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GENERALIZED DESCENT ALGEBRA AND CONSTRUCTION OF IRREDUCIBLE CHARACTERS OF HYPEROCTAHEDRAL GROUPS

by Cédric BONNAFÉ & Christophe HOHLWEG (*)

WITH AN APPENDIX

by Pierre BAUMANN & Christophe HOHLWEG

ABSTRACT. — We construct a subalgebra $\Sigma'(W_n)$ of dimension $2 \cdot 3^{n-1}$ of the group algebra of the Weyl group W_n of type B_n containing its usual Solomon algebra and the one of \mathfrak{S}_n : $\Sigma'(W_n)$ is nothing but the Mantaci-Reutenauer algebra but our point of view leads us to a construction of a surjective morphism of algebras $\Sigma'(W_n) \rightarrow \mathbf{Z}\text{Irr}(W_n)$. Jöllenbeck's construction of irreducible characters of the symmetric group by using the coplactic equivalence classes can then be transposed to W_n . In an appendix, P. Baumann and C. Hohlweg present in an explicit and combinatorial way the relation between this construction of the irreducible characters of W_n and that of W. Specht.

RÉSUMÉ. — Nous construisons une sous-algèbre $\Sigma'(W_n)$ de dimension $2 \cdot 3^{n-1}$ de l'algèbre du groupe de Weyl W_n de type B_n contenant son algèbre de Solomon usuelle ainsi que celle de \mathfrak{S}_n : $\Sigma'(W_n)$ n'est autre que l'algèbre de Mantaci-Reutenauer mais notre point de vue nous permet de construire un morphisme d'algèbres surjectif $\Sigma'(W_n) \rightarrow \mathbf{Z}\text{Irr}(W_n)$. La construction de Jöllenbeck des caractères irréductibles de \mathfrak{S}_n à partir des classes d'équivalence coplaxique se transpose alors à W_n . Un appendice à cet article, écrit par P. Baumann et C. Hohlweg, donne le lien combinatoire explicite entre cette construction des caractères irréductibles de W_n et celle obtenue par W. Specht en 1932.

1. Introduction

Let (W, S) be a finite Coxeter system and let $\ell : W \rightarrow \mathbf{N}$ denote the length function. If $I \subset S$, $W_I = \langle I \rangle$ is the standard parabolic subgroup

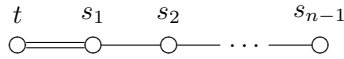
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generated by I and $X_I = \{w \in W \mid \forall s \in I, \ell(ws) > \ell(w)\}$ is a cross-section of W/W_I . Write $x_I = \sum_{w \in X_I} w \in \mathbf{Z}W$, then $\Sigma(W) = \bigoplus_{I \subset S} \mathbf{Z}x_I$ is a subalgebra of $\mathbf{Z}W$ and the \mathbf{Z} -linear map $\theta : \Sigma(W) \rightarrow \mathbf{Z} \text{Irr } W, x_I \mapsto \text{Ind}_{W_I}^W 1$ is a morphism of algebras: $\Sigma(W)$ is called the *descent algebra* or the *Solomon algebra* of W [18]. However, the morphism θ is surjective if and only if W is a product of symmetric groups.

The aim of this paper is to construct, whenever W is of type C , a subalgebra $\Sigma'(W)$ of $\mathbf{Z}W$ containing $\Sigma(W)$ and a surjective morphism of algebras $\theta' : \Sigma'(W) \rightarrow \mathbf{Z} \text{Irr } W$ build similarly as $\Sigma(W)$ by starting with a bigger generating set. More precisely, let (W_n, S_n) denote a Coxeter system of type C_n and write $S_n = \{t, s_1, \dots, s_{n-1}\}$ where the Dynkin diagram of (W_n, S_n) is:



Let $t_1 = t, t_i = s_{i-1}t_{i-1}s_{i-1}$ ($2 \leq i \leq n$) and $S'_n = S_n \cup \{t_1, \dots, t_n\}$. Let $\mathcal{P}_0(S'_n)$ denote the set of subsets I of S'_n such that $I = \langle I \rangle \cap S'_n$. If $I \in \mathcal{P}_0(S'_n)$, let W_I, X_I and x_I be defined as before. Then:

THEOREM. — $\Sigma'(W_n) = \bigoplus_{I \in \mathcal{P}_0(S'_n)} \mathbf{Z}x_I$ is a subalgebra of $\mathbf{Z}W_n$ and the \mathbf{Z} -linear map $\theta_n : \Sigma'(W_n) \rightarrow \mathbf{Z} \text{Irr } W_n, x_I \mapsto \text{Ind}_{W_I}^W 1$ is a surjective morphism of algebras. Moreover, $\text{Ker } \theta_n = \sum_{I \equiv I'} \mathbf{Z}(x_I - x_{I'})$ and $\mathbf{Q} \otimes_{\mathbf{Z}} \text{Ker } \theta_n$ is the radical of the \mathbf{Q} -algebra $\mathbf{Q} \otimes_{\mathbf{Z}} \Sigma'(W_n)$.

In this theorem, the notation $I \equiv I'$ means that there exists $w \in W_n$ such that $I' = {}^wI$, that is, W_I and $W_{I'}$ are conjugated. This theorem is stated and proved in §3.3. Note that it is slightly differently formulated: in fact, it turns out that there is a natural bijection between signed compositions of n and $\mathcal{P}_0(S'_n)$ (see Lemma 2.5). So, everything in the text is indexed by signed compositions instead of $\mathcal{P}_0(S'_n)$. It must also be noticed that, by opposition with the classical case, the multiplication $x_I x_{I'}$ may involve negative coefficients. Using another basis, we show that $\Sigma'(W_n)$ is precisely the generalized descent algebra discovered by Mantaci and Reutenauer [16].

Using this theorem and the Robinson-Schensted correspondence for type C constructed by Stanley [20] and a Knuth version of it given in [4], we obtain an analog of Jöllenbeck’s result (on the construction of characters of the symmetric group [11]) using an extension $\tilde{\theta}_n : \mathcal{Q}_n \rightarrow \mathbf{Z} \text{Irr } W_n$ of θ_n to the coplactic space \mathcal{Q}_n (see Theorem 4.14). The coplactic space refers to Jöllenbeck’s construction revised in [3].

Now, let $\mathcal{SP} = \bigoplus_{n \geq 0} \mathbf{Z}W_n, \Sigma' = \bigoplus_{n \geq 0} \Sigma'(W_n)$ and $\mathcal{Q} = \bigoplus_{n \geq 0} \mathcal{Q}_n$. Let $\theta = \bigoplus_{n \geq 0} \theta_n$ and $\tilde{\theta} = \bigoplus_{n \geq 0} \tilde{\theta}_n$. Aguiar and Mahajan have proved that \mathcal{SP}

is naturally a Hopf algebra and that Σ' is a Hopf subalgebra [1]. We prove here that \mathcal{Q} is also a Hopf subalgebra of \mathcal{SP} (containing Σ') and that θ and $\bar{\theta}$ are surjective morphisms of Hopf algebras (see Theorem 5.8). This generalizes similar results in symmetric groups ([17] and [3]), which are parts of combinatorial tools used within the framework of the representation theory of type A (see for instance [21]).

In the last section of this paper, we give some explicit computations in $\Sigma'(W_2)$ (characters, complete set of orthogonal primitive idempotents, Cartan matrix of $\Sigma'(W_2)\dots$).

In the Appendix, P. Baumann and the second author link the above construction with the Specht construction and symmetric functions (see [14]).

