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THE THEORY OF SCHUR POLYNOMIALS REVISITED

by Harry TAMVAKIS*)

ABSTRACT. We use Young's raising operators to give short and uniform proofs of several well-known results about Schur polynomials and symmetric functions, starting from the Jacobi-Trudi identity.

1. INTRODUCTION

One of the earliest papers to study the symmetric functions later known as the *Schur polynomials* s_{λ} is that of Jacobi [J], where the following two formulas are found. The first is Cauchy's definition of s_{λ} as a quotient of determinants:

(1)
$$s_{\lambda}(x_1,\ldots,x_n) = \det(x_i^{\lambda_i+n-j})_{i,j} / \det(x_i^{n-j})_{i,j},$$

where $\lambda = (\lambda_1, \dots, \lambda_n)$ is an integer partition with at most *n* non-zero parts. The second is the *Jacobi-Trudi identity*

(2)
$$s_{\lambda} = \det(h_{\lambda_i+j-i})_{1 \le i, j \le n}$$

which expresses s_{λ} as a polynomial in the complete symmetric functions h_r , $r \ge 0$. Nearly a century later, Littlewood [L] obtained the positive combinatorial expansion

(3)
$$s_{\lambda}(x) = \sum_{T} x^{c(T)},$$

where the sum is over all semistandard Young tableaux T of shape λ , and c(T) denotes the content vector of T.

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The traditional approach to the theory of Schur polynomials begins with the classical definition (1); see for example [FH, M, Ma]. Since equation (1) is a special case of the Weyl character formula, this method is particularly suitable for applications to representation theory. The more combinatorial treatments [Sa, Sta] use (3) as the definition of $s_{\lambda}(x)$, and proceed from there. It is not hard to relate formulas (1) and (3) to each other directly; see e.g. [Pr, Ste].

In this article, we take the Jacobi-Trudi formula (2) as the starting point, where the h_r represent algebraically independent variables. We avoid the use of the *x* variables or 'alphabets' and try to prove as much as we can without them. For this purpose, it turns out to be very useful to express (2) in the alternative form

(4)
$$s_{\lambda} = \prod_{i < j} (1 - R_{ij}) h_{\lambda} ,$$

where the R_{ij} are Young's raising operators [Y] and $h_{\lambda} = h_{\lambda_1}h_{\lambda_2}\cdots h_{\lambda_n}$. The equivalence of (2) and (4) follows immediately from the Vandermonde identity.

The motivation for this approach to the subject comes from *Schubert calculus*. It is well known that the algebra of Schur polynomials agrees with that of the Schubert classes in the cohomology ring of the complex Grassmannian G(k, r), when k and r are sufficiently large. Giambelli [G] showed that the Schubert classes on G(k, r) satisfy the determinantal formula (2); the closely related *Pieri rule* [P] had been obtained geometrically a few years earlier. Recently, with Buch and Kresch [BKT1, BKT2], we proved analogues of the Pieri and Giambelli formulas for the isotropic Grassmannians which are quotients of the symplectic and orthogonal groups. Our Giambelli formulas for the Schubert classes on these spaces are not determinantal, but rather are stated in terms of raising operators. In [T], we used raising operators to obtain a tableau formula for the corresponding theta polynomials, which is an analogue of Littlewood's equation (3) in this context. Moreover, the same methods were applied loc. cit. to provide new proofs of similar facts about the Hall-Littlewood functions.

Our aim here is to give a self-contained treatment of those aspects of the theory of Schur polynomials and symmetric functions which follow naturally from the above raising operator approach. Using (4) as the definition of Schur polynomials, we give short proofs of the Pieri and Littlewood-Richardson rules, and follow this with a discussion — in this setting — of the duality

involution, Cauchy identities, and skew Schur polynomials. We next introduce the variables $x = (x_1, x_2, ...)$ and study the ring Λ of symmetric functions in xfrom scratch. In particular, we derive the bialternant and tableau formulas (1) and (3) for $s_{\lambda}(x)$. See [La] for an approach to these topics which begins with (2) but is based on alphabets and properties of determinants such as the Binet-Cauchy formula, and [vL, Ste] for a different treatment which employs alternating sums stemming from (1).

Most of the proofs in this article are streamlined versions of more involved arguments contained in [BKT2], [M], and [T]. The proof we give of the Littlewood-Richardson rule from the Pieri rule is essentially that of Remmel-Shimozono [RS] and Gasharov [G], but expressed in the concise form adapted by Stembridge [Ste]. Each of these proofs employs the same sign reversing involution on a certain set of Young tableaux, which originates in the work of Berenstein-Zelevinsky [BZ]. The version given here does not use formulas (1) and (3) at all, but relies on the alternating property of the determinant (2), which serves the same purpose.

The reduction formula (22) for the number of variables in $s_{\lambda}(x_1, \ldots, x_n)$ is classically known as a 'branching rule' for the characters of the general linear group [Pr, W]. Our terminology differs because there are similar results in situations where the connection with representation theory is not available (see [T]). We use the reduction formula to derive (3) from (4); a different cancellation argument relating formulas (2) and (3) to each other is due to Gessel-Viennot [GV, Sa].

We find that the short arguments in this article are quite uniform, especially when compared to other treatments of the same material. On the other hand, much of the theory of Schur polynomials does not readily fit into the present framework. Missing from the discussion are the Hall inner product, the Hopf algebra structure on Λ , the basis of power sums, the character theory of the symmetric and general linear groups, Young tableau algorithms such as *jeu de taquin*, the *plactic algebra*, and noncommutative symmetric functions. These topics and many more can be added following standard references such as [F, La, M, Ma, Sa, Sta, Z], but are not as natural from the point of view adopted here, which stems from Grassmannian Schubert calculus. A similar approach may be used to study the theory of Schur *Q*-polynomials and more generally of Hall-Littlewood functions; some of this story may be found in [T].

