ can be described in the following way: let $g, h \in G$ and $\omega \in (\Lambda^d(g)\Lambda_V^g)^*$; left multiplication by $h^{-1}$ induces an isomorphism $V_2^0 \to V_2^g$ which, in turn, determines an isomorphism $h^*: (\Lambda^d(g)\Lambda_V^g)^* \to (\Lambda^d(hgh^{-1})\Lambda_V^{hgh^{-1}})^*$; in this notation, we have

$$h(\omega g) = h^*(\omega)hgh^{-1}.$$

The verification of this claim reduces to a simple computation.

### 3.7

Since obviously $\text{Tor}_{A_n^e}(A_n, A_n) = 0$, we know that

$$A_n \otimes \Lambda^* V \otimes A_n \otimes \Lambda^* V \otimes A_n \cong (A_n^e \otimes \Lambda^* V) \otimes_{A_n} (A_n^e \otimes \Lambda^* V) \to A_n \otimes_{A_n} A_n \cong A_n$$

is a projective resolution of $A_n$ as a left $A_n^e$-module. There is a morphism of resolutions of $A_n$ over $A_n$, $\Delta: A_n \otimes \Lambda^* V \otimes A_n \to A_n \otimes \Lambda^* V \otimes A_n \otimes \Lambda^* V \otimes A_n$, given, in each degree $d$, by

$$\Delta(a \otimes v_1 \wedge \cdots \wedge v_d \otimes b) = \sum_{p+q=n} \varepsilon(i,j) (a \otimes v_{i_1} \wedge \cdots \wedge v_{i_p} \otimes 1 \otimes v_{j_1} \wedge \cdots \wedge v_{j_q} \otimes b),$$

if we let $S_{p,q}$ be the set of $(p, q)$-shuffles in the symmetric group $S_{p+q}$ and, for each such shuffle $(i, j)$, $\varepsilon(i, j)$ is the signature of $(i, j)$.

Given $A_n^e$-modules $M$ and $N$, the product

$$\cup: \text{Ext}_{A_n^e}(A_n, M) \otimes \text{Ext}_{A_n^e}(A_n, N) \to \text{Ext}_{A_n^e}(A_n, M \otimes_{A_n} N)$$  \hfill (7)

is as explained in section 2. Explicitly, under the usual identifications, if $\xi \in \text{hom}(\Lambda^p V, M)$ and $\zeta \in \text{hom}(\Lambda^q V, N)$, the product $\xi \cup \zeta \in \text{hom}(\Lambda^{p+q} V, M \otimes_{A_n} N)$ is such that

$$(\xi \cup \zeta)(v_1 \wedge \cdots \wedge v_{p+q}) = \sum_{(i, j) \in S_{p,q}} \varepsilon(i, j) \xi(v_{i_1} \wedge \cdots \wedge v_{i_p}) \otimes \zeta(v_{j_1} \wedge \cdots \wedge v_{j_q}).$$

If there is a group $G$ acting like in 3.6, from general principles or simply in view of this formula, we know that if $M$ and $N$ are $A_n^e \times G$-modules, the product (7) is $G$-equivariant.

### 3.8

In the situation of 3.6, choose an arbitrary $G$-invariant inner product on $V$. It is easy to see that, for each $g \in G$, $V_1^g$ and $V_2^g$ are mutual orthogonal complements in $V$. If $g, h \in G$, we have

$$(V_2^g + V_2^h)^\perp = V_2^{g\perp} \cap V_2^{h\perp} = V_1^g \cap V_1^h \subset V_1^{gh}$$

so that

$$V_2^{gh} = V_1^{gh\perp} \subset (V_2^g + V_2^h)^{\perp\perp} = V_2^g + V_2^h.$$  \hfill (8)
There is an isomorphism \( A_n g \otimes A_n h \cong A_n gh \) of \( A_n^c \)-modules, which we regard as an identification. Setting \( M = A_n g \) and \( N = A_n h \) in (7), we have a product map
\[
\cup : \text{Ext}^\bullet_{A_n}(A_n, A_n g) \otimes \text{Ext}^\bullet_{A_n}(A_n, A_n h) \to \text{Ext}^\bullet_{A_n}(A_n, A_n gh)
\]
(9)