Remark. — It seems interesting to try to construct a subalgebra $\Sigma'(W)$ of $\mathbf{Z}W$ containing $\Sigma(W)$ and a morphism $\theta' : \Sigma'(W) \rightarrow \mathbf{Z} \text{Irr } W$ extending θ for arbitrary Coxeter group W . But it is in general impossible to do so in a same way as we did for type C (by extending the generating set). Computations using CHEVIE programs [7] show us that it is impossible to work it in type D_4 and that the reasonable choices in F_4 fail (we do not obtain a subalgebra!). However, it is possible to do something similar for type G_2 . More precisely, let (W, S) be of type G_2 . Write $S = \{s, t\}$ and let $S' = \{s, t, sts, tstst\}$ and repeat the procedure described above to obtain a sub- \mathbf{Z} -module $\Sigma'(W)$ of $\mathbf{Z}W$ and a morphism $\theta' : \Sigma'(W) \rightarrow \mathbf{Z} \text{Irr } W$. Then $\Sigma'(W)$ is a subalgebra of $\mathbf{Z}W$, θ' is surjective but θ' is not a morphism of algebras. We have $\text{rank}_{\mathbf{Z}} \Sigma'(W) = 8$ and $\text{rank}_{\mathbf{Z}} \text{Ker } \theta' = 2$.

2. Some reflection subgroups of hyperoctahedral groups

In this article, we denote $[m, n] = \{i \in \mathbf{Z} \mid m \leq i \leq n\} = \{m, m + 1, \dots, n - 1, n\}$, for all $m \leq n \in \mathbf{Z}$, and $\text{sign}(i) \in \{\pm 1\}$ the sign of $i \in \mathbf{Z} \setminus \{0\}$. If E is a set, we denote by $\mathfrak{S}(E)$ the group of permutations on the set E . If $m \in \mathbf{Z}$, we often denote by \bar{m} the integer $-m$.

2.1. The hyperoctahedral group

We begin by making clear some notation and definitions concerning the *hyperoctahedral group* W_n . Denote 1_n the identity of W_n (or 1 if no confusion is possible). We denote by $\ell_t(w)$ the number of occurrences of t in a reduced decomposition of w and we define $\ell_s(w) = \ell(w) - \ell_t(w)$.

It is well-known that W_n acts on the set $I_n = [1, n] \cup [\bar{n}, \bar{1}]$ by permutations as follows: $t = (\bar{1}, 1)$ and $s_i = (\bar{i} + \bar{1}, \bar{i})(i, i + 1)$ for any $i \in [1, n - 1]$. Through this action, we have

$$W_n = \{w \in \mathfrak{S}(I_n) \mid \forall i \in I_n, w(\bar{i}) = \overline{w(i)}\}.$$

We often represent $w \in W_n$ as the word $w(1)w(2)\dots w(n)$ in examples.

The subgroup $W_{\bar{n}} = \{w \in W_n \mid w([1, n]) = [1, n]\}$ of W_n is naturally identified with \mathfrak{S}_n , the symmetric group of degree n , by restriction of its elements to $[1, n]$. Note that $W_{\bar{n}}$ is generated, as a reflection subgroup of W_n , by $S_{\bar{n}} = \{s_1, \dots, s_{n-1}\}$.

A *standard parabolic subgroup* of W_n is a subgroup generated by a subset of S_n (a *parabolic subgroup* of W_n is a subgroup conjugate to some standard parabolic subgroup). Note that $(W_{\bar{n}}, S_{\bar{n}})$ is a Coxeter group, which is a standard parabolic subgroup of W_n . If $m \leq n$, then S_m is naturally identified with a subset of S_n and W_m will be identified with the standard parabolic subgroup of W_n generated by S_m .

