FPSAC 2009, Hagenberg, Austria DMTCS proc. **AK**, 2009, 13–24

Unital versions of the higher order peak algebras

Marcelo Aguiar[1]†, Jean-Christophe Novelli[2] and Jean-Yves Thibon[2] ‡

[1] *Department of Mathematics, Texas A&M University, College Station, TX 77843, USA*
[2] *Institut Gaspard Monge, Université Paris-Est Marne-la-Vallée, 77454 Marne-la-Vallée cedex 2, France*

Abstract. We construct unital extensions of the higher order peak algebras defined by Krob and the third author in [Ann. Comb. 9 (2005), 411–430], and show that they can be obtained as homomorphic images of certain subalgebras of the Mantaci-Reutenauer algebras of type B. This generalizes a result of Bergeron, Nyman and the first author [Trans. AMS 356 (2004), 2781–2824].

Résumé. Nous construisons des extensions unitaires des algèbres de pics d'ordre supérieur définies par Krob et le troisième auteur dans [Ann. Comb. 9 (2005), 411–430], et nous montrons qu'elles peuvent être obtenues comme images homomorphes de certaines sous-algèbres des algèbres de Mantaci-Reutenauer de type B. Ceci généralise un résultat dû à Bergeron, Nyman et au premier auteur [Trans. AMS 356 (2004), 2781–2824].

Keywords: Descent algebras, Noncommutative symmetric functions, Peak algebras

1 Introduction

A *descent* of a permutation $\sigma \in \mathfrak{S}_n$ is an index i such that $\sigma(i) > \sigma(i+1)$. A descent is a *peak* if moreover $i > 1$ and $\sigma(i) > \sigma(i-1)$. The sums of permutations with a given descent set span a subalgebra of the group algebra, the *descent algebra* Σ_n. The *peak algebra* $\mathring{\mathcal{P}}_n$ of $\mathfrak{S}_n$ is a subalgebra of its descent algebra, spanned by sums of permutations having the same peak set. This algebra has no unit. Descent algebras can be defined for all finite Coxeter groups [19]. In [2], it is shown that the peak algebra of $\mathfrak{S}_n$ can be naturally extended to a unital algebra, which is obtained as a homomorphic image of the descent algebra of the hyperoctahedral group B_n.

The direct sum of the peak algebras turns out to be a Hopf subalgebra of the direct sum of all descent algebras, which can itself be identified with $\mathbf{Sym}$, the Hopf algebra of noncommutative symmetric functions [9]. As explained in [5], it turns out that a fair amount of results on the peak algebras can be deduced from the case $q = -1$ of a q-identity of [11]. Specializing q to other roots of unity, Krob and the third author introduced and studied *higher order peak algebras* in [12]. Again, these are non-unital, and it is natural to ask whether the construction of [2] can be extended to this case.

†Partially supported by NSF grant DMS-0600973.
‡Partially supported by ANR grant 06-BLAN-0380.

We will show that this is indeed possible. We first construct the unital versions of the higher order peak algebras by a simple manipulation of generating series. We then show that they can be obtained as homomorphic images of the *Mantaci-Reutenauer algebras* of type B. Hence no Coxeter groups other than B_n and $\mathfrak{S}_n$ are involved in the process; in fact, the construction is related to the notion of superization, as defined in [16], rather than to root systems or wreath products.

2 Notations and background

2.1 Noncommutative symmetric functions

We will assume familiarity with the notations of [9] and with the main results of [12]. We recall a few definitions for the convenience of the reader.

The Hopf algebra of noncommutative symmetric functions is denoted by $\mathbf{Sym}$, or by $\mathbf{Sym}(A)$ if we consider the realization in terms of an auxiliary alphabet A. Linear bases of $\mathbf{Sym}_n$ are labelled by compositions $I = (i_1, \dots, i_r)$ of n (we write $I \vDash n$). The noncommutative complete and elementary functions are denoted by S_n and Λ_n, and $S^I = S_{i_1} \cdots S_{i_r}$. The ribbon basis is denoted by R_I. The *descent set* of I is $\mathrm{Des}(I) = \{i_1,\ i_1+i_2, \dots, i_1+\cdots+i_{r-1}\}$. The *descent composition* of a permutation $\sigma \in \mathfrak{S}_n$ is the composition $I = D(\sigma)$ of n whose descent set is the descent set of σ.

Recall from [8] that for an infinite totally ordered alphabet A, $\mathbf{FQSym}(A)$ is the subalgebra of $\mathbb{C}\langle A\rangle$ spanned by the polynomials

$$\mathbf{G}_\sigma(A) = \sum_{\mathrm{std}(w)=\sigma} w, \tag{1}$$

that is, the sum of all words in A^n whose standardization is the permutation $\sigma \in \mathfrak{S}_n$. The noncommutative ribbon Schur function $R_I \in \mathbf{Sym}$ is then

$$R_I = \sum_{\mathrm{D}(\sigma)=I} \mathbf{G}_\sigma\,. \tag{2}$$

This defines a Hopf embedding $\mathbf{Sym} \to \mathbf{FQSym}$. The Hopf algebra $\mathbf{FQSym}$ is self-dual under the pairing $(\mathbf{G}_\sigma\,,\, \mathbf{G}_\tau) = \delta_{\sigma,\tau^{-1}}$ (Kronecker symbol). Let $\mathbf{F}_\sigma := \mathbf{G}_{\sigma^{-1}}$, so that $\{\mathbf{F}_\sigma\}$ is the dual basis of $\{\mathbf{G}_\sigma\}$. The *internal product* $*$ of $\mathbf{FQSym}$ is induced by composition $\circ$ in $\mathfrak{S}_n$ in the basis $\mathbf{F}$, that is,

$$\mathbf{F}_\sigma * \mathbf{F}_\tau = \mathbf{F}_{\sigma\circ\tau} \quad \text{and} \quad \mathbf{G}_\sigma * \mathbf{G}_\tau = \mathbf{G}_{\tau\circ\sigma}\,. \tag{3}$$

