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COMMUTATIVE AND NONCOMMUTATIVE INVARIANT THEORY

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1. Introduction

In this survey paper we point out some similarities and some differences between the theory of invariants of commuting and noncommuting variables. We begin by making some definitions.

Let k be a field and V a finite-dimensional vector space over k. Let further G be a subgroup of $\mathrm{GL}(V)$. Choosing a basis $x_1, \ldots, x_n$ for V we can identify G with a group of $n \times n$-matrices with entries in k.

Then we have the *symmetric k-algebra* of V,

$$k[V] = S^{\cdot} V = \bigoplus_{r \geqslant 0} S^r V = k[x_1, \ldots, x_n],$$

the polynomial algebra in n *commuting* variables.

We also have the *tensor algebra* of V,

$$k\langle V\rangle = T^{\cdot} V = \bigoplus_{r \geqslant 0} T^r V = k\langle x_1, \ldots, x_n\rangle,$$

the polynomial algebra in n *noncommuting* variables.

G acts on both $k[V]$ and $k\langle V\rangle$ in a natural way. We define the *k-algebra of G-invariants*, $k[V]^G$ ($k\langle V\rangle^G$), as the polynomials in $k[V]$ ($k\langle V\rangle$) that are left-invariant by G.

For any graded k-algebra $A = \bigoplus_{r \geqslant 0} A_r$ where $\dim_k A_r < \infty$ for all r, we define the *Hilbert series* $H(A, t)$ in $\mathbf{Z}[[t]]$ by

$$H(A, t) = \sum_{r \geqslant 0} \dim_k A_r t^r.$$

This paper is in final form and no version of it will be submitted for publication elsewhere.

2. G finite

Usually it is too hard to "compute" $k[V]^G$. We will compare three problems that are solved in both cases:

(a) Find a formula for the Hilbert series.
(b) When is $k[V]^G$ ($k\langle V\rangle^G$) finitely generated (as a k-algebra)?
(c) When is $k[V]^G$ ($k\langle V\rangle^G$) free (i.e. a polynomial algebra)?

THEOREM 1. (a) (Molien's formula). *For* $k = \mathbf{C}$

$$H(\mathbf{C}[V]^G, t) = \frac{1}{|G|}\sum_{g\in G}\frac{1}{\det(1-tg)}.$$

(b) $k[V]^G$ *is finitely generated* (*for any characteristic*) (E. Noether 1916, [13]).

(c) $\mathbf{C}[V]^G$ *is a polynomial algebra if and only if G is generated by pseudoreflections* (*$g\in G$ is a pseudoreflection if and only if* $\operatorname{rank}(g-1) = 1$) (Shephard–Todd 1954, [16]).

THEOREM 2. (a) $H(\mathbf{C}\langle V\rangle^G, t) = \dfrac{1}{|G|}\displaystyle\sum_{g\in G}\frac{1}{1-t\operatorname{Tr} g}$ (Dicks–Formanek 1982, [8]).

(b) $\mathbf{C}\langle V\rangle^G$ *is finitely generated if and only if G acts diagonally* (*and hence G is cyclic*) (Dicks–Formanek 1982, [8], Kharchenko 1984, [10]).

(c) $k\langle V\rangle^G$ *is always free* (*any G, any characteristic*) (Lane 1976, Kharchenko 1978, [9]).

Finally, we would like to mention a case where Problem (a) has been solved in characteristic p. Let p be a prime $\geqslant 3$. Let G be the cyclic group of order p, generated by the $(n+1)\times(n+1)$-matrix

$$\begin{bmatrix} 1 & 1 & 0 & \cdots & \cdot \\ 0 & 1 & 1 & \cdots & \cdot \\ \cdot & \cdot & \cdot & \cdots & \cdot \\ 0 & 0 & 0 \ldots & 1 & 1 \\ 0 & 0 & 0 \ldots & 0 & 1 \end{bmatrix}.$$

Then G acts on the $(n+1)$-dimensional k-vector space V ($\operatorname{char} k = p$).

Let further G' be the cyclic group of order p generated by the $(n+1)\times(n+1)$-matrix (over $\mathbf{C}$)

$$\begin{bmatrix} \lambda^n & & 0 \\ & \lambda^{n-2} & \\ & & \ddots & \\ 0 & & & \lambda^{-n} \end{bmatrix}$$

where $\lambda = e^{2\pi i/p}$. Then G' acts on $U = \mathbf{C}^{n+1}$.