Now, we set $T_n = \{t_1, \dots, t_n\}$, with t_i as in the Introduction. As a permutation of I_n , note that $t_i = (i, \bar{i})$. Then the reflection subgroup \mathfrak{T}_n generated by T_n is naturally identified with $(\mathbf{Z}/2\mathbf{Z})^n$. Therefore $W_n = W_{\bar{n}} \rtimes \mathfrak{T}_n$ is just the wreath product of \mathfrak{S}_n by $\mathbf{Z}/2\mathbf{Z}$. If $w \in W_n$, we denote by (w_S, w_T) the unique pair in $\mathfrak{S}_n \times \mathfrak{T}_n$ such that $w = w_S w_T$. Note that $\ell_t(w) = \ell_t(w_T)$. In this article, we will consider reflection subgroups generated by subsets of $S'_n = S_n \cup T_n$.

2.2. Root system

Before studying the reflection subgroups generated by subsets of S'_n , let us recall some basic facts about Weyl groups of type C (see [5]). Let us endow \mathbf{R}^n with its canonical euclidean structure. Let (e_1, \dots, e_n) denote the canonical basis of \mathbf{R}^n : this is an orthonormal basis. If $\alpha \in \mathbf{R}^n \setminus \{0\}$, we denote by s_α the orthogonal reflection such that $s_\alpha(\alpha) = -\alpha$. Let

$$\Phi_n^+ = \{2e_i \mid 1 \leq i \leq n\} \cup \{e_j + \nu e_i \mid \nu \in \{1, -1\} \text{ and } 1 \leq i < j \leq n\},$$

$\Phi_n^- = -\Phi_n^+$ and $\Phi_n = \Phi_n^+ \cup \Phi_n^-$. Then Φ_n is a root system of type C_n and Φ_n^+ is a positive root system of Φ_n . By sending t to s_{2e_1} and s_i to $s_{e_{i+1}-e_i}$ (for $1 \leq i \leq n - 1$), we will identify W_n with the Weyl group of Φ_n . Then

$$\Delta_n = \{2e_1, e_2 - e_1, e_3 - e_2, \dots, e_n - e_{n-1}\}$$

is the basis of Φ_n contained in Φ_n^+ and the subset S_n of W_n is naturally identified with the set of simple reflections $\{s_\alpha \mid \alpha \in \Delta_n\}$. Therefore, for any $w \in W_n$ we have

$$\ell(w) = |\Phi_n^+ \cap w^{-1}(\Phi_n^-)|;$$

and $\ell(ws_\alpha) < \ell(w)$ if and only if $w(\alpha) \in \Phi^-$, for all $\alpha \in \Phi^+$.

Remark 2.1. — If $i \in [1, n - 1]$, then

$$\ell(ws_i) < \ell(w) \Leftrightarrow w(i) > w(i + 1),$$

and, if $j \in [1, n]$, then

$$\ell(wt_j) < \ell(w) \Leftrightarrow w(j) < 0.$$

Therefore, we deduce from the strong exchange condition (see [10, §5.8])

$$(2.2) \quad \ell_t(w) = |\{i \in [1, n] \mid w(i) < 0\}|.$$

2.3. Some closed subsystems of Φ_n

Consider the subsets $\{s_1, t_1\}$ and $\{s_1, t_2\}$ of S'_n ($n \geq 2$). It is readily seen that these two sets of reflections generate the same reflection subgroup of W_n . This lead us to find a parametrization of subgroups generated by a subset of S'_n .

A *signed composition* is a sequence $C = (c_1, \dots, c_r)$ of non-zero elements of \mathbf{Z} . The number r is called the *length* of C . We set $|C| = \sum_{i=1}^r |c_i|$. If $|C| = n$, we say that C is a *signed composition of n* and we write $C \models n$. We also define $C^+ = (|c_1|, \dots, |c_r|) \models n$, $C^- = -C^+$ and $\overline{C} = -C$. We denote by $\text{Comp}(n)$ the set of signed compositions of n . In particular, any composition is a signed composition (any part is positive). Note that