Each subspace $\mathbf{Sym}_n$ is stable under this operation, and anti-isomorphic to the descent algebra Σ_n of $\mathfrak{S}_n$. For $f_i \in \mathbf{FQSym}$ and $g \in \mathbf{Sym}$, we have the splitting formula

$$(f_1 \dots f_r) * g = \mu_r \cdot (f_1 \otimes \cdots \otimes f_r) *_r \Delta^r g\,, \tag{4}$$

where μ_r is r-fold multiplication, and Δ^r the iterated coproduct with values in the r-th tensor power.

2.2 The Mantaci-Reutenauer algebra of level 2

We denote by $\mathbf{MR}$ the free product $\mathbf{Sym} \star \mathbf{Sym}$ of two copies of the Hopf algebra of noncommutative symmetric functions [14]. That is, $\mathbf{MR}$ is the free associative algebra on two sequences (S_n) and $(S_{\bar{n}})$ $(n \geq 1)$. We regard the two copies of $\mathbf{Sym}$ as noncommutative symmetric functions on two auxiliary alphabets: $S_n = S_n(A)$ and $S_{\bar n} = S_n(\bar A)$. We denote by $F \mapsto \bar F$ the involutive automorphism which exchanges S_n and $S_{\bar n}$. The bialgebra structure is defined by the requirement that the series

$$\sigma_1 = \sum_{n\geq 0} S_n \text{ and } \bar\sigma_1 = \sum_{n\geq 0} S_{\bar n} \tag{5}$$

are grouplike. The internal product of $\mathbf{MR}$ can be computed from the splitting formula and the conditions that σ_1 is neutral, $\bar\sigma_1$ is central, and $\bar\sigma_1 * \bar\sigma_1 = \sigma_1$.

In [15], an embedding of $\mathbf{MR}$ in the Hopf algebra $\mathbf{BFQSym}$ of free quasi-symmetric functions of type B (spanned by colored permutations) is described. Under this embedding, left $*$-multiplication by $\Lambda_n = \mathbf{G}_{n\,n-1\ldots 2,1}$ corresponds to right multiplication by $n\,n-1\ldots 2, 1$ in the group algebra of B_n. This implies that left $*$-multiplication by λ_1 is an involutive anti-automorphism of $\mathbf{BFQSym}$, hence of $\mathbf{MR}$.

2.3 Noncommutative symmetric functions of type B

The hyperoctahedral analogue $\mathbf{BSym}$ of $\mathbf{Sym}$, defined in [6], is the right $\mathbf{Sym}$-module freely generated by another sequence $(\tilde S_n)$ ($n \geq 0$, $\tilde S_0 = 1$) of homogeneous elements, with $\tilde\sigma_1$ grouplike. This is a coalgebra, but not an algebra. It is endowed with an internal product, for which each homogeneous component $\mathbf{BSym}_n$ is anti-isomorphic to the descent algebra of B_n.

3 Solomon descent algebras of type B

3.1 Descents in B_n

The hyperoctahedral group B_n is the group of signed permutations. A signed permutation can be denoted by $w = (\sigma, \epsilon)$ where σ is an ordinary permutation and $\epsilon \in \{\pm 1\}^n$, such that $w(i) = \epsilon_i \sigma(i)$. If we set $w(0) = 0$, then, $i \in [0, n-1]$ is a descent of w if $w(i) > w(i+1)$. Hence, the descent set of w is a subset $D = \{i_0, i_0 + i_1, \ldots, i_0 + i_1 + \cdots i_{r-1}\}$ of $[0, n-1]$. We then associate to D a so-called type-B composition (a composition whose first part can be zero) $(i_0 - 0, i_1, \ldots, i_{r-1}, n - i_{r-1})$. The sum of all signed permutations whose descent set is contained in D is mapped to $\tilde S^I := \tilde S_{i_0} S^{I'}$ by Chow's anti-isomorphism [6], where $I' = (i_1, \ldots, i_r)$.

3.2 Noncommutative supersymmetric functions

An embedding of $\mathbf{BSym}$ as a sub-coalgebra and sub-$\mathbf{Sym}$-module of $\mathbf{MR}$ can be deduced from [14]. To describe it, let us define, for $F \in \mathbf{Sym}(A)$,

$$F^\sharp = F(A|\bar A) = F(A - q\bar A)|_{q=-1} \tag{6}$$

(the supersymmetric version of F). The superization of $F \in \mathbf{Sym}(A)$ can also be given by

$$F^\sharp = F * \sigma_1^\sharp\,. \tag{7}$$

Indeed, $\sigma_1^\sharp$ is grouplike, and for $F = S^I$, the splitting formula gives

$$(S_{i_1} \cdots S_{i_r}) * \sigma_1^\sharp = \mu_r[(S_{i_1} \otimes \cdots \otimes S_{i_r}) * (\sigma_1^\sharp \otimes \cdots \otimes \sigma_1^\sharp)] = S^{I\sharp}\,. \tag{8}$$

We have

$$\sigma_1^\sharp = \bar\lambda_1\sigma_1 = \sum \Lambda_{\bar i} S_j\,. \tag{9}$$

The element $\bar\sigma_1$ is central for the internal product, and

$$\bar\sigma_1 * F = \bar F = F * \bar\sigma_1\,. \tag{10}$$

Hence,

$$\bar\sigma_1 * \sigma_1^\sharp = \lambda_1\bar\sigma_1 =: \sigma_1^\flat\,. \tag{11}$$

The basis element $\tilde S^I$ of $\mathbf{BSym}$, where $I=(i_0,i_1,\dots,i_r)$ is a type B-composition, can be embedded as

$$\tilde S^I = S_{i_0}(A) S^{i_1 i_2\cdots i_r}(A|\bar A)\,. \tag{12}$$

We will identify $\mathbf{BSym}$ with its image under this embedding.