THEOREM 3 (Almkvist [1], p. 18–21). *Let n be even. Then*

$$H(k[V]^G, t) = H(\mathbf{C}[U]^{G'}, t) = \frac{1}{|G'|} \sum_{g' \in G'} \frac{1}{\det(1-tg')}.$$

THEOREM 4 (Dicks–Formanek [8], p. 27). *Let n be even. Then*

$$H(k\langle V\rangle^G, t) = H(\mathbf{C}\langle U\rangle^{G'}, t) = \frac{1}{|G'|} \sum_{g' \in G'} \frac{1}{1-t\,\mathrm{Tr}\,g'}.$$

Furthermore, $k\langle V\rangle^G$ is not finitely generated.

Remark 5. If n is odd the formulas are more complicated. That the Hilbert series in characteristic zero and p agree, seems to be a combinatorial accident. The corresponding rings of invariants are far from being isomorphic.

2. G infinite

When G is finite, it is immediate from the explicit formulas that the Hilbert series are rational functions. This is also true when G is infinite in the commutative case (Hilbert–Samuel). But in the noncommutative case this is not true even for the cyclic infinite group.

EXAMPLE 6. Let G be the cyclic group generated by

$$\begin{bmatrix} 2 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 1/6 \end{bmatrix}$$

acting on $V = \mathbf{C}^3$. Then

$$H(\mathbf{C}\langle V\rangle^G, t) = \sum_{m \geq 0} \frac{(3m)!}{(m!)^3} t^{3m}$$

is a transcendental function of t (it is ${}_2F_1(1/3, 2/3, 1, 27t^3)$ and $(1/3, 2/3, 1)$ is not on the Schwarz-list characterizing the algebraic hypergeometric functions). However, we have the following result.

THEOREM 7 (Almkvist–Dicks–Formanek [6]). *Let G be the cyclic group generated by $1+N$ where N is nilpotent. Then $H(\mathbf{C}\langle V\rangle^G, t)$ is an algebraic function of t.*

Molien's formula can be extended to compact subgroups G of $\mathrm{GL}(V, \mathbf{C})$. Thus we have

$$H(\mathbf{C}[V]^G, t) = \int_G \frac{d\mu(g)}{\det(1-\mathrm{tg})} \qquad \text{(H. Weyl)},$$

$$H(\mathbf{C}\langle V\rangle^G, t) = \int_G \frac{d\mu(g)}{1-t\,\mathrm{Tr}(g)} \qquad \text{(Almkvist [3], Almkvist–Dicks–Formanek [6])}$$

for $|t| < 1/\dim V$ (here μ is the Haar measure on G).

For infinite G, $k[V]^G$ need not be finitely generated (Nagata's famous counterexample from 1959 [12]). V. L. Popov [15] has shown that finite generation for all rational actions of G is equivalent to that G is linearly reductive.

3. Classical invariant theory

"Classical" means that $G = \mathrm{SL}(2, \mathbf{C})$. We will keep this notation in this whole section. One can use Weyl's integration formula (and his "unitarian trick") to reduce to an integral over $\mathrm{SU}(2, \mathbf{C})$, see [3] and [6]. Here we prefer to use a more combinatorial approach. (See [2] and [4] for details.)

A. Partitions

DEFINITION 8. (a) $A(m, n, d)$ = the number of partitions of m into at most n parts of size $\leqslant d$.

(b) $B(m, n, d)$ = the number of solutions $(x_1, \ldots, x_n)$ in $\mathbf{N}^n$ satisfying

$$x_1 + \ldots + x_n = m$$

with $0 \leqslant x_i \leqslant d$.

EXAMPLE 9. $A(3, 3, 2) = 2$ since we only have two partitions $2+1$ and $1+1+1$. But $B(3, 3, 2) = 7$ since $x_1+x_2+x_3 = 3$, $0 \leqslant x_i \leqslant 2$ has the solutions $(2, 1, 0)$, $(2, 0, 1)$, $(1, 2, 0)$, $(1, 0, 2)$, $(0, 2, 1)$, $(0, 1, 2)$ and $(1, 1, 1)$.

DEFINITION 10. (a) $\begin{bmatrix} n \\ d \end{bmatrix} = \dfrac{(1-t^n)(1-t^{n-1})\ldots(1-t^{n-d+1})}{(1-t)(1-t^2)\ldots(1-t^d)}$ is the *Gaussian polynomial.*

(b) $\begin{Bmatrix} n \\ d \end{Bmatrix} = (1+t+\ldots+t^d)^n$.