From degree considerations, we see that this is trivial unless \( d(gh) = d(g) + d(h) \); if this is the case, (8) implies that \( V_2^{gh} = V_2^g \oplus V_2^h \). Let \( \omega \in (\Lambda^d(g)V^g_2)^* \) and \( \phi \in (\Lambda^d(h)V^h_2)^* \) be non-zero forms, and consider a basis \( v_1, \ldots, v_{2n} \) of \( V \) such that \( v_1, \ldots, v_{d(g)} \) is a basis of \( V_2^g \), \( v_{d(g)+1}, \ldots, v_{d(g)+d(h)} \) is a basis of \( V_2^h \), and \( v_{d(g)+d(h)+1}, \ldots, v_{2n} \) is a basis of \( V^gh_1 \). Let \( 1 \leq r_1 < \cdots < r_{d(g)+d(h)} \leq 2n \) be arbitrary indices. If \( r_{d(g)} > d(g) \) then
\[
(\tilde{\omega} \cup \tilde{\phi})(v_1 \wedge \cdots \wedge v_{d(g)+d(h)}) = \sum_{(i,j) \in S_{d(g),d(h)}} \epsilon(i,j)\tilde{\omega}(v_{r_1} \wedge \cdots \wedge v_{r_{d(g)}})\tilde{\phi}(v_{r_{d(g)+1}} \wedge \cdots \wedge v_{r_{d(g)+d(h)}})
\]
(10)
is zero because, for each \((i,j) \in S_{d(g),d(h)}\), \( v_{r_{d(g)}} > d \), so the second factor in each term of the sum vanishes. If \( r_{d(g)} \leq d \) but \( r_{d(g)+d(h)} > d(g) + d(h) \), a similar reasoning shows (10) is also zero.

We thus see that unless \( r_i = i \) for each \( 1 \leq i \leq d(g) + d(h) \), \((\tilde{\omega} \cup \tilde{\phi})(v_1 \wedge \cdots \wedge v_{d(g)+d(h)}) = 0\); that is, \( \tilde{\omega} \cup \tilde{\phi} \) is one of the cocycles constructed in 3.3. It is not cohomologous to zero, because it is not zero on \( \Lambda^d(gh)V^{gh}_2 \), since
\[
(\tilde{\omega} \cup \tilde{\phi})(v_1 \wedge \cdots \wedge v_{d(g)+d(h)}) = \omega(v_1 \wedge \cdots \wedge v_{d(g)})\phi(v_{d(g)+1} \wedge \cdots \wedge v_{d(g)+d(h)}) \neq 0.
\]

We conclude that (9) is either an isomorphism or zero, depending on whether \( d(gh) = d(g) + d(h) \) or not.

3.9. We can choose a non-zero element \( \omega_g \in (\Lambda^d(g)V^g_2)^* \) for each \( g \in G \) in the following way: let \( \nu \in (\Lambda^2 V)^* \) be the symplectic form on \( V \); since the action of \( G \) preserves \( \nu, \nu|_{\Lambda^2 V^g_2} \) is a symplectic form on \( V^g_2 \) for each \( g \); in particular, the \( d(g)/2 \)-th exterior power \( \omega_g = (\nu|_{\Lambda^2 V^g_2})^{d(g)/2} \in (\Lambda^d(g)V^g_2)^* \setminus 0 \). It is clear that when \( g, h \in G \) are such that \( d(g) + d(h) = d(gh) \), \( \tilde{\omega}_g \cup \tilde{\omega}_h = \tilde{\omega}_{gh} \) because \( V^g_2 \oplus V^h_2 = V^{gh}_2 \). Moreover, these elements are compatible with the action of \( G \) on \( \text{Ext}^\bullet_{A_n}(A_n, A_n \rtimes G) \), in the sense that \( g\tilde{\omega}_h = \tilde{\omega}_{gh^{-1}} \), because the action is symplectic.