The author is indebted to his collaborators Anders Buch and Andrew Kresch for their efforts on the related projects [BKT1, BKT2].

2. THE ALGEBRA OF SCHUR POLYNOMIALS

2.1 PRELIMINARIES

An integer sequence or integer vector is a sequence of integers $\alpha = (\alpha_1, \alpha_2, ...)$ with only finitely α_i non-zero. The *length* of α , denoted $\ell(\alpha)$, is largest integer $\ell \ge 0$ such that $\alpha_\ell \ne 0$. We identify an integer sequence of length ℓ with the vector consisting of its first ℓ terms. We let $|\alpha| = \sum \alpha_i$ and write $\alpha \ge \beta$ if $\alpha_i \ge \beta_i$ for each *i*. An integer sequence α is a *composition* if $\alpha_i \ge 0$ for all *i* and a *partition* if $\alpha_i \ge \alpha_{i+1} \ge 0$ for all *i*.

Consider the polynomial ring $\mathbf{A} = \mathbf{Z}[u_1, u_2, ...]$ where the u_i are countably infinite commuting independent variables. We regard \mathbf{A} as a graded ring with each u_i having graded degree i, and adopt the convention here and throughout the paper that $u_0 = 1$ while $u_r = 0$ for r < 0. For each integer vector α , set $u_{\alpha} = \prod_i u_{\alpha_i}$; then \mathbf{A} has a free \mathbf{Z} -basis consisting of the monomials u_{λ} for all partitions λ .

For two integer sequences α , β such that $|\alpha| = |\beta|$, we say that α dominates β and write $\alpha \succeq \beta$ if $\alpha_1 + \cdots + \alpha_i \ge \beta_1 + \cdots + \beta_i$ for each *i*. Given any integer sequence $\alpha = (\alpha_1, \alpha_2, \ldots)$ and i < j, we define

$$R_{ij}(\alpha) = (\alpha_1, \ldots, \alpha_i + 1, \ldots, \alpha_j - 1, \ldots).$$

A raising operator R is any monomial in these R_{ij} 's. Note that we have $R\alpha \succeq \alpha$ for all integer sequences α . For any raising operator R, define $Ru_{\alpha} = u_{R\alpha}$. Here the operator R acts on the index α , and not on the monomial u_{α} itself. Thus, if the components of α are a permutation of the components of β , then $u_{\alpha} = u_{\beta}$ as elements of \mathbf{A} , but it may happen that $Ru_{\alpha} \neq Ru_{\beta}$. Formal manipulations using these raising operators are justified carefully in the following section. Note that if $\alpha_{\ell} < 0$ for $\ell = \ell(\alpha)$, then $Ru_{\alpha} = 0$ in \mathbf{A} for any raising operator R.

2.2 SCHUR POLYNOMIALS

For any integer vector α , define the *Schur polynomial* U_{α} by the formula

(5)
$$U_{\alpha} := \prod_{i < j} (1 - R_{ij}) u_{\alpha}$$

Although the product in (5) is infinite, if we expand it into a formal series we find that only finitely many of the summands are nonzero; hence, U_{α} is well

defined. We will show that equation (5) may be written in the determinantal form

(6)
$$U_{\alpha} = \det(u_{\alpha_i+j-i})_{1 \le i, j \le \ell} = \sum_{w \in S_{\ell}} (-1)^w u_{w(\alpha+\rho_{\ell})-\rho_{\ell}},$$

where ℓ denotes the length of α and $\rho_{\ell} = (\ell - 1, \ell - 2, \dots, 1, 0)$.

Algebraic expressions and identities involving raising operators like the above can be justified by viewing them as the image of a **Z**-linear map $\mathbf{Z}[\mathbf{Z}^{\ell}] \rightarrow \mathbf{A}$, where $\mathbf{Z}[\mathbf{Z}^{\ell}]$ denotes the group algebra of $(\mathbf{Z}^{\ell}, +)$. We let x_1, \ldots, x_{ℓ} be independent variables and identify $\mathbf{Z}[\mathbf{Z}^{\ell}]$ with $\mathbf{Z}[x_1, x_1^{-1}, \ldots, x_{\ell}, x_{\ell}^{-1}]$. For any integer vector $\alpha = (\alpha_1, \ldots, \alpha_{\ell})$ and raising operator R, set $x^{\alpha} = x_1^{\alpha_1} \cdots x_{\ell}^{\alpha_{\ell}}$ and $Rx^{\alpha} = x^{R\alpha}$. Then if $\psi: \mathbf{Z}[\mathbf{Z}^{\ell}] \rightarrow \mathbf{A}$ is the **Z**-linear map determined by $\psi(x^{\alpha}) = u_{\alpha}$ for each α , we have $Ru_{\alpha} = \psi(x^{R\alpha})$. It follows from the Vandermonde identity

$$\prod_{1 \le i < j \le \ell} (x_j - x_i) = \det(x_i^{j-1})_{1 \le i, j \le \ell}$$

that

$$\prod_{1 \le i < j \le \ell} (1 - R_{ij}) x^{\alpha} = \prod_{1 \le i < j \le \ell} (1 - x_i x_j^{-1}) x^{\alpha} = \det(x_i^{\alpha_i + j - i})_{1 \le i, j \le \ell}.$$

Now apply the map ψ to both ends of the above equation to obtain (6).