3.3 A proof that $\mathbf{BSym}$ is $*$-stable

We are now in a position to understand why $\mathbf{BSym}$ is a $*$-subalgebra of $\mathbf{MR}$. The argument will be extended below to the case of unital peak algebras. Let $F,G \in \mathbf{Sym}$. We want to understand why $\sigma_1F^\sharp * \sigma_1G^\sharp$ is in $\mathbf{BSym}$. Using the splitting formula, we rewrite this as

$$\mu[(\sigma_1\otimes F^\sharp) * \Delta\sigma_1\Delta G^\sharp] = \sum_{(G)} (\sigma_1 G^\sharp_{(1)})(F^\sharp * \sigma_1 G^\sharp_{(2)}). \tag{13}$$

We now only have to show that each term $F^\sharp * \sigma_1 G^\sharp_{(2)}$ is in $\mathbf{Sym}^\sharp$. We may assume that $F=S^I$, and for any $G\in\mathbf{Sym}$,

$$S^{I\sharp} * \sigma_1 G^\sharp = \sum_{(G)} \mu_r[(S^\sharp_{i_1}\otimes\cdots\otimes S^\sharp_{i_r}) * (\sigma_1 G^\sharp_{(1)}\otimes\cdots\otimes\sigma_1 G^\sharp_{(r)})] \tag{14}$$

so that it is sufficient to prove the property for $F=S_n$. Now,

$$\begin{aligned}\sigma_1^\sharp * \sigma_1 G^\sharp &= (\bar\lambda_1\sigma_1) * \sigma_1 G^\sharp \\ &= \sum_{(G)} (\bar\lambda_1 * \sigma_1 G^\sharp_{(1)})(\sigma_1 G^\sharp_{(2)}) \\ &= \sum_{(G)} (\bar\sigma_1 * \lambda_1 * \sigma_1 G^\sharp_{(1)})\cdot\sigma_1\cdot G^\sharp_{(2)}\end{aligned} \tag{15}$$

Now,

$$\lambda_1 * \sigma_1 G^\sharp_{(1)} = (\lambda_1 * G^\sharp_{(1)})(\lambda_1*\sigma_1) = (\lambda_1 * G^\sharp_{(1)})\lambda_1, \tag{16}$$

since λ_1 is an anti-automorphism. We then get

$$\begin{aligned}\sigma_1^\sharp * \sigma_1 G^\sharp &= \sum_{(G)} (\bar\sigma_1 * ((\lambda_1 * G^\sharp_{(1)})\lambda_1)\cdot\sigma_1\cdot G^\sharp_{(2)} \\ &= \sum_{(G)} (\bar\sigma_1 * \lambda_1 * G^\sharp_{(1)})\cdot(\bar\sigma_1*\lambda_1)\sigma_1\cdot G^\sharp_{(2)} \\ &= \sum_{(G)} (\bar\lambda_1 * G^\sharp_{(1)})\cdot\sigma_1^\sharp\cdot G^\sharp_{(2)}\end{aligned} \tag{17}$$

Now, the result will follow if we can prove that $\bar{\lambda}_1 * G^\sharp$ is in $\mathbf{Sym}^\sharp$ for any $G \in \mathbf{Sym}$.

For $G = S^I$,

$$\bar{\lambda}_1 * S^{I\sharp} = \lambda_1 * \bar{\sigma}_1 * S^I * \sigma_1^\sharp = \lambda_1 * S^I * \bar{\sigma}_1 * \sigma_1^\sharp = \lambda_1 * S^I * \sigma_1^\flat \,. \tag{18}$$

Since left $*$-multiplication by λ_1 in an anti-automorphism, we only need to prove that $\lambda_1 * S_n^\flat$ is of the form $G^\sharp$. And indeed,

$$\begin{aligned}\lambda_1 * S_n^\flat &= \sum_{i+j=n} \lambda_1 * (\Lambda_i S_{\bar{j}}) \\ &= \sum_{i+j=n} (\lambda_1 * S_{\bar{j}})(\lambda_1 * \Lambda_i) \\ &= \sum_{i+j=n} \Lambda_{\bar{j}} S_i = S_n^\sharp \,.\end{aligned} \tag{19}$$

This concludes the proof that $\mathbf{BSym}$ is a $*$-subalgebra of $\mathbf{BFQSym}$.

4 Unital versions of the higher order peak algebras

As shown in [5], much of the theory of the peak algebra can be deduced from a formula of [11] for $R_I((1-q)A)$, in the special case $q = -1$. In [12], this formula was studied in the case where q is an arbitrary root of unity, and higher order analogs of the peak algebra were obtained. In [2], it was shown that the classical peak algebra can be extended to a unital algebra, which is obtained as a homomorphic image of the descent algebra of type B. In this section, we construct unital extensions of the higher order peak algebras.