We thus see that in terms of the basis \( \{\tilde{\omega}_g\}_{g \in G} \) both the structure constants and the action of \( G \) become particularly pleasant.

3.10. Consider the filtration \( F_n C G \) on \( C G \) such that \( F_p C G \) is spanned by the elements \( g \in G \) such that \( d(g) \leq p \). Equation (8) implies that this is an algebra filtration on \( C G \).

It is clear from the previous paragraph that the map
\[
\tilde{\omega}_g \in \text{Ext}^\bullet_{A_n}(A_n, A_n \rtimes G) \to s(g) \in \text{gr} C G
\]
is an algebra isomorphism. The compatibility of the chosen basis of the domain of this map with the action of \( G \) tells us that this map in in fact \( G \)-equivariant, and, hence, that there is an isomorphism of graded algebras \( \text{Ext}^\bullet_{A_n}(A_n, A_n \rtimes G)^G \cong (\text{gr} C G)^G \).

3.11. Write \( Z G \) the center of \( C G \), and consider on it the filtration induced by \( F_n C G \). It is clear that \((C G)^G = Z G\), so that \( \text{gr} Z G \subset (\text{gr} C G)^G \), and in fact this is an equality, because passing to the associated graded objects preserves the dimension. This proves theorem 1.8.
4. Some examples

4.1. As mentioned in the introduction, it is very easy to construct examples of the situation considered in our theorem 1.8. Indeed, let \( G \) be a finite group and choose a faithful \( G \)-module \( V \) of degree \( n \); \( G \) acts faithfully on the algebra of regular algebraic differential operators on \( V \), which is isomorphic to \( A_n \), so we can regard \( G \subset \text{Aut}(A_n) \). It is very easy to show that—in the notation of the theorem—\( d(g) \) is simply two times the codimension of the subspace of \( V \) fixed by \( g \in G \).

4.2. Let us write \( C[G] \) the algebra of \( \mathbb{C} \)-valued central functions on \( G \). It is well-known—cf. [10]—that \( C[G] \) is canonically endowed with the structure of a \( \lambda \)-ring with respect to which the Adams operations are given by \( \psi_k(f)(g) = f(g^k) \) for \( k \geq 0 \), \( f \in C[G] \) and \( g \in G \).

Let \( t \) be a variable, and let \( p \in C[G][t] \) be the central function with polynomial values such that, for each \( g \in G \), \( p(g) \) is the characteristic polynomial of \( g \) in the representation \( V \); define now \( q \in C[G][t] \) by setting, identically on \( G \), \( q(t) = t^n p(t^{-1}) \). A simple computation shows that, if we let \( \chi \) be the character of \( V \), we have

\[
\frac{d}{dt} \ln q(t) = - \sum_{k \geq 0} \psi^{k+1}(\chi) t^k.
\]

It is clear that \( p \) and \( q \) have 1 as a zero of the same multiplicity, so that the function \( d \in C[G] \) defined in 1.8 is given by

\[
d = 2n + 2 \text{res}_1 \sum_{k \geq 0} \psi^{k+1}(\chi) t^k,
\]

where we have written \( \text{res}_1 f \) the residue at 1 of a function \( f \) meromorphic in a neighborhood of 1.

This equation implies that the numbers \( \dim_{\mathbb{C}} \text{HH}^k(A_n G) \) are determined by the character \( \chi \) and the \( \lambda \)-ring structure on \( C[G] \). Since we are working over a field of characteristic zero, this last structure is determined by the Adams operations, and these, in turn, depend only on the power-maps, i.e. the maps induced on the set of the conjugacy classes of \( G \) by exponentiation.

We thus see that if two groups \( G \) and \( G' \) are such that both their character tables and power-maps coincide—such pairs are shown to exist in [8]—and we choose corresponding faithful representations, which will of course have the same degree \( n \), say, \( \text{HH}^*(A_n G) \) and \( \text{HH}^*(A_n G') \) will be isomorphic as graded vector spaces.