EXAMPLE 1. We have

$$U_{(5,4,2)} = (1 - R_{12})(1 - R_{13})(1 - R_{23})u_{(5,4,2)}$$

= $(1 - R_{12} - R_{13} - R_{23} + R_{12}R_{13} + R_{12}R_{23} + R_{13}R_{23} - R_{12}R_{13}R_{23})u_{(5,4,2)}$
= $u_{(5,4,2)} - u_{(6,3,2)} - u_{(6,4,1)} - u_{(5,5,1)} + u_{(7,3,1)} + u_{(6,4,1)} + u_{(6,5,0)} - u_{(7,4,0)}$
= $u_5u_4u_2 - u_6u_3u_2 - u_5^2u_1 + u_7u_3u_1 + u_6u_5 - u_7u_4 = \begin{vmatrix} u_5 & u_6 & u_7 \\ u_3 & u_4 & u_5 \\ 1 & u_1 & u_2 \end{vmatrix}$.

If $\alpha = (\alpha_1, \ldots, \alpha_\ell)$ and $\beta = (\beta_1, \ldots, \beta_m)$ are two integer vectors and r, $s \in \mathbb{Z}$, we let (α, r, s, β) denote the integer vector $(\alpha_1, \ldots, \alpha_\ell, r, s, \beta_1, \ldots, \beta_m)$. The next lemma is known as a 'straightening law' for the U_{α} .

LEMMA 1.

(a) Let α and β be integer vectors. Then for any $r, s \in \mathbb{Z}$ we have

$$U_{(\alpha,r,s,\beta)} = -U_{(\alpha,s-1,r+1,\beta)}.$$

(b) Let α = (α₁,..., α_ℓ) be any integer vector. Then U_α = 0 unless α + ρ_ℓ = w(μ + ρ_ℓ) for a (unique) permutation w ∈ S_ℓ and partition μ. In the latter case, we have U_α = (-1)^wU_μ.

Proof. Both parts follow immediately from (6) and the alternating property of the determinant. \Box

If λ is any partition, clearly (5) implies that $U_{\lambda} = u_{\lambda} + \sum_{\mu \succ \lambda} a_{\lambda\mu} u_{\mu}$ where $a_{\lambda\mu} \in \mathbb{Z}$ and the sum is over partitions μ which strictly dominate λ . We deduce that the U_{λ} for λ a partition form another \mathbb{Z} -basis of \mathbb{A} .

2.3 MIRROR IDENTITIES

We will represent a partition λ by its Young diagram of boxes, arranged in left-justified rows, with λ_i boxes in row *i*. We write $\lambda \subset \mu$ instead of $\lambda \leq \mu$ for the containment relation between two Young diagrams; in this case the set-theoretic difference $\mu \setminus \lambda$ is the skew diagram μ/λ . A skew diagram is a *horizontal* (resp. *vertical*) *strip* if it does not contain two boxes in the same column (resp. row). We write $\lambda \xrightarrow{p} \mu$ if μ/λ is a horizontal strip with *p* boxes.

LEMMA 2. Let
$$\lambda$$
 be a partition and $p \ge 0$ be an integer. Then we have
(7) $\sum_{\alpha \ge 0, \ |\alpha|=p} U_{\lambda+\alpha} = \sum_{\lambda \xrightarrow{p} \mu} U_{\mu}$ and $\sum_{\alpha \ge 0, \ |\alpha|=p} U_{\lambda-\alpha} = \sum_{\mu \xrightarrow{p} \lambda} U_{\mu}$,

where the sums are over compositions $\alpha \ge 0$ with $|\alpha| = p$ and partitions $\mu \supset \lambda$ (respectively $\mu \subset \lambda$) such that $\lambda \xrightarrow{p} \mu$ (respectively, $\mu \xrightarrow{p} \lambda$). Moreover, for every $n \ge \ell(\lambda)$, the identities (7) remain true if the sums are taken over α and μ of length at most n.

Proof. The proofs of the two identities are very similar, so we will only discuss the second. Let us rewrite the sum $\sum_{\alpha\geq 0} U_{\lambda-\alpha}$ as $\sum_{\nu\leq\lambda} U_{\nu}$, where the latter sum is over integer sequences ν such that $\nu_i \leq \lambda_i$ for each *i* and $|\nu| = |\lambda| - p$. Call any such sequence ν bad if there exists a $j \geq 1$ such that $\nu_j < \lambda_{j+1}$, and let *X* be the set of all bad sequences. Define an involution $\iota: X \to X$ as follows: for $\nu \in X$, choose *j* minimal such that $\nu_j < \lambda_{j+1}$, and set

$$\iota(\nu) = (\nu_1, \ldots, \nu_{j-1}, \nu_{j+1} - 1, \nu_j + 1, \nu_{j+2}, \ldots).$$

Lemma 1(a) implies that $U_{\nu} + U_{\iota(\nu)} = 0$ for every $\nu \in X$. Therefore all bad indices may be omitted from the sum $\sum_{\nu < \lambda} U_{\nu}$, and this completes the proof.

Moreover, to evaluate $\sum_{\nu \leq \lambda} U_{\nu}$ in the situation where $\nu_j = 0$ for all j > n, notice that if the minimal j such that $\nu_j < \lambda_{j+1}$ is j = n, then $\nu_n < 0$ and therefore $U_{\nu} = 0$. \Box

2.4 The Pieri Rule

For any $d \ge 1$ define the operator R^d by

$$R^d = \prod_{1 \le i < j \le d} (1 - R_{ij}).$$

For p > 0 and any partition λ of length ℓ , we compute

$$u_{p} \cdot U_{\lambda} = u_{p} \cdot R^{\ell} u_{\lambda} = R^{\ell} u_{(\lambda,p)} = R^{\ell+1} \cdot \prod_{i=1}^{\ell} (1 - R_{i,\ell+1})^{-1} u_{(\lambda,p)}$$
$$= R^{\ell+1} \cdot \prod_{i=1}^{\ell} (1 + R_{i,\ell+1} + R_{i,\ell+1}^{2} + \cdots) u_{(\lambda,p)} = \sum_{\alpha \ge 0} U_{\lambda+\alpha} ,$$

where the sum is over all compositions α such that $|\alpha| = p$ and $\alpha_j = 0$ for $j > \ell + 1$. Applying Lemma 2, we arrive at the *Pieri rule*