Let q be a primitive r-th root of unity. All objects introduced below will depend on q (and r), although this dependence will not be made explicit in the notation. We denote by θ_q the endomorphism of $\mathbf{Sym}$ defined by

$$\tilde{f} = \theta_q(f) = f((1-q)A) = f(A) * \sigma_1((1-q)A) \,. \tag{20}$$

We denote by $\mathring{\mathcal{P}}$ the image of θ_q and by $\mathcal{P}$ the right $\mathring{\mathcal{P}}$-module generated by the S_n for $n \geq 0$. Note that $\mathring{\mathcal{P}}$ is by definition a left $*$-ideal of $\mathbf{Sym}$.

Theorem 4.1 *$\mathcal{P}$ is a unital $*$-subalgebra of* $\mathbf{Sym}$. *Its Hilbert series is*

$$\sum_{n\geq 0} \dim \mathcal{P}_n t^n = \frac{1}{1 - t - t^2 - \cdots - t^r} \,. \tag{21}$$

Proof – Since the internal product of homogeneous elements of different degrees is zero, it is enough to show that, for any $f, g \in \mathbf{Sym}$, $\sigma_1 \tilde{f} * \sigma_1 \tilde{g}$ is in $\mathcal{P}$. Thanks to the splitting formula,

$$\begin{aligned}\sigma_1 \tilde{f} * \sigma_1 \tilde{g} &= \mu[(\sigma_1 \otimes \tilde{f}) * \sum_{(g)} \sigma_1 \tilde{g}_{(1)} \otimes \sigma_1 \tilde{g}_{(2)}] \\ &= \sum_{(g)} (\sigma_1 \tilde{g}_{(1)})(\tilde{f} * \sigma_1 \tilde{g}_{(2)}) \,.\end{aligned} \tag{22}$$

Thus, it is enough to check that $\tilde{f} * \sigma_1\tilde{h}$ is in $\mathring{\mathcal{P}}$ for any $f, h \in \mathbf{Sym}$. Now,

$$\tilde{f} * \sigma_1\tilde{h} = f * \sigma_1((1-q)A) * \sigma_1\tilde{h}\,, \tag{23}$$

and since $\mathring{\mathcal{P}}$ is a $\mathbf{Sym}$ left $*$-ideal, we only have to show that $\sigma_1((1-q)A) * \sigma_1\tilde{h}$ is in $\mathring{\mathcal{P}}$. One more splitting yields

$$\begin{aligned} \sigma_1((1-q)A) * \sigma_1\tilde{h} &= (\lambda_{-q}\sigma_1) * \sigma_1\tilde{h} \\ &= \mu[(\lambda_{-q}\otimes\sigma_1) * \sum_{(h)} \sigma_1\tilde{h}_{(1)} \otimes \sigma_1\tilde{h}_{(2)}] \\ &= \sum_{(h)} (\lambda_{-q} * \sigma_1\tilde{h}_{(1)})(\sigma_1\tilde{h}_{(2)}) \\ &= \sum_{(h)} (\lambda_{-q} * \tilde{h}_{(1)})\lambda_{-q}\sigma_1\tilde{h}_{(2)} \end{aligned} \tag{24}$$

(since left $*$-multiplication by λ_{-q} is an anti-automorphism, namely the composition of the antipode and q^{degree}). The first parentheses $(\lambda_{-q} * \tilde{h}_{(1)})$ are in $\mathring{\mathcal{P}}$ since it is a left $*$-ideal. The middle term is $\sigma_1((1-q)A)$, and the last one is in $\mathring{\mathcal{P}}$ by definition.

Recall from [12, Prop. 3.5] that the Hilbert series of $\mathring{\mathcal{P}}$ is

$$\sum_{n\geq 0} \dim \mathring{\mathcal{P}}_n t^n = \frac{1-t^r}{1-t-t^2-\ldots-t^r}\,. \tag{25}$$

From [12, Lemma 3.13 and Eq. (3.9)], it follows that $S_n \notin \mathring{\mathcal{P}}$ if and only if $n \equiv 0 \mod r$, so that the Hilbert series of $\mathcal{P}$ is

$$\sum_{n\geq 0} \dim \mathcal{P}_n t^n = \frac{1}{1-t-t^2-\ldots-t^r}\,. \tag{26}$$

■

5 Back to the Mantaci-Reutenauer algebra

The above proofs are in fact special cases of a master calculation in the Mantaci-Reutenauer algebra, which we carry out in this section.

Let q be an arbitrary complex number or an indeterminate, and define, for any $F \in \mathbf{MR}$,

$$F^\sharp = F * \sigma_1(A - q\bar{A}) = F * \sigma_1^\sharp\,. \tag{27}$$

Since $\sigma_1^\sharp$ is grouplike, it follows from the splitting formula that

$$F \mapsto F^\sharp \tag{28}$$

is an automorphism of $\mathbf{MR}$ for the Hopf structure. In addition, it is clear from the definition that it is also a endomorphism of left $*$-modules. We refer to it as the $\sharp$ *transform*.

We now define

$$\mathring{\mathcal{Q}} = \mathbf{MR}^\sharp, \tag{29}$$

the image of the $\sharp$ transform. Since the latter is an endomorphism of Hopf algebras and of left $*$-modules, $\mathring{\mathcal{Q}}$ is both a Hopf subalgebra of $\mathbf{MR}$ and a left $*$-ideal. When q is a root of unity, its image under the specialization $\bar{A} = A$ is the non-unital peak algebra $\mathring{\mathcal{P}}$ of Section 4 (and for generic q, it is $\mathbf{Sym}$).