PROPOSITION 11. (a) $\begin{bmatrix} n+d \\ d \end{bmatrix} = \sum\limits_{m=0}^{nd} A(m, n, d)\, t^m$.

(b) $\begin{Bmatrix} n \\ d \end{Bmatrix} = \sum\limits_{m=0}^{nd} B(m, n, d)\, t^m$.

DEFINITION 12. A polynomial $a_0+a_1 t+\ldots+a_N t^N$ in $\mathbf{Z}[t]$ is *unimodal* (usually called *symmetric unimodal*) if

(i) $a_{n-i} = a_i$ for all i,

(ii) $0 < a_0 \leqslant a_1 \leqslant \ldots \leqslant a_{[N/2]}$.

EXAMPLE 13. $\begin{bmatrix} n+d \\ d \end{bmatrix}$ (Sylvester) and $\begin{Bmatrix} n \\ d \end{Bmatrix}$ (trivial) are unimodal.

PROPOSITION 14.

$$B(m, n, d) = \sum_{j \geq 0} (-1)^j \binom{n}{j} \binom{m-j(d+1)+n-1}{n-1}$$

(*here* $\binom{k}{j} = 0$ *if* $k < j$).

There is no such simple formula known for $A(m, n, d)$.

B. SL(2, C)-modules

As before we have $G = \mathrm{SL}(2, \mathbf{C})$. We use the following facts (proved elementarily in Springer's book [17]).

(a) G is semisimple and there is exactly one irreducible G-module, V_n, in each dimension $n = 1, 2, \ldots$

(b) The *Clebsch–Gordan rule*:

$$V_m \otimes_{\mathbf{C}} V_n = V_m V_n = V_{m+n-1} + V_{m+n-3} + \ldots + V_{m-n+1} \qquad \text{if } m \geq n.$$

A formal finite sum $V = \sum_j c_j V_j$ with $c_j \in \mathbf{Z}$ is a G-module if and only if all $c_j \geq 0$. Call V *homogeneous* if it has only even (or only odd) components (e.g. $2V_1 + 5V_3$ and $3V_2 + 5V_{10}$ are homogeneous).

THEOREM 15 (Almkvist [4]). *The map*

$$a_0 + a_1 t + \ldots + a_1 t^{N-1} + a_0 t^N \mapsto a_0 V_{N+1} + (a_1 - a_0) V_{N-1} + (a_2 - a_1) V_{N-3} + \ldots + (a_{N/2} - a_{N/2-1}) V_1$$

is a bijection preserving the multiplication

$$\{\textit{unimodal polynomials}\} \to \{\textit{homogeneous } G\textit{-modules}\}.$$

In particular, if N is odd there is no V_1-component on the right-hand side.

THEOREM 16.

(a) $$S^n V_{d+1} \leftrightarrow \begin{bmatrix} n+d \\ d \end{bmatrix} = \sum_{m=0}^{nd} A(m, n, d) t^m.$$

(b) $$T^n V_{d+1} \leftrightarrow \begin{Bmatrix} n \\ d \end{Bmatrix} = \sum_{m=0}^{nd} B(m, n, d) t^m.$$

At this moment the author would like to state his favorite

CONJECTURE 17. $\prod_{k=1}^{r} (1 - t^{kn})/(1 - t^k)$ is unimodal if

(a) n is even,
(b) $n = 3$ and $r \geq 11$,
(c) $n = 5$ and $r \geq 7$,
(d) $n = 4k + 1 \geq 9$ and $r \geq 5$,
(e) $n = 4k + 3 \geq 7$ and $r \geq 7$.

For $n = 2$ the conjecture says that

$$(1+t)(1+t^2)\dots(1+t^r)$$

is unimodal and this was proved by Stanley and others. By using a refinement of an analytic method used by Odlyzko–Richmond [14] for $n = 2$, the author has proved the conjecture for $2 \leqslant n \leqslant 20$ and for $n = 100$ and 101 (see [4] and [5] for an explanation of the strange numbers).

It should perhaps be pointed out that the conjecture is equivalent to

$$\prod_{j=1}^{r} \psi^j V_n \quad \text{is a homogeneous } G\text{-module}$$

for n and r as above (here $\psi^j V_n$ are the formal Adams operations, which usually are *not* modules).

C. Invariants

DEFINITION 18. If V is a G-module we denote by

$$V^G = \{v \in V;\ g \cdot v = v \text{ for all } g \text{ in } G\}$$

the submodule of G-invariants.