$$(2.3) \quad |\text{Comp}(n)| = 2 \cdot 3^{n-1}.$$

Now, to each $C = (c_1, \dots, c_r) \models n$, we associate a reflection subgroup W_C of W_n which is isomorphic to $W_{c_1} \times \dots \times W_{c_r}$. We proceed as follows: for $1 \leq i \leq r$, set

$$I_C^{(i)} = \begin{cases} I_{C,+}^{(i)} & \text{if } c_i < 0, \\ I_{C,+}^{(i)} \cup -I_{C,+}^{(i)} & \text{if } c_i > 0, \end{cases}$$

where $I_{C,+}^{(i)} = [|c_1| + \dots + |c_{i-1}| + 1, |c_1| + \dots + |c_i|]$. Then

$$W_C = \{w \in W_n \mid \forall 1 \leq i \leq r, w(I_C^{(i)}) = I_C^{(i)}\}$$

is a reflection subgroup generated by

$$S_C = \{s_p \in S_{\bar{n}} \mid \forall 1 \leq i \leq r, p \neq |c_1| + \dots + |c_i|\} \\ \cup \{t_{|c_1| + \dots + |c_{j-1}| + 1} \in T_n \mid c_j > 0\} \subset S'_n$$

Therefore, $W_C \simeq W_{c_1} \times \dots \times W_{c_r}$: we denote by $(w_1, \dots, w_r) \mapsto w_1 \times \dots \times w_r$ the natural isomorphism $W_{c_1} \times \dots \times W_{c_r} \xrightarrow{\sim} W_C$.

Example. — The group $W_{(\bar{2}, 3, \bar{1}, \bar{3}, 1)} \simeq \mathfrak{S}_2 \times W_3 \times \mathfrak{S}_1 \times \mathfrak{S}_3 \times W_1$ is generated, as a reflection subgroup of W_{10} , by $S_{(\bar{2}, 3, \bar{1}, \bar{3}, 1)} = \{s_1\} \cup \{t_3, s_3, s_4\} \cup \{s_7, s_8\} \cup \{t_{10}\} \subset S'_{10}$.

The signed composition C is said *semi-positive* if $c_i \geq -1$ for every $i \in [1, r]$. Note that a composition is a semi-positive composition. We say that C is *negative* if $c_i < 0$ for every $i \in [1, r]$. We say that C is *parabolic* if $c_i < 0$ for $i \in [2, r]$. Note that C is parabolic if and only if W_C is a standard parabolic subgroup.

Now, let $S'_C = S'_n \cap W_C$, $\Phi_C = \{\alpha \in \Phi_n \mid s_\alpha \in W_C\}$ and $\Phi_C^+ = \Phi_C \cap \Phi_n^+$. Then W_C is the Weyl group of the closed subsystem Φ_C of Φ_n . Moreover, Φ_C^+ is a positive root system of Φ_C and we denote by Δ_C the basis of Φ_C contained in Φ_C^+ . We have $S_C = \{s_\alpha \mid \alpha \in \Delta_C\}$. Then (W_C, S_C) is a Coxeter group.

Let $\ell_C : W_C \rightarrow \mathbf{N}$ denote the length function on W_C with respect to S_C . Let w_C denote the longest element of W_C with respect to ℓ_C . If C is a composition, we denote by σ_C the longest element of $\mathfrak{S}_C = W_{\bar{C}}$ with respect to $\ell_{\bar{C}}$ (which is the restriction of ℓ to \mathfrak{S}_C). In other words, $\sigma_C = w_{\bar{C}}$. In particular, w_n (resp. σ_n) denotes the longest element of W_n (resp. \mathfrak{S}_n).

Write $T_C = T_n \cap W_C$ and $\mathfrak{T}_C = \mathfrak{T}_n \cap W_C$, then observe that

$$(2.4) \quad W_C = W_{C^-} \rtimes \mathfrak{T}_C = \mathfrak{S}_{C^+} \rtimes \mathfrak{T}_C.$$

Remarks.