Let $\mathcal{Q}$ be the right $\mathring{\mathcal{Q}}$-module generated by the S_n, for all $n \geq 0$. Clearly, the identification $\bar{A} = A$ maps $\mathcal{Q}$ onto $\mathcal{P}$, the unital peak algebra of Section 4.

Theorem 5.1 *$\mathcal{Q}$ is a $*$-subalgebra of $\mathbf{MR}$, containing $\mathring{\mathcal{Q}}$ as a left ideal.*

Proof – Let $F, G \in \mathbf{MR}$. As above, we want to show that $\sigma_1 F^\sharp * \sigma_1 G^\sharp$ is in $\mathcal{Q}$. Using the splitting formula, we rewrite this as

$$\mu[(\sigma_1 \otimes F^\sharp) * \Delta\sigma_1 \Delta G^\sharp] = \sum_{(G)} (\sigma_1 G^\sharp_{(1)})(F^\sharp * \sigma_1 G^\sharp_{(2)}) \tag{30}$$

and we only have to show that each term $F^\sharp * \sigma_1 G^\sharp_{(2)}$ is in $\mathring{\mathcal{Q}}$. We may assume that $F = S^I$, where I is now a bicolored composition, and for any $G \in \mathbf{MR}$,

$$S^{I\sharp} * \sigma_1 G^\sharp = \sum_{(G)} \mu_r[(S^\sharp_{i_1} \otimes \cdots \otimes S^\sharp_{i_r}) * (\sigma_1 G^\sharp_{(1)} \otimes \cdots \otimes \sigma_1 G^\sharp_{(r)})] \tag{31}$$

so that it is sufficient to prove the property for $F = S_n$ or $S_{\bar{n}}$. Now,

$$\begin{aligned} \sigma_1^\sharp * \sigma_1 G^\sharp &= (\bar{\lambda}_{-q}\sigma_1) * \sigma_1 G^\sharp \\ &= \sum_{(G)} (\bar{\lambda}_{-q} 1 * \sigma_1 G^\sharp_{(1)})(\sigma_1 G^\sharp_{(2)}) \\ &= \sum_{(G)} (\bar{\lambda}_{-q} * G^\sharp_{(1)}) \cdot \sigma_1^\sharp \cdot G^\sharp_{(2)} \end{aligned} \tag{32}$$

which is in $\mathring{\mathcal{Q}}$, since it is a subalgebra and a left $*$-ideal, and similarly,

$$\begin{aligned} \bar{\sigma}_1^\sharp * \sigma_1 G^\sharp &= (\lambda_{-q}\bar{\sigma}_1) * \sigma_1 G^\sharp \\ &= \sum_{(G)} (\lambda_{-q} * \sigma_1 G^\sharp_{(1)})(\bar{\sigma}_1 \bar{G}^\sharp_{(2)}) \\ &= \sum_{(G)} (\lambda_{-q} * G^\sharp_{(1)}) \cdot \bar{\sigma}_1^\sharp \cdot \bar{G}^\sharp_{(2)} \end{aligned} \tag{33}$$

is also in $\mathring{\mathcal{Q}}$. ∎

The various algebras introduced in this paper and their interrelationships are summarized in the following diagram.

$$\begin{array}{ccccccc} \mathring{\mathcal{Q}} & \subseteq & \mathcal{Q} & \subseteq & \mathbf{MR} & \subseteq & \mathbf{BFQSym} \\ \downarrow & & \downarrow & & \downarrow & & \downarrow \\ \mathring{\mathcal{P}} & \subseteq & \mathcal{P} & \subseteq & \mathbf{Sym} & \subseteq & \mathbf{FQSym} \end{array} \tag{34}$$

Note that in the special case $q=-1$, by the results of Section 3.3, $\mathcal{Q}_n$ is the (Solomon) descent algebra of B_n, $\mathcal{Q}$ is isomorphic to $\mathbf{BSym}$, and $\mathcal{P}$ is the unital peak algebra of [2].

6 Further developments

6.1 Inversion of the generic $\sharp$ transform

For generic q, the endomorphism (27) of $\mathbf{MR}$ is invertible; therefore

$$\mathring{\mathcal{Q}} \sim \mathbf{MR}. \tag{35}$$

The inverse endomorphism of $\mathbf{MR}$ arises from the transformation of alphabets

$$A \mapsto (q\bar{A}+A)/(1-q^2), \tag{36}$$

which is to be understood in the following sense:

$$\sigma_1\left(\frac{q\bar{A}+A}{1-q^2}\right) := \prod_{k\geq 0} \sigma_{q^{2k+1}}(\bar{A})\sigma_{q^{2k}}(A)\,. \tag{37}$$

Indeed,

$$\begin{aligned}\sigma_1\left(\frac{q\bar{A}+A}{1-q^2}\right) * \sigma_1(A-q\bar{A}) &= \prod_{k\geq 0} \sigma_{q^{2k+1}}(\bar{A}-qA)\sigma_{q^{2k}}(A-q\bar{A}) \\ &= \prod_{k\geq 0} \lambda_{-q^{2k+2}}(A)\sigma_{q^{2k+1}}(\bar{A})\lambda_{-q^{2k+1}}(\bar{A})\sigma_{q^{2k}}(A) \\ &= \sigma_1(A)\,.\end{aligned} \tag{38}$$

By normalizing the term of degree n in (37), we obtain B_n-analogs of the q-Klyachko elements defined in [9]:

$$K_n(q;A,\bar{A}) := \prod_{i=1}^{n}(1-q^{2\,i})S_n\left(\frac{q\bar{A}+A}{1-q^2}\right) = \sum_{I\vDash n} q^{2\,\mathrm{maj}(I)}R_I(q\bar{A}+A)\,. \tag{39}$$