For the irreducibles V_n we have $V_n^G = 0$ if $n > 1$ and $V_1^G = V_1$. It follows that if $V = \sum c_j V_j$ then $\dim V^G = c_1$.

THEOREM 19. (a) (Cayley–Sylvester). *The number of linearly independent invariant homogeneous polynomials of degree n in $d+1$ commuting variables is*

$$c(d, n) = A(nd/2, n, d) - A(nd/2-1, n, d).$$

(b) (M. Brion 1982). *The number of linearly independent invariant homogeneous polynomials of degree n in $d+1$ noncommuting variables is*

$$\tilde{c}(d, n) = B(nd/2, n, d) - B(nd/2-1, n, d).$$

Proof. Take the coefficient of V_1 using Theorems 15 and 16.

More suitable for computations is the following result ([2] and [6]).

THEOREM 20.

(a) $$\tilde{c}(d, n) = \sum_{j \geqslant 0} (-1)^j \binom{n}{j} \binom{nd/2+n-2-j(d+1)}{n-2} \quad \text{for } n \geqslant 2,$$

(b) $$\tilde{c}(d, n) = \frac{1}{\pi} \int_0^{2\pi} \left(\frac{\sin(d+1)y}{\sin y} \right)^n \sin^2 y \, dy,$$

(c) $$H(\mathbf{C}\langle V_{d+1}\rangle^G, t) = \frac{1}{\pi}\int_0^{2\pi} \frac{\sin^2 y}{1 - t\dfrac{\sin(d+1)y}{\sin y}}\,dy$$
$$= \frac{1}{t}\sum_{j=1}^{d} \frac{\eta_j^2 - 1}{d\eta_j^d + (d-2)\eta_j^{d-2} + \ldots - d\eta_j^{-d}},$$

where $\eta_1, \ldots, \eta_d$ are the roots of $z^{2d} + z^{2d-2} + \ldots + 1 = z^d/t$ which lie in the unit circle for small t. In particular, the Hilbert series is an algebraic function of t.

EXAMPLE 21. We have a small table

d	$H(\mathbf{C}\langle V_{d+1}\rangle^G, t)$
1	$\frac{1}{2t^2}(1-\sqrt{1-4t^2}) = 1+t^2+2t^4+5t^6+14t^8+\ldots$
2	$\frac{1}{2t}\left(1-\sqrt{\frac{1-3t}{1+t}}\right) = 1+t^2+t^3+3t^4+6t^5+\ldots$
4	$\frac{\sqrt{2}}{\sqrt{(1-t)}\,\lfloor 1+5t+\sqrt{(1-5t)(1-t)}\rfloor} = 1+t^2+t^3+5t^4+16t^5\ldots$

EXAMPLE 22. It seems very hard to find the invariants explicitly (see Section E, though). We have

$$\sum_{i=0}^{d}(-1)^i\binom{d}{i}x_i x_{d-i} \in T^2 V_{d+1}^G$$

is the only invariant of degree 2. (It is a noncommutative discriminant.) If $d = 2v$ we have

$$\sum_{i,j,k=0}^{v}(-1)^{i+j+k}\binom{v}{i}\binom{v}{j}\binom{v}{k}x_{v-i+j}x_{v-j+k}x_{v-k+i} \in T^3 V_{d+1}^G.$$

D. Asymptotics

Hilbert has shown that for large even n

$$c(d, n) = \frac{n^{d-3}}{d!}\cdot\frac{4}{\pi}\int_0^{\infty}\left(\frac{\sin y}{y}\right)^d y^2\,dy + O(n^{d-5})$$

(see [17], p. 63). Hence $c(d, n)$ grows *polynomially* with n (the degree being $d-3$ means that the Krull dimension of $\mathbf{C}[V_{d+1}]^G$ is $d-2$).

Using Theorem 20(b) one can show that for even n and with $s = d+1$ one has

$$\tilde{c}(d, n) = s^{n-3}\cdot\frac{4}{\pi}\int_0^{\infty}\left(\frac{\sin y}{y}\right)y^2\,dy + s^{n-5}\cdot\frac{2(n-2)}{3\pi}\int_0^{\infty}\left(\frac{\sin y}{y}\right)^n y^4\,dy + O(s^{n-7}).$$

Thus $\tilde{c}(d, n)$ grows *exponentially* with n. The leading terms of $c(d, n)$ and $\tilde{c}(d, n)$ are (except for a factor $d!$) very similar if we interchange d and n (see [2] for proofs).