- (1) This class of reflection subgroups contains the standard parabolic subgroups, since $S_n \subset S'_n$. But it contains also some other subgroups which are not parabolic (for instance, consider the subgroup generated by $\{t_1, t_2\}$). In other words, it may happen that $\Delta_C \not\subset \Delta_n$. In fact, $\Delta_C \subset \Delta_n$ if and only if W_C is a standard parabolic subgroup of W_n .
- (2) If W_C is not a standard parabolic subgroup of W_n , then ℓ_C is not the restriction of ℓ to W_C .

We close this subsection by an easy characterization of the subsets S'_C :

LEMMA 2.5. — *Let X be a subset of S'_n . Then the following are equivalent:*

- (1) $\langle X \rangle \cap S'_n = X$.
- (2) $X \cap T_n$ is stable under conjugation by $\langle X \rangle$.
- (3) $X \cap T_n$ is stable under conjugation by $\langle X \cap S_{\bar{n}} \rangle$.
- (4) There exists a signed composition C of n such that $X = S'_C$.

COROLLARY 2.6. — *Let $w \in W_n$ and let $C \Vdash n$. If ${}^w S'_C \subset S'_n$, then there exists a (unique) signed composition D such that ${}^w S'_C = S'_D$.*

Proof. — Indeed, ${}^w S'_C \cap T_n = {}^w(S'_C \cap T_n)$ and ${}^w S'_C \cap S_{\bar{n}} = {}^w(S'_C \cap S_{\bar{n}})$. \square

2.4. Orbits of closed subsystems of Φ_n

In this subsection, we determine when two subgroups W_C and W_D of W_n are conjugated. A *bipartition* of n is a pair $\lambda = (\lambda^+, \lambda^-)$ of partitions such that $|\lambda| := |\lambda^+| + |\lambda^-| = n$. We write $\lambda \Vdash n$ to say that λ is a bipartition of n , and the set of bipartitions of n is denoted by $\text{Bip}(n)$. It is well-known that the conjugacy classes of W_n are in bijection with $\text{Bip}(n)$ (see [8, 14]). We define $\hat{\lambda}$ as the signed composition of n obtained by concatenation of λ^+ and $-\lambda^-$. The map $\text{Bip}(n) \rightarrow \text{Comp}(n)$, $\lambda \mapsto \hat{\lambda}$ is injective.

Now, let C be a signed composition of n . We define $\lambda(C) = (\lambda^+, \lambda^-)$ as the bipartition of n such that λ^+ (resp. λ^-) is obtained from C by reordering in decreasing order the positive parts of C (resp. the absolute value of the negative parts of C). One can easily check that the map

$$\lambda : \text{Comp}(n) \longrightarrow \text{Bip}(n)$$

is surjective (indeed, if $\lambda \in \text{Bip}(n)$, then $\lambda(\hat{\lambda}) = \lambda$) and that the following proposition holds:

PROPOSITION 2.7. — *Let $C, D \Vdash n$, then W_C and W_D are conjugate in W_n if and only if $\lambda(C) = \lambda(D)$. If Ψ is a closed subsystem of Φ_n , then there exists a unique bipartition λ of n and some $w \in W_n$ such that $\Psi = w(\Phi_{\hat{\lambda}})$.*

The above proposition gives a classification of W_n -orbits of closed subsystems of Φ_n in terms of bipartitions. However, this does not give the classification of W -conjugacy classes of reflection subgroups of W_n (for instance, the subgroup of type D_n is not in this list).

Let $C, D \Vdash n$, then we write $C \subset D$ if $W_C \subset W_D$. Moreover, if $C, C' \subset D$ and if W_C and $W_{C'}$ are conjugate under W_D , then we write $C \equiv_D C'$.