This expression can be completely expanded on signed ribbons. From the expression of R_I in $\mathbf{FQSym}$, we have

$$R_I(\bar{A}+A) = \sum_{C(\sigma)=I} \mathbf{G}_\sigma(\bar{A}+A) \tag{40}$$

where $\bar{A}+A$ is the ordinal sum. If we order $\bar{A}$ by

$$\bar{a}_1 < \bar{a}_2 < \ldots < \bar{a}_k < \ldots \tag{41}$$

then, arguing as in [16], we have

$$\mathbf{G}_\sigma(\bar{A}+A) = \sum_{\mathrm{std}(\tau,\epsilon)=\sigma} \mathbf{G}_{\tau,\epsilon} \tag{42}$$

so that

$$R_I(\bar{A}+A) = \sum_{\rho(\mathrm{J})=I} R_{\mathrm{J}} \tag{43}$$

where for a signed composition $\mathrm{J} = (J, \epsilon)$, the unsigned composition $\rho(\mathrm{J})$ is defined as the shape of $\mathrm{std}(\sigma, \epsilon)$, where σ is any permutation of shape J.

Replacing $\bar{A}$ by $q\bar{A}$, one obtains the expansion of the q-Klyachko elements of type B:

$$K_n(q; A, \bar{A}) = \sum_{\mathrm{J}} q^{\mathrm{bmaj(J)}} R_{\mathrm{J}} \tag{44}$$

where

$$\mathrm{bmaj(J)} = 2\,\mathrm{maj}(\rho(\mathrm{J})) + |\epsilon|\,, \tag{45}$$

where $|\epsilon|$ is the number of minus signs in ϵ.

For example,

$$K_2(q) = R_2 + q^2\, R_{\bar{2}} + q^2\, R_{11} + q^3\, R_{1\bar{1}} + q\, R_{\bar{1}1} + q^4\, R_{\bar{1}\bar{1}}. \tag{46}$$

$$\begin{aligned} K_3(q) = {} & R_3 + q^3\, R_{\bar{3}} + q^4\, R_{21} + q^5\, R_{2\bar{1}} + q^2\, R_{\bar{2}1} + q^7\, R_{\bar{2}\bar{1}} + q^2\, R_{12} + q^4\, R_{1\bar{2}} \\ & + q\, R_{\bar{1}2} + q^5\, R_{\bar{1}\bar{2}} + q^6\, R_{111} + q^7\, R_{11\bar{1}} + q^3\, R_{1\bar{1}1} + q^8\, R_{1\bar{1}\bar{1}} \\ & + q^5\, R_{\bar{1}11} + q^6\, R_{\bar{1}1\bar{1}} + q^4\, R_{\bar{1}\bar{1}1} + q^9\, R_{\bar{1}\bar{1}\bar{1}}. \end{aligned} \tag{47}$$

This major index of type B is the flag major index defined in [1].

Following [1] and considering the signed composition (where ϵ is encoded as boolean vector for readability)

$$\mathrm{J} = (2, 1, 1, \bar{3}, \bar{1}, \bar{2}, 4, \bar{1}, 2, 2) = (2113124122, 0000111111000100000) \tag{48}$$

we can take the smallest permutation of shape $(2, 1, 1, 3, 1, 2, 4, 1, 2, 2)$, which is

$$\alpha = 1\,5\,4\,3\,2\,6\,9\,8\,7\,11\,10\,12\,13\,16\,15\,14\,18\,17\,19 \tag{49}$$

sign it according to ϵ, which yields

$$1\,5\,4\,3\,\bar{2}\,\bar{6}\,\bar{9}\,\bar{8}\,\bar{7}\,\overline{11}\,10\,12\,13\,16\,\overline{15}\,14\,18\,17\,19 \tag{50}$$

whose standardized is

$$8\,11\,10\,9\,1\,2\,5\,4\,3\,6\,12\,13\,14\,16\,7\,15\,18\,17\,19 \tag{51}$$

and has shape $\rho(\mathrm{J}) = (2, 1, 1, 3, 1, 6, 3, 2)$. The major index of $\rho(\mathrm{J})$ is 55, the number of minus signs in ϵ is 7, so $\mathrm{bmaj(J)} = 2 \times 55 + 7 = 117$.

The major index of type B can be read directly on signed compositions without reference to signed permutations as follows: one can get $\rho(\mathrm{J})$ by first adding the absolute values of two consecutive parts if the left one is signed and the second one is not, then remove the signs and proceed as before.

A different solution consists in reading the composition from right to left, then associate weight 0 (resp. 1) to the rightmost part if it is positive (resp. negative) and then proceed left by adding 2 to the weight if the two parts are of the same sign and 1 if not. Finally, add up the product of the absolute values of the parts with their weight.

For example, with the same J as above we have the following weights:

$$\begin{aligned} \mathrm{J} = {} & (2, 1, 1, \ \bar{3}, \bar{1}, \bar{2}, 4, \bar{1}, 2, 2) \\ \text{weights}: {} & 14\ 12\ 10\ \ 9\ \ 7\ \ 5\ \ 4\ \ 3\ \ 2\ \ 0 \end{aligned} \tag{52}$$

so that we get $2 \cdot 14 + 1 \cdot 12 + 1 \cdot 10 + 3 \cdot 9 + 1 \cdot 7 + 2 \cdot 5 + 4 \cdot 4 + 1 \cdot 3 + 2 \cdot 2 + 2 \cdot 0 = 117$.