4.3. In fact, these isomorphism can be taken to be multiplicative. Let \( \langle G \rangle \) be the set of conjugacy classes of \( G \), and, for \( c \in \langle G \rangle \), let \( \hat{c} = \sum_{g \in c} g \in \mathbb{C} G \). The set \( \{ \hat{c} \}_{c \in \langle G \rangle} \) is a basis of \( \mathfrak{E} G \), the center of \( \mathbb{C} G \). 

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4.4. For each \( n \geq 0 \), let \( S_n \) be the symmetric group on \( \{1, \ldots, n\} \), and let \( i_n : S_n \to S_{n+1} \) be the standard injection, under which \( S_n \) fixes \( n+1 \); let \( S_\infty = \lim S_n \) be the injective limit, the restricted symmetric group on a countable infinite number of letters.

4.5. A partition \( \lambda \) is a non-increasing sequence of non-negative integers \( (\lambda_i)_{i \geq 1} \) which eventually vanish; let \( \Pi \) be the set of all partitions. If \( \lambda \in \Pi \), let \( l(\lambda) \) stand for the number of non-zero terms in \( \lambda \), and define the weight of \( \lambda \) to be \( |\lambda| = \sum_{i \geq 1} \lambda_i \). Let \( \Pi_n \) be the set of partitions of weight \( n \).

4.6. If \( \pi \in S_n \), the type of \( \pi \) is the partition \( \rho(\pi) \) listing the lengths of the cycles in a disjoint cycle decomposition of \( \pi \); clearly, \( |\rho(\pi)| = n \). If \( \rho(\pi) = (r_1, \ldots, r_l) \), \( \rho(i_n(\pi)) = (r_1, \ldots, r_1, 1) \), so that if we define the stable type of \( \pi \) to be the partition \( \rho^\#(\pi) = (r_1 - 1, \ldots, r_l - 1) \), we see that this is compatible with the injections \( i_n \), and in consequence \( \rho^\# \) is defined on \( S_\infty \). For \( \lambda \in \Pi \), we set \( C_\lambda = \{ \pi \in S_\infty : \rho^\#(\pi) = \lambda \} \); it is easy to show that \( \{C_\lambda\}_{\lambda \in \Pi} \) is precisely the decomposition of \( S_\infty \) into conjugacy classes.

4.7. For \( n \geq 0 \), let \( \mathcal{Z}_n = \mathcal{Z}(\mathbb{Z} S_n) \), and if \( \lambda \in \Pi \), \( c_\lambda(n) = \sum_{g \in C_\lambda \cap S_n} g \in \mathcal{Z}_n \). Obviously we have \( c_\lambda(n) = 0 \) if \( |\lambda| + l(\lambda) > n \).

4.8. If \( \lambda, \mu \in \Pi \), there are integers \( a_{\lambda \mu}^\nu(n), \nu \in \Pi \), such that
\[
c_\lambda(n) c_\mu(n) = \sum_{\nu \in \Pi} a_{\lambda \mu}^\nu(n) c_\nu(n),
\]
with \( a_{\lambda \mu}^\nu(n) = 0 \) if \( |\nu| > |\lambda| + |\mu| \). These numbers have great combinatorial interest, and explicit computations of specific cases can be found in the literature. In general, cf. [9], \( a_{\lambda \mu}^\nu(n) \) depends polynomially on \( n \), and is actually independent of \( n \) when \( |\nu| = |\lambda| + |\mu| \).