(8)
$$u_p \cdot U_{\lambda} = \sum_{\lambda \xrightarrow{p} \mu} U_{\mu} \,.$$

Conversely, suppose that we are given a family $\{X_{\lambda}\}$ of elements of \mathbf{A} , one for each partition λ , such that $X_p = u_p$ for every integer $p \ge 0$ and the X_{λ} satisfy the Pieri rule $X_p \cdot X_{\lambda} = \sum_{\lambda \xrightarrow{p} \to \mu} X_{\mu}$. We claim then that

$$X_{\lambda} = U_{\lambda} = \prod_{i < j} (1 - R_{ij}) u_{\lambda}$$

for every partition λ . To see this, note that the Pieri rule implies that

(9)
$$U_{\lambda} + \sum_{\mu \succ \lambda} a_{\lambda \mu} U_{\mu} = u_{\lambda_{1}} \cdots u_{\lambda_{\ell}} = X_{\lambda} + \sum_{\mu \succ \lambda} a_{\lambda \mu} X_{\mu}$$

for some constants $a_{\lambda\mu} \in \mathbb{Z}$. The claim now follows by induction on λ .

EXAMPLE 2. We have

$$u_2 \cdot U_{(3,3,1)} = U_{(5,3,1)} + U_{(4,3,2)} + U_{(4,3,1,1)} + U_{(3,3,3)} + U_{(3,3,2,1)}.$$

2.5 KOSTKA NUMBERS

A (semistandard) tableau T on the skew shape λ/μ is a filling of the boxes of λ/μ with positive integers, so that the entries are weakly increasing along each row from left to right and strictly increasing down each column. We can identify such a tableau T with a sequence of partitions

$$\mu = \lambda^0 \xrightarrow{c_1} \lambda^1 \xrightarrow{c_2} \cdots \xrightarrow{c_r} \lambda^r = \lambda$$

such that for $1 \le i \le r$ the horizontal strip $\lambda^i / \lambda^{i-1}$ consists of the c_i boxes in *T* with entry *i*. The composition $c(T) = (c_1, \ldots, c_r)$ is called the *content* of *T*.

Let μ be a partition and α any integer vector. The equation

$$u_{\alpha} U_{\mu} = \sum_{\lambda} K_{\lambda/\mu,\alpha} U_{\lambda}$$

summed over partitions λ such that $\lambda \supset \mu$ defines the *Kostka numbers* $K_{\lambda/\mu,\alpha}$. If α is not a composition such that $|\alpha| = |\lambda/\mu|$ then we have $K_{\lambda/\mu,\alpha} = 0$. Otherwise, iteration of the Pieri rule shows that $K_{\lambda/\mu,\alpha}$ equals the number of tableaux *T* of shape λ/μ and content vector $c(T) = \alpha$. We deduce from equation (9) that the *Kostka matrix* $K = \{K_{\lambda,\mu}\}$, whose rows and columns are indexed by partitions, is lower unitriangular with respect to the dominance order.

2.6 THE LITTLEWOOD-RICHARDSON RULE

Define the *Littlewood-Richardson coefficients* to be the structure constants $c^{\lambda}_{\mu\nu}$ in the equation

(10)
$$U_{\mu} \cdot U_{\nu} = \sum_{\lambda} c_{\mu\nu}^{\lambda} U_{\lambda} \,.$$

If $\ell = \ell(\nu)$, we compute that

$$U_{\mu} \cdot U_{\nu} = \sum_{w \in S_{\ell}} (-1)^{w} u_{w(\nu+\rho_{\ell})-\rho_{\ell}} U_{\mu}$$
$$= \sum_{\lambda} \sum_{w \in S_{\ell}} (-1)^{w} K_{\lambda/\mu,w(\nu+\rho_{\ell})-\rho_{\ell}} U_{\lambda}$$

from which we deduce that

(11)
$$c_{\mu\nu}^{\lambda} = \sum_{(w,T)} (-1)^w,$$

where the sum is over all pairs (w, T) such that $w \in S_{\ell}$ and T is a tableau on λ/μ with $c(T) + \rho_{\ell} = w(\nu + \rho_{\ell})$. Observe that c(T) is a partition if and

only if $c(T) + \rho_{\ell}$ is a strict partition, in which case $c(T) + \rho_{\ell} = w(\nu + \rho_{\ell})$ implies that w = 1.

For any tableau T, let $T_{>r}$ denote the subtableau of T formed by the entries in columns r and higher, and define $T_{>r}$ and $T_{< r}$ similarly. We say that a pair (w, T) is bad if $c(T_{>r})$ is not a partition for some r. Let Y denote the set of bad pairs indexing the sum (11), and define a sign reversing involution $\iota: Y \to Y$ as follows. Given $(w,T) \in Y$, choose r maximal such that $c(T_{\geq r})$ is not a partition, and let j be minimal such that $c_j(T_{>r}) < c_{j+1}(T_{>r})$. Call an entry j (resp. j+1) in T free if there is no j+1 (resp. j) in its column. Let T' denote the filling of λ/μ obtained from T by replacing all free j's (resp. (j+1)'s) that lie in $T_{< r}$ with (j + 1)'s (resp. j's), and then arranging the entries of each row in weakly increasing order. Since $c(T_{>r})$ is a partition, we deduce that T contains a single entry j + 1 in column r, and no j in column r, while $c_j(T_{>r}) + 1 = c_{j+1}(T_{>r})$. It follows easily from this that T' is a tableau. We define $\iota(w,T) = (\epsilon_i w,T')$, where ϵ_i denotes the transposition (j,j+1). Since $\epsilon_i c(T_{\leq r}) = c(T'_{\leq r})$ and $\epsilon_i (c(T_{>r}) + \rho_\ell) = c(T_{>r}) + \rho_\ell$, while $T_{>r}$ coincides with $T'_{>r}$, it follows that $\epsilon_j(c(T) + \rho_\ell) = c(T') + \rho_\ell$ and $\iota(w, T) \in Y$. We conclude that the bad pairs can be cancelled from the sum (11).