This technique generalizes immediately to colored compositions with a fixed number c of colors $0, 1, \ldots, c-1$: the weight of the rightmost cell is its color and the weight of a part is equal to the sum of the weight of the next part and the unique representative of the difference of the colors of those parts modulo c belonging to the interval $[1, c]$.

6.2 Generators and Hilbert series

For $n \geq 0$, let

$$S_n^{\pm} = S_n(A) \pm S_n(\bar{A}) \,, \tag{53}$$

and denote by $\mathcal{H}_n$ the subalgebra of $\mathbf{MR}$ generated by the $S_k^{\pm}$ for $k \leq n$. For $n \geq 0$, we have

$$(S_n^{\pm})^{\sharp} \equiv (1 \mp q^n) S_n^{\pm} \mod \mathcal{H}_{n-1} \,, \tag{54}$$

so that the $(S_n^{\pm})^{\sharp}$ such that $1 \mp q^n \neq 0$ form a set of free generators in $\mathbf{MR}^{\sharp}$.

Conjecture 6.1 *If r is odd, a basis of $\mathbf{MR}^{\sharp}$ will be parametrized by colored compositions such that parts of color 0 are not $\equiv 0 \mod r$ and parts of color 1 are arbitrary. The Hilbert series is then*

$$H_r(t) = \frac{1 - t^r}{1 - 2(t + t^2 + \cdots + t^r)}. \tag{55}$$

If r is even, there is the extra condition that parts of color 1 are not $\equiv r/2 \mod r$. The Hilbert series is then

$$H_r(t) = \frac{1 - t^r}{1 - 2(t + t^2 + \cdots + t^r) + t^{r/2}} \,. \tag{56}$$

For example,

$$H_2(t) = 1 + t + 2\,t^2 + 4\,t^3 + 8\,t^4 + 16\,t^5 + 32\,t^6 + 64\,t^7 + 128\,t^8 + O\left(t^9\right) \tag{57}$$

$$H_3(t) = 1 + 2\,t + 6\,t^2 + 17\,t^3 + 50\,t^4 + 146\,t^5 + 426\,t^6 + 1244\,t^7 + 3632\,t^8 + O\left(t^9\right) \tag{58}$$

$$H_4(t) = 1 + 2\,t + 5\,t^2 + 14\,t^3 + 38\,t^4 + 104\,t^5 + 284\,t^6 + 776\,t^7 + 2120\,t^8 + O\left(t^9\right) \tag{59}$$

If these conjectures are correct, the Hilbert series of the right $\mathbf{MR}^{\sharp}$-modules generated by the S_n are respectively

$$\frac{1}{1 - 2(t + t^2 + \ldots + t^r)} \,, \tag{60}$$

or

$$\frac{1}{1 - 2(t + t^2 + \ldots + t^r) + t^{r/2}} \,. \tag{61}$$

according to whether r is odd or even.

The cases $r = 1$ and $r = 2$ are easily proved as follows. Assume first that $q = 1$. Set

$$f = 1 + (\sigma_1^{+})^{\sharp} = (\sigma_1 + \lambda_{-1})(A - \bar{A}) \,, \tag{62}$$

$$g = (\sigma_1^{-})^{\sharp} - 1 = (\sigma_1 - \lambda_{-1})(A - \bar{A}) \,. \tag{63}$$

Then, $f^2 = g^2 + 4$, so that

$$f = 2\left(1 + \frac{1}{4} g^2\right)^{\frac{1}{2}} \tag{64}$$

which proves that the $(S_n^{+})^{\sharp}$ can be expressed in terms of the $(S_m^{-})^{\sharp}$.

Similarly, for $q = -1$, one can express

$$f = \sum_{n \geq 1} (S_{2n}^{+})^{\sharp} + \sum_{n \geq 0} (S_{2n+1}^{-})^{\sharp} \tag{65}$$

in terms of

$$g = \sum_{n\geq 1} (S_{2n}^-)^\sharp + \sum_{n\geq 0} (S_{2n+1}^+)^\sharp \tag{66}$$

since, as is easily verified,

$$(f+2)^2 = g^2 + 4\,,\ i.e.,\, f = -2 + 2\left(1 + \frac{1}{4}g^2\right)^{\frac{1}{2}}\ . \tag{67}$$

Apparently, this approach does not work anymore for higher roots of unity.

7 Appendix: monomial expansion of the $(1-q)$-kernel

The results of [16, 7] allow us to write down a new expansion of $S_n((1-q)A)$, in terms of the monomial basis of [4]. The special case $q=1$ gives back a curious expression of Dynkin's idempotent, first obtained in [3].

Let σ be a permutation. We then define its *left-right minima* set $\mathrm{LR}(\sigma)$ as the values of σ that have no smaller value to their left. We will denote by $\mathrm{lr}(\sigma)$ the cardinality of $\mathrm{LR}(\sigma)$. For example, with $\sigma = 46735182$, we have $\mathrm{LR}(\sigma) = \{4,3,1\}$, and $\mathrm{lr}(\sigma) = 3$.