4.9. Let \( \mathcal{B} \subset \mathbb{Q}[t] \) of polynomials which take integer values on integers, and let \( \mathcal{Z}_\infty \) be the (possibly non-associative) \( \mathcal{B} \)-algebra which as a \( \mathcal{B} \)-module is free on the set \( \{c_\lambda\}_{\lambda \in \Pi} \), and whose product is determined by
\[
c_\lambda c_\mu = \sum_{\nu \in \Pi, |\nu| \leq |\lambda| + |\mu|} a_{\lambda \mu}^\nu c_\nu.
\]
There are multiplicative \( \mathbb{Z} \)-linear morphisms \( \mathcal{Z}_\infty \to \mathcal{Z}_n \) given by specialization \( c_\lambda \mapsto c_\lambda(n) \) on the basis, and by evaluation of polynomials at \( n \) on the coefficients, which collect to give a multiplicative map \( \mathcal{Z}_\infty \to \Pi_{n>0} \mathcal{Z}_n \), which turns out to be injective. This implies that \( \mathcal{Z}_\infty \) is an associative algebra. Clearly, the kernel of \( \mathcal{Z}_\infty \to \mathcal{Z}_n \) is generated by those \( c_\lambda \) such that \( |\lambda| + l(\lambda) > n \) and polynomials in \( \mathcal{B} \) which vanish on \( n \).

4.10. Let \( F_n \mathcal{Z}_\infty \) be the \( \mathcal{B} \)-submodule spanned by the \( c_\lambda \) with \( |\lambda| \leq n \). We see at once that this defines an algebra filtration \( F_\bullet \mathcal{Z}_\infty \) on \( \mathcal{Z}_\infty \), and, in view of the last statement of 4.8, we can describe the associated graded algebra as follows: let \( \mathcal{G} \) be the \( \mathcal{B} \)-algebra with \( \mathbb{Z} \)-basis \( \{c_\lambda\}_{\lambda \in \Pi} \), and product given by \( c_\lambda c_\mu = \sum_{|\nu| = |\lambda| + |\mu|} a_{\lambda \mu}^\nu c_\nu \); then \( \text{gr} \mathcal{Z}_\infty = \mathcal{B} \otimes \mathcal{G} \).

4.11. The epimorphisms \( \mathcal{Z}_\infty \to \mathcal{Z}_n \) of 4.9 are compatible with the filtrations on the objects involved, so they give epimorphisms on associated graded objects; but it is easy to see that these are actually determined by epimorphisms \( \mathcal{G} \to \text{gr} \mathcal{Z}_n \), given by \( c_\lambda \mapsto c_\lambda(n) \).

4.12. Let us write, for \( \lambda = (r) \), \( c_r = c_\lambda \). It is not difficult to show that the set \( \{c_r\}_{r \geq 1} \) is algebraically independent in \( \mathcal{G} \), and generates it rationally.
4.13. Let $\Lambda$ be the ring of symmetric functions with integer coefficients on an countably infinite number of variables, and, for each $i \geq 0$, let $h_i$ be the $i$-th complete symmetric function, which is the sum of all monomials of total degree $i$. It turns out that $\Lambda = \mathbb{Z}[[\{h_i\}_{i \geq 1}]]$. If $\lambda = (r_1, \ldots, r_l) \in \Pi$, we set $h_\lambda = h_{r_1} \cdots h_{r_l}$.

4.14. Define $u = \sum_{i \geq 0} h_i t^{i+1} \in \Lambda[[t]]$, and define elements $h_i^* \in \Lambda$ so that $t = \sum_{i \geq 0} h_i^* u^{i+1}$. Since the $h_i$ freely generate $\Lambda$, we can define a ring morphism $\Psi : \Lambda \to \Lambda$ with $\Psi(h_i) = h_i^*$. Now one can verify from their definition that the $h_i^*$ are also algebraically independent and generate $\Lambda$, so, in view of the symmetry of the contraction, we see that $\Psi$ is actually an involution.

4.15. Let $\langle - | - \rangle$ be the bilinear form on $\Lambda$ with values in $\mathbb{Z}$ such that $\langle h_\lambda | m_\mu \rangle = \delta_{\lambda\mu}$, where the $m_\mu$ are the monomial symmetric functions, obtained, for $\lambda = (r_1, \ldots, r_l)$, by symmetrization from $x_1^{r_1} \cdots x_l^{r_l}$. Define functions $\{g_\lambda\}_{\lambda \in \Pi}$ such that $\langle g_\lambda, h_\mu^* \rangle = \delta_{\lambda\mu}$.