The above argument proves that $c_{\mu\nu}^{\lambda}$ is equal to the number of tableaux T of shape λ/μ and content ν such that $T_{\geq r}$ is a partition for each r. This is one among many equivalent forms of the *Littlewood-Richardson rule*.

2.7 DUALITY INVOLUTION

Let $v_r = U_{(1')}$ for $r \ge 1$, $v_0 = 1$, and $v_r = 0$ for r < 0. By expanding the determinant $U_{(1')} = \det(u_{1+j-i})_{1\le i,j\le r}$ along the first row, we obtain the identity

(12)
$$v_r - u_1 v_{r-1} + u_2 v_{r-2} - \dots + (-1)^r u_r = 0.$$

Define a ring homomorphism $\omega \colon \mathbf{A} \to \mathbf{A}$ by setting $\omega(u_r) = v_r$ for every integer r. For any integer sequence α , let $v_{\alpha} = \prod_i v_{\alpha_i}$, and for any partition λ , set

$$V_{\lambda} = \omega(U_{\lambda}) = \prod_{i < j} (1 - R_{ij}) v_{\lambda}.$$

We deduce from (8) that the V_{λ} satisfy the Pieri rule

(13)
$$v_p \cdot V_{\lambda} = \sum_{\lambda \xrightarrow{p} \mu} V_{\mu} \,.$$

On the other hand, the Littlewood-Richardson rule easily implies that

(14)
$$U_{(1^p)} \cdot U_{\lambda} = \sum_{\mu} U_{\mu}$$

summed over all partitions $\mu \supset \lambda$ such that μ/λ is a *vertical p-strip*. It follows from (13), (14), and induction on λ that $V_{\lambda} = U_{\lambda'}$ for each λ . Here λ' denotes the partition which is conjugate to λ , i.e. such that $\lambda'_i = \#\{j \mid \lambda_j \ge i\}$ for all *i*. In particular, the equality $\omega(U_{\lambda}) = U_{\lambda'}$ proves that ω is an involution of **A**, a fact that can also be deduced from (12).

2.8 CAUCHY IDENTITIES AND SKEW SCHUR POLYNOMIALS

Define a new **Z**-basis t_{λ} of **A** by the transition equations

(15)
$$U_{\lambda} = \sum_{\mu} K_{\lambda,\mu} t_{\mu} \,.$$

In other words, the transition matrix M(U,t) between the bases U_{λ} and t_{λ} of **A** is defined to be the lower unitriangular Kostka matrix *K*. Then $A := M(t, U) = K^{-1}$ and $B := M(u, U) = K^{t}$. We have

$$\sum_{\lambda} t_{\lambda} \otimes u_{\lambda} = \sum_{\lambda,\mu,\nu} A_{\lambda\mu} B_{\lambda\nu} U_{\mu} \otimes U_{\nu}$$
$$= \sum_{\lambda,\mu,\nu} A_{\mu\lambda}^{t} B_{\lambda\nu} U_{\mu} \otimes U_{\nu} = \sum_{\mu} U_{\mu} \otimes U_{\mu}$$

in $\mathbf{A} \otimes_{\mathbf{Z}} \mathbf{A}$, where the above sums are either formal or restricted to run over partitions of a fixed integer *n*. We deduce the Cauchy identity

(16)
$$\sum_{\lambda} U_{\lambda} \otimes U_{\lambda} = \sum_{\lambda} t_{\lambda} \otimes u_{\lambda}$$

and, by applying the automorphism $1 \otimes \omega$ to (16), the dual Cauchy identity

(17)
$$\sum_{\lambda} U_{\lambda} \otimes V_{\lambda} = \sum_{\lambda} t_{\lambda} \otimes v_{\lambda} \,.$$

For any skew diagram λ/μ , define the *skew Schur polynomial* $U_{\lambda/\mu}$ by generalizing equation (15):

$$U_{\lambda/\mu} := \sum_{\nu} K_{\lambda/\mu,\nu} t_{\nu} \,.$$

We have the following computation in the ring $A \otimes_Z A \otimes_Z A$:

$$\sum_{\mu,\nu} U_{\mu} \otimes U_{\nu} \otimes U_{\mu} U_{\nu} = \sum_{\mu,\nu} U_{\mu} \otimes t_{\nu} \otimes U_{\mu} u_{\nu} = \sum_{\lambda,\mu,\nu} U_{\mu} \otimes t_{\nu} \otimes K_{\lambda/\mu,\nu} U_{\lambda}$$
$$= \sum_{\lambda,\mu} U_{\mu} \otimes U_{\lambda/\mu} \otimes U_{\lambda}.$$

By comparing the coefficient of $U_{\mu} \otimes U_{\nu} \otimes U_{\lambda}$ on either end of the previous equation, we obtain

(18)
$$U_{\lambda/\mu} = \sum_{\nu} c_{\mu\nu}^{\lambda} U_{\nu} ,$$

where the coefficients $c^{\lambda}_{\mu\nu}$ are the same as the ones in (10). Since $\omega(U_{\lambda}) = U_{\lambda'}$ implies the identity $c^{\lambda}_{\mu\nu} = c^{\lambda'}_{\mu'\nu'}$, we deduce from (18) that

(19)
$$\omega(U_{\lambda/\mu}) = U_{\lambda'/\mu'}.$$

3. SYMMETRIC FUNCTIONS

3.1 INITIAL DEFINITIONS

Let $x = (x_1, x_2, ...)$ be an infinite sequence of commuting variables. For any composition α we set $x^{\alpha} = \prod_i x_i^{\alpha_i}$. Given $k \ge 0$, let Λ^k denote the abelian group of all formal power series $\sum_{|\alpha|=k} c_{\alpha} x^{\alpha} \in \mathbb{Z}[[x_1, x_2, ...]]$ which are invariant under any permutation of the variables x_i . The elements of Λ^k are called *homogeneous symmetric functions of degree* k, and the graded ring $\Lambda = \bigoplus_{k>0} \Lambda^k$ is the ring of symmetric functions.