Let us now decompose $S_n((1-q)A)$ on the monomial basis $\mathbf{M}_\sigma$ (see [4]) of $\mathbf{FQSym}$. Thanks to the Cauchy formula of $\mathbf{FQSym}$ [7], we have

$$S_n((1-q)A) = \sum_\sigma \mathbf{S}^\sigma(1-q)\mathbf{M}_\sigma(A), \tag{68}$$

where $\mathbf{S}$ is the dual basis of $\mathbf{M}$. Given the transition matrix between $\mathbf{M}$ and $\mathbf{G}$, we see that

$$\mathbf{S}^\sigma = \sum_{\tau\leq\sigma^{-1}} \mathbf{F}_\tau, \tag{69}$$

where $\leq$ is the right weak order, e.g., $\mathbf{S}^{312} = \mathbf{F}_{123} + \mathbf{F}_{213} + \mathbf{F}_{231}$. Thanks to [16], we know that $\mathbf{F}_\sigma(1-q)$ is either $(-q)^k$ if $\mathrm{Des}(\sigma) = \{1,\ldots,k\}$ or 0 otherwise. Let us define *hook permutations* of hook k the permutations σ such that $\mathrm{Des}(\sigma) = \{1,\ldots,k\}$. Now, $\mathbf{S}^\sigma(1-q)$ amounts to compute the list of *hook permutations* smaller than σ. Note that hook permutations are completely characterized by their left-right minima. Moreover, if τ is smaller than σ in the right weak order, then $\mathrm{LR}(\tau) \subset \mathrm{LR}(\sigma)$.

Hence all hook permutations smaller than a given permutation σ belong to the set of hook permutations with left-right minima in $\mathrm{LR}(\sigma)$. Since by elementary transpositions decreasing the length, one can get from σ to the hook permutation with the same left-right minima and then from this permutation to all the others, we have:

Theorem 7.1 *Let n be an integer. Then*

$$S_n((1-q)A) = \sum_{\sigma\in\mathfrak{S}_n} (1-q)^{\mathrm{lr}(\sigma)}\mathbf{M}_\sigma. \tag{70}$$

■

In the particular case $q=1$, we recover a result of [3]:

$$\Psi_n = \sum_{\substack{\sigma\in\mathfrak{S}_n\\ \sigma(1)=1}} \mathbf{M}_\sigma, \tag{71}$$

where Ψ_n is the noncommutative power sum associated with Dynkin's idempotent [11, Prop. 5.2].

Acknowledgements

This work started during a stay of the first author at the University Paris-Est Marne-la-Vallée. The authors would also like to thank the contributors of the MuPAD project, and especially those of the combinat package, for providing the development environment for their research (see [10] for an introduction to MuPAD-Combinat).

References

[1] R. ADIN and Y. ROICHMAN, *The flag major index and group actions on polynomial rings*, Europ. J. Combin, **22** (2001), 431–446.

[2] M. AGUIAR, N. BERGERON, and K. NYMAN, *The peak algebra and the descent algebra of type B and D*, Trans. of the AMS. **356** (2004), 2781–2824.

[3] M. AGUIAR and M. LIVERNET, *The associative operad and the weak order on the symmetric group*, J. Homotopy and Related Structures, **2** n.1 (2007), 57–84.

[4] M. AGUIAR and F. SOTTILE, *Structure of the Malvenuto-Reutenauer Hopf algebra of permutations*, Adv. in Math. **191** (2005), 225–275.

[5] N. BERGERON, F. HIVERT and J.-Y. THIBON, *The peak algebra and the Hecke-Clifford algebras at $q = 0$*, J. Combinatorial Theory A **117** (2004), 1–19.

[6] C.-O. CHOW, *Noncommutative symmetric functions of type B*, Thesis, MIT, 2001.

[7] G. DUCHAMP, F. HIVERT, J.-C. NOVELLI, and J.-Y. THIBON, *Noncommutative Symmetric Functions VII: Free Quasi-Symmetric Functions Revisited*, preprint, math.CO/0809.4479.

[8] G. DUCHAMP, F. HIVERT, and J.-Y. THIBON, *Noncommutative symmetric functions VI: free quasi-symmetric functions and related algebras*, Internat. J. Alg. Comput. **12** (2002), 671–717.

[9] I.M. GELFAND, D. KROB, A. LASCOUX, B. LECLERC, V. S. RETAKH, and J.-Y. THIBON, *Noncommutative symmetric functions*, Adv. in Math. **112** (1995), 218–348.

[10] F. HIVERT and N. THIÉRY, *MuPAD-Combinat, an open-source package for research in algebraic combinatorics*, Sém. Lothar. Combin. **51** (2004), 70p. (electronic).

[11] D. KROB, B. LECLERC, and J.-Y. THIBON, *Noncommutative symmetric functions II: Transformations of alphabets*, Internal J. Alg. Comput. **7** (1997), 181–264.

[12] D. KROB and J.-Y. THIBON, *Higher order peak algebras*, Ann. Combin. **9** (2005), 411–430.

[13] I.G. MACDONALD, *Symmetric functions and Hall polynomials*, 2nd ed., Oxford University Press, 1995.

[14] R. MANTACI and C. REUTENAUER, *A generalization of Solomon's descent algebra for hyperoctahedral groups and wreath products*, Comm. Algebra **23** (1995), 27–56.

[15] J.-C. NOVELLI and J.-Y. THIBON, *Free quasi-symmetric functions of arbitrary level*, preprint math.CO/0405597.

[16] J.-C. NOVELLI and J.-Y. THIBON, *Superization and (q,t)-specialization in combinatorial Hopf algebras*, math.CO/0803.1816.

[17] S. POIRIER, *Cycle type and descent set in wreath products*, Disc. Math., **180** (1998), 315–343.

[18] C. REUTENAUER, *Free Lie algebras*, Oxford University Press, 1993.

[19] L. SOLOMON, *A Mackey formula in the group ring of a Coxeter group*, J. Algebra, **41**, (1976), 255-268.

[20] R. P. STANLEY, *Enumerative combinatorics*, vol. 2, Cambridge University Press, 1999.