4.16. Now we can give a very concrete description of the ring $\mathcal{G}$ and, using the fact that the kernel of the epimorphisms $\mathcal{G} \to \mathfrak{g} \mathfrak{z}_n$ is easily identifiable, of the algebras $HH(A^S_n)$. Indeed, it is a theorem proved in [11], example I.7.25, that the map $\phi : \Lambda \to \mathcal{G}$ such that $\phi(g_\lambda) = c_\lambda$ is a ring isomorphism. This allows us to do explicit computations in the algebras $HH(A^S_n)$, by translating the problem into one involving symmetric polynomials.

For each $n \geq 0$, let $RS_n$ be the representation ring of $S_n$; the sum $RS = \bigoplus_{n \geq 0} RS_n$ is a strictly commutative graded ring with product determined by its restrictions $RS_n \otimes RS_m \to RS_{n+m}$, given by $\chi \cdot \eta = \text{ind}^{S_{n+m}}_{S_n \times S_m} (\chi \times \eta)$. There is a very natural isomorphism of rings $\Theta : RS \to \Lambda$, essentially corresponding to taking the character of representations. It would be interesting to be able to explicitly relate elements and their products in $HH^*(A^S_n)$ to actual representations of the symmetric groups using the composition $\phi \circ \Theta$ of isomorphisms at hand. Unfortunately, one cannot expect to be able to restrict oneself to actual representations, since already $g_{(1)}$ corresponds under $\Theta$ to $-1 \in RS_1$, the opposite of the trivial representation of $S_1$, which, of course, is only a virtual representation.

5. References

[1] J. Alev, Actions de groupes sur $A_1(\mathbb{C})$. In: Ring theory (Antwerp, 1985), 1–9, Lecture Notes in Mathematics 1197, Springer, Berlin-New York, 1986.

[2] J. Alev, T. Lambre, Homologie des invariants d’une algèbre de Weyl. K-Theory 18 (1999), 401–411.

[3] J. Alev, T. Lambre, Comparaison de l’homologie de Hochschild et de l’homologie de Poisson pour une déformation des surfaces de Klein. In: Khakimdjanov, Yusupov (ed.) et al., Algebra and operator theory. Proceedings of the colloquium, Tashkent, Uzbekistan, September 29–October 5, 1997. Dordrecht: Kluwer Academic Publishers, 1998. 25–38.

[4] J. Alev, M. A. Farinati, T. Lambre, A. L. Solotar, Hochschild homology of invariants of the Weyl Algebra. Publication Université de Paris 11, 2000.

[5] H. Cartan, S. Eilenberg, Homological Algebra. Princeton University Press, Princeton NJ, 1956.

[6] R. W. Carter, Conjugacy classes in the Weyl group. Compositio Math. 25 (1972), 1–59.

[7] P.-J. Cahen, J.-L. Chabert, Integer-valued polynomials. Mathematical Surveys and Monographs 48. Providence: American Mathematical Society, 1997.
[8] E. C. Dade, *Answer to a question of R. Brauer*. J. of Algebra 1 (1964), 1–4.

[9] H. K. Farahat, *The centres of symmetric group rings*. Proc. Roy. Soc (A), 250, 212-221.

[10] D. Knutson, *λ-rings and the representation theory of the symmetric group*. Lecture Notes in Mathematics 308. Berlin-New York: Springer-Verlag, 1973.

[11] I. G. Macdonald, *Symmetric functions and Hall polynomials*, 2nd. ed. Oxford Mathematical Monographs. Oxford Science Publications. New York: The Clarendon Press, Oxford University Press, 1995.

[12] D. Stefan, *Hochschild cohomology of Hopf Galois extensions*. J. Pure Appl. Algebra 103 (1995), 221–233.

[13] R. Sridharan, *Filtered algebras and representations of Lie algebras*. Trans. Amer. Math. Soc. 100 (1961), 530–550.