For each partition λ of k, we obtain an element $m_{\lambda} \in \Lambda^{k}$ by symmetrizing the monomial x^{λ} . In other words, $m_{\lambda}(x) = \sum_{\alpha} x^{\alpha}$ where the sum is over all distinct permutations $\alpha = (\alpha_{1}, \alpha_{2}, ...)$ of $\lambda = (\lambda_{1}, \lambda_{2}, ...)$. We call m_{λ} a monomial symmetric function. The definition implies that if $f = \sum_{\alpha} c_{\alpha} x^{\alpha} \in \Lambda^{k}$, then $f = \sum_{\lambda} c_{\lambda} m_{\lambda}$. It follows that the m_{λ} for all partitions λ of k (respectively, for all partitions λ) form a **Z**-basis of Λ^{k} (respectively, of Λ).

Let $h_r = h_r(x)$ denote the *r*-th complete symmetric function, defined by

$$h_r(x) = \sum_{\lambda : |\lambda| = r} m_\lambda(x) = \sum_{i_1 \le \dots \le i_r} x_{i_1} \cdots x_{i_r}.$$

We have the generating function equation

(20)
$$H(t) = \sum_{r=0}^{\infty} h_r(x)t^r = \prod_{i=1}^{\infty} (1 - x_i t)^{-1}.$$

Let $h_{\alpha} = \prod_{i} h_{\alpha_{i}}$ for any integer sequence α .

There is a unique ring homomorphism $\phi: \mathbf{A} \to \Lambda$ defined by setting $\phi(u_r) = h_r$ for every $r \ge 0$. For any integer sequence α , the *Schur* function s_{α} is defined by $s_{\alpha} = \phi(U_{\alpha})$. We have

$$s_{\alpha} = \prod_{i < j} (1 - R_{ij}) h_{\alpha} = \det(h_{\alpha_i + j - i})_{i, j}.$$

3.2 REDUCTION AND TABLEAU FORMULAS

Let $y = (y_1, y_2, ...)$ be a second sequence of variables, choose $n \ge 1$, and set $x^{(n)} = (x_1, ..., x_n)$. It follows easily from equation (20) that for any integer p,

$$h_p(x^{(n)}, y) = \sum_{i=0}^p h_i(x_n) h_{p-i}(x^{(n-1)}, y).$$

Therefore, for any integer vector ν , we have

$$h_{\nu}(x^{(n)}, y) = \sum_{\alpha \ge 0} h_{\alpha}(x_n) h_{\nu-\alpha}(x^{(n-1)}, y) = \sum_{\alpha \ge 0} x_n^{|\alpha|} h_{\nu-\alpha}(x^{(n-1)}, y)$$

summed over all compositions α . If *R* denotes any raising operator and λ is any partition, we obtain

(21)
$$R h_{\lambda}(x^{(n)}, y) = \sum_{\alpha \ge 0} x_n^{|\alpha|} h_{R\lambda - \alpha}(x^{(n-1)}, y) = \sum_{\alpha \ge 0} x_n^{|\alpha|} R h_{\lambda - \alpha}(x^{(n-1)}, y).$$

Since $s_{\lambda} = \prod_{i < j} (1 - R_{ij}) h_{\lambda}$, we deduce from (21) that

$$s_{\lambda}(x^{(n)}, y) = \sum_{\alpha \ge 0} x_n^{|\alpha|} s_{\lambda-\alpha}(x^{(n-1)}, y) = \sum_{p=0}^{\infty} x_n^p \sum_{|\alpha|=p} s_{\lambda-\alpha}(x^{(n-1)}, y)$$

Applying Lemma 2, we obtain the reduction formula

(22)
$$s_{\lambda}(x^{(n)}, y) = \sum_{p=0}^{\infty} x_n^p \sum_{\mu \to \lambda} s_{\mu}(x^{(n-1)}, y) \, .$$

Repeated application of the reduction equation (22) results in

(23)
$$s_{\lambda}(x^{(n)}, y) = \sum_{\mu \subset \lambda} s_{\mu}(y) \sum_{T \text{ on } \lambda/\mu} x^{c(T)},$$

where the first sum is over partitions $\mu \subset \lambda$ and the second over all tableau *T* of shape λ/μ with entries at most *n*. As *n* is arbitrary, equation (23) holds with $x = (x_1, x_2, ...)$ in place of $x^{(n)}$. It follows that

$$s_{\lambda}(x, y) = \sum_{\mu \subset \lambda} s_{\mu}(y) \sum_{T \text{ on } \lambda/\mu} x^{c(T)}$$

where the second sum is over all tableau T of shape λ/μ . Substituting y = 0 proves Littlewood's tableau formula

(24)
$$s_{\lambda}(x) = \sum_{T \text{ on } \lambda} x^{c(T)} = \sum_{\mu} K_{\lambda,\mu} m_{\mu}(x) \,.$$

From (24) we deduce immediately that the s_{λ} for λ a partition form a **Z**-basis of Λ , and comparing with (15) shows that $\phi(t_{\lambda}) = m_{\lambda}$. It follows that the functions h_{λ} for λ a partition also form a **Z**-basis of Λ .