E. The work of T. Tambour

T. Tambour has developed a symbolic method for noncommutative invariants and covariants for $G = \mathrm{SL}(2, \mathbf{C})$ (see [20]). We will only state a few of this results.

The Hilbert series

$$H(\mathbf{C}\langle V_{d+1}\rangle^G, t) = \sum_{m \geqslant 0} \dim(\mathbf{C}\langle V_{d+1}\rangle^G)_m t^m$$

is algebraic but not rational for $d \geqslant 2$. Let us sum over the wrong index d (see also Teranishi [22]):

$$F_m(t) = \sum_{d \geqslant 0} \dim(\mathbf{C}\langle V_{d+1}\rangle^G{}_m t^d.$$

THEOREM 23. (a) *$F_m(t)$ is a rational function of t.*

(b) $F_m(1/t) = (-1)^m t^2 F_m(t)$.

(c) $F_m(t) = \dfrac{1}{2t} \displaystyle\sum_{0 \leqslant j < m/2} (-1)^{j+1} \binom{m}{j} \Phi_{m-2j}\left(\frac{t^{m-2}}{(1-t^2)^{m-2}}\right)$

where

$$(\Phi_n f)(t^n) = \frac{1}{n} \sum_{\gamma \in \mu_n} f(\gamma t)$$

with μ_n = the group of n-th roots of unity.

The last result resembles a formula by Springer [18] for the Hilbert series of $\mathbf{C}[V_{d+1}]^G$. Tambour has also found a *commutative* algebra having $F_m(t)$ as its Hilbert series.

The symmetric group S_m acts by permuting the factors of $(\mathbf{C}\langle V_{d+1}\rangle^G)_m$. Let $a(d, m)$ be the number of irreducible components in the S_m-module decomposition of $(\mathbf{C}\langle V_{d+1}\rangle^G)_m = (\tilde{I}_d)_m$. Consider the power series ("false" Hilbert series)

$$\tilde{H}(\tilde{I}_d, t) = \sum_{m \geqslant 0} a(d, m) t^m.$$

Then

$$\tilde{H}(\tilde{I}_1, t) = \frac{1}{1-t^2},$$

$$\tilde{H}(\tilde{I}_2, t) = \frac{1}{(1-t^2)(1-t^3)(1-t^4)},$$

$$\tilde{H}(\tilde{I}_3, t) = \frac{1 + 2t^8 + 3t^{10} + 5t^{12} + 3t^{14} + 2t^{16} + t^{24}}{(1-t^2)(1-t^4)^2(1-t^6)^2(1-t^8)(1-t^{10})}.$$

THEOREM 24.

(a) $\tilde{H}(\tilde{I}_d, 1/t) = (-1)^{\binom{d}{2}} t^{(d+1)^2} \tilde{H}(\tilde{I}_d, t)$.

(b) $\tilde{H}(\tilde{I}_d, t) = H(\mathbf{C}[V_{d+1} \oplus \Lambda^2 V_{d+1}]^G, t)$.

where the elements of $\Lambda^2 V_{d+1}$ *have degree* 2.

(c) $$\tilde{H}(\mathbf{C}\langle V_{d+1}\rangle, t) = H(\mathbf{C}[V_{d+1} \oplus \Lambda^2 V_{d+1}], t) = \frac{1}{(1-t)^{d+1}(1-t^2)^{d(d+2)/2}}.$$

(d) *If* G *is a finite subgroup of* $\mathrm{GL}(V)$ *then*

$$\tilde{H}(\mathbf{C}\langle V\rangle^G, t) = \frac{1}{|G|} \sum_{g \in G} \frac{1}{\det(1-tg)\det(1-t^2 \Lambda^2 g)}.$$

Tambour [21] has also found the generators of $\mathbf{C}\langle x, y\rangle^G$ where G is one of the five polyhedral (finite) subgroups of $\mathrm{SL}(2, \mathbf{C})$.

The generators are obtained as all permutations of factors of

$$(xy-ys)^q f_i, \quad i = 1, 2, 3, \quad q \in N,$$

where f_1, f_2, f_3 are the generators of $\mathbf{C}[x, y]^G$ (see Springer [17], p. 94).

Research problem

It would be of great interest to give a combinatorial explanation to the remarkable coincidences of the Hilbert series of two seemingly unrelated algebras in Theorems 3, 4 and 24(b), (c). See also the remark after Theorem 23.

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