3.3 DUALITY AND CAUCHY IDENTITIES

Let $e_r = e_r(x)$ denote the *r*-th *elementary symmetric function* in the variables *x*, so that

$$e_r(x) = m_{(1^r)}(x) = \sum_{i_1 < \cdots < i_r} x_{i_1} \cdots x_{i_r}.$$

The generating function E(t) for the e_r satisfies

$$E(t) = \sum_{r=0}^{\infty} e_r(x)t^r = \prod_{i=1}^{\infty} (1 + x_i t).$$

Since E(t)H(-t) = 1, we obtain

(25)
$$e_r - h_1 e_{r-1} + h_2 e_{r-2} - \dots + (-1)^r h_r = 0$$

for each $r \ge 1$. For any integer sequence α , we set $e_{\alpha} = \prod_{i} e_{\alpha_{i}}$.

By comparing equations (12) and (25), we deduce that $\phi(v_r) = e_r$ for each r, and hence $\phi(v_{\lambda}) = e_{\lambda}$ and $\phi(V_{\lambda}) = s_{\lambda'}$. The duality involution on **A** transfers to an automorphism $\omega: \Lambda \to \Lambda$ which sends h_{λ} to e_{λ} and s_{λ} to $s_{\lambda'}$, for each partition λ . We deduce that the e_{λ} form another **Z**-basis of Λ . Moreover, by applying ϕ to (16) and (17), we obtain the usual form of the *Cauchy identities*

$$\sum_{\lambda} s_{\lambda}(x) s_{\lambda}(y) = \sum_{\lambda} m_{\lambda}(x) h_{\lambda}(y) = \prod_{i,j} \frac{1}{1 - x_i y_j}$$

and

$$\sum_{\lambda} s_{\lambda}(x) s_{\lambda'}(y) = \sum_{\lambda} m_{\lambda}(x) e_{\lambda}(y) = \prod_{i,j} (1 + x_i y_j),$$

where the sums are taken over all partitions λ .

3.4 Skew Schur functions

Define the *skew Schur functions* $s_{\lambda/\mu}$ by

$$s_{\lambda/\mu}(x) = \phi(U_{\lambda/\mu}) = \sum_{\nu} K_{\lambda/\mu,\nu} m_{\nu}(x) = \sum_{T \text{ on } \lambda/\mu} x^{c(T)}.$$

Equation (23) then implies that

(26)
$$s_{\lambda}(x,y) = \sum_{\mu \subset \lambda} s_{\lambda/\mu}(x) s_{\mu}(y) = \sum_{\mu \subset \lambda} s_{\mu}(x) s_{\lambda/\mu}(y) \,.$$

Applying the operator $\prod_{i < j} (1 - R_{ij})$ to both sides of the equation

$$h_{\lambda}(x, y) = \sum_{\alpha \ge 0} h_{\alpha}(x) h_{\lambda - \alpha}(y)$$

gives

(27)
$$s_{\lambda}(x,y) = \sum_{\alpha \ge 0} h_{\alpha}(x) s_{\lambda-\alpha}(y) \, .$$

Since $h_{\alpha} = \sum_{\mu} K_{\mu,\alpha} s_{\mu}$, comparing (26) with (27) proves that

(28)
$$s_{\lambda/\mu} = \sum_{\alpha \ge 0} K_{\mu,\alpha} s_{\lambda-\alpha}$$

Observe that (28) is a generalization of the second identity in Lemma 2.

Using Lemma 1(b) in (27), we obtain that

(29)
$$s_{\lambda}(x,y) = \sum_{\mu} s_{\mu}(y) \sum_{w \in S_{\ell}} (-1)^{w} h_{\lambda + \rho_{\ell} - w(\mu + \rho_{\ell})}(x),$$

where the first sum is over all partitions μ and $\ell = \ell(\lambda)$. Equating the coefficients of $s_{\mu}(y)$ in (26) and (29) proves the following generalization of the Jacobi-Trudi identity (2):

(30)
$$s_{\lambda/\mu} = \sum_{w \in S_{\ell}} (-1)^w h_{\lambda+\rho_{\ell}-w(\mu+\rho_{\ell})} = \det(h_{\lambda_i-\mu_j+j-i})_{i,j}$$

By applying the involution ω to (30) and using (19), we derive the dual equation

$$s_{\lambda'/\mu'} = \det(e_{\lambda_i - \mu_i + j - i})_{i,j}.$$

3.5 THE CLASSICAL DEFINITION OF SCHUR POLYNOMIALS

In this section we fix *n*, the number of variables, and work with integer vectors and partitions in \mathbb{Z}^n . Let $x = (x_1, \ldots, x_n)$ and set $\rho = \rho_n = (n - 1, \ldots, 1, 0)$. For each $\alpha \in \mathbb{Z}^n$, define

$$A_{\alpha} = \sum_{w \in S_n} (-1)^w x^{w(\alpha)} = \det(x_i^{\alpha_j})_{1 \le i, j \le n}$$

and set $\tilde{s}_{\alpha}(x) = A_{\alpha+\rho}/A_{\rho}$. Consider the **Z**-linear map $\mathbf{A} \to \mathbf{Z}[x_1, \ldots, x_n]$ sending U_{λ} to $A_{\lambda+\rho}$ for any partition λ with $\ell(\lambda) \leq n$, and to zero, if $\ell(\lambda) > n$. It follows from Lemma 1(b) that this map sends U_{α} to $A_{\alpha+\rho}$ for any composition $\alpha \in \mathbf{Z}^n$. Lemma 2 therefore implies that for any partition $\lambda \in \mathbf{Z}^n$ and integer $r \geq 0$, we have

(31)
$$\sum_{\alpha \ge 0} A_{\lambda + \alpha + \rho} = \sum_{\lambda \xrightarrow{r} \mu} A_{\mu + \rho},$$

where the sums are over compositions $\alpha \ge 0$ with $|\alpha| = r$ and $\ell(\alpha) \le n$ and partitions μ with $\lambda \xrightarrow{r} \mu$ and $\ell(\mu) \le n$. Furthermore, we have

$$A_{\lambda+\rho} h_r(x) = \sum_{w \in S_n} (-1)^w \sum_{\alpha \ge 0: \ |\alpha| = r} x^{w(\lambda+\rho)+\alpha}$$
$$= \sum_{w \in S_n} (-1)^w \sum_{\alpha \ge 0: \ |\alpha| = r} x^{w(\lambda+\rho)+w(\alpha)}$$
$$= \sum_{\alpha \ge 0: \ |\alpha| = r} A_{\lambda+\alpha+\rho} = \sum_{\lambda \xrightarrow{r} \mu} A_{\mu+\rho} ,$$

by (31). Now divide by A_{ρ} to deduce that

(32)
$$\tilde{s}_{\lambda}(x) h_r(x) = \sum_{\lambda \xrightarrow{r} \mu} \tilde{s}_{\mu}(x)$$

Applying (32) with $\lambda = 0$ gives $\tilde{s}_r(x) = h_r(x)$, for every $r \ge 1$. Since the $\tilde{s}_{\lambda}(x)$ satisfy the Pieri rule, it follows by induction on λ as in §2.4 that

$$\tilde{s}_{\lambda}(x) = \prod_{i < j} (1 - R_{ij}) h_{\lambda}(x) = s_{\lambda}(x)$$

for each partition λ of length at most *n*. We have thus proved equation (1).

REFERENCES

[BZ]

BERENSTEIN, A.D. and A.V. ZELEVINSKY. Involutions on Gel'fand-Tsetlin schemes and multiplicities in skew *GL_n*-modules. *Dokl. Akad. Nauk SSSR 300* (1988), 1291–1294; English translation: *Soviet Math. Dokl. 37* (1988), 799–802.

- [BKT1] BUCH, A.S., A. KRESCH and H. TAMVAKIS. Quantum Pieri rules for isotropic Grassmannians. *Invent. Math.* 178 (2009), 345–405.
- [BKT2] BUCH, A.S., A. KRESCH and H. TAMVAKIS. A Giambelli formula for isotropic Grassmannians. Preprint (2010).
- [F] FULTON, W. Young Tableaux. With applications to representation theory and geometry. London Mathematical Society Student Texts 35. Cambridge University Press, Cambridge, 1997.
- [FH] FULTON, W. and J. HARRIS. *Representation Theory. A First Course*. Graduate Texts in Mathematics 129. Springer-Verlag, New York, 1991.
- [Ga] GASHAROV, V. A short proof of the Littlewood-Richardson rule. *European* J. Combin. 19 (1998), 451–453.
- [GV] GESSEL, I. and V. VIENNOT. Determinants, paths, and plane partitions. Preprint (1989).
- [G] GIAMBELLI, G.Z. Risoluzione del problema degli spazi secanti. Mem. R. Accad. Sci. Torino (2) 52 (1902), 171–211.
- JACOBI, C.G.J. De functionibus alternantibus earumque divisione per productum e differentiis elementorum conflatum. *Crelle's Journal* 22 (1841), 360–371. Reprinted in Gesammelte Werke 3, 439–452, Chelsea, New York, 1969.
- [La] LASCOUX, A. Symmetric Functions and Combinatorial Operators on Polynomials. CBMS Regional Conference Series in Mathematics 99. Amer. Math. Soc., Providence, RI, 2003.
- [vL] VAN LEEUWEN, M.A.A. Schur functions and alternating sums. *Electron*. *J. Combin. 11* (2006), Art. 5, 42pp.
- [L] LITTLEWOOD, D.E. The construction of invariant matrices. *Proc. London Math. Soc.* (2) 43 (1937), 226–240.
- [M] MACDONALD, I.G. Symmetric Functions and Hall Polynomials. Second edition. Oxford Mathematical Monographs. Oxford Science Publications. The Clarendon Press, Oxford University Press, New York, 1995.
- [Ma] MANIVEL, L. Fonctions symétriques, polynômes de Schubert et lieux de dégénérescence. Cours Spécialisés 3. Société Mathématique de France, Paris, 1998.
- [P] PIERI, M. Sul problema degli spazi secanti. Nota 1^a. Rend. Ist. Lombardo (2) 26 (1893), 534–546.
- [Pr] PROCTOR, R.A. Equivalence of the combinatorial and the classical definitions of Schur functions. J. Combin. Theory Ser. A 51 (1989), 135–137.
- [RS] REMMEL, J.B. and M. SHIMOZONO. A simple proof of the Littlewood-Richardson rule and applications. *Discrete Math. 193* (1998), 257– 266.
- [Sa] SAGAN, B.E. The Symmetric Group. Representations, Combinatorial Algorithms, and Symmetric Functions. Second edition. Graduate Texts in Mathematics 203. Springer-Verlag, New York, 2001.

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[Sta]	STANLEY, R.P. <i>Enumerative Combinatorics, Vol.</i> 2. Cambridge Studies in Advanced Mathematics 62. Cambridge University Press, Cambridge, 1999.
[Ste]	STEMBRIDGE, J.R. A concise proof of the Littlewood-Richardson rule. <i>Electron. J. Combin. 9</i> (2002), N5, 4pp.
[T]	TAMVAKIS, H. Giambelli, Pieri, and tableau formulas via raising operators. <i>J. Reine Angew. Math.</i> 652 (2011), 207–244.
[W]	WEYL, H. The Theory of Groups and Quantum Mechanics. Methuen, London, 1931.
[Y]	YOUNG, A. On quantitative substitutional analysis VI. Proc. London Math. Soc. (2) 34 (1932), 196–230.
[Z]	ZELEVINSKY, A.V. Representations of Finite Classical Groups. A Hopf Algebra Approach. Lecture Notes in Mathematics 869. Springer- Verlag, Berlin-New York, 1981.

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