2.5. Distinguished coset representatives

Let $C \models n$, then

$$X_C = \{x \in W_n \mid \forall w \in W_C, \ell(xw) \geq \ell(x)\}$$

is a distinguished set of *minimal coset representatives* for W_n/W_C (see proposition below). It is readily seen that

$$\begin{aligned} X_C &= \{w \in W_n \mid w(\Phi_C^+) \subset \Phi_n^+\} \\ &= \{w \in W_n \mid \forall \alpha \in \Delta_C, w(\alpha) \in \Phi_n^+\}. \end{aligned}$$

Finally

$$X_C = \{w \in W_n \mid \forall r \in S_C, \ell(wr) > \ell(w)\}.$$

We need a relative notion: if $D \models n$ such that $C \subset D$, the set $X_C^D = X_C \cap W_D$ is a distinguished set of minimal coset representatives for W_D/W_C .

PROPOSITION 2.8. — *Let $C \models n$, then:*

- (a) *The map $X_C \times W_C \rightarrow W_n, (x, w) \mapsto xw$ is bijective.*
- (b) *If $C \subset D$, then the map $X_D \times X_C^D \rightarrow X_C, (x, y) \mapsto xy$ is bijective.*
- (c) *If $x \in X_C$ and $w \in W_C$, then $\ell_t(xwx^{-1}) \geq \ell_t(w)$. Consequently, $\mathfrak{S}_n \cap {}^xW_C = \mathfrak{S}_n \cap {}^x\mathfrak{S}_{C^+}$.*

Proof. — (a) is stated, in a general case, in [13, Lemma 1.9]. (b) follows easily from (a). Let us now prove (c). Let $x \in X_C$ and $w \in W_C$. Let $I = \{i \in I_n \mid w(i) < 0\}$ and $J = \{i \in I_n \mid xwx^{-1}(i) < 0\}$, then $\ell_t(w) = |I|$ and $\ell_t(xwx^{-1}) = |J|$, by (2.2). Now let $i \in I$, then $t_i \in W_C$, so $\ell_t(xt_i) > \ell_t(x)$. In other words, $x(i) > 0$. Now, we have $xwx^{-1}(x(i)) = xw(i)$. But, $w(i) < 0$ and $t_{-w(i)} = wt_iw^{-1} \in W_C$. Therefore, $x(-w(i)) = -xw(i) > 0$. This shows that $x(i) \in J$. So, the map $I \rightarrow J, i \mapsto x(i)$ is well-defined and clearly injective, implying $|I| \leq |J|$ as desired.

The last assertion of this proposition follows easily from this inequality and from the fact that $\mathfrak{S}_{C^+} = \{w \in W_C \mid \ell_t(w) = 0\}$. □

PROPOSITION 2.9. — *Let $C \models n$ and $x \in X_C$ be such that ${}^xS'_C \subset S'_n$. Let D be the unique signed composition of n such that ${}^xS'_C = S'_D$ (see Corollary 2.6). Then $X_C = X_Dx$.*

Proof. — By symmetry, it is sufficient to prove that, if $w \in X_D$, then $wx \in X_C$. Let $\alpha \in \Phi_C^+$. Then, since $x \in X_C$, we have $x(\alpha) \in \Phi_n^+ \cap {}^x\Phi_C = \Phi_D^+$. So $w(x(\alpha)) \in \Phi_n^+$ since $w \in X_D$. So $wx \in X_C$. □

2.6. Maximal element in X_C

It turns out that, for every signed composition C of n , X_C contains a unique element of maximal length (see Proposition 2.12). First, note the following two examples:

(1) if C is parabolic, it is well-known that ℓ_C is the restriction of ℓ and that, for all $(x, w) \in X_C \times W_C$, we have

$$\ell(xw) = \ell(x) + \ell(w)$$

In particular, $w_n w_C$ is the longest element of X_C (see [8, Lemma 2.2.1]);

(2) let C be a composition of n , then W_C is not in general a standard parabolic subgroup of W_n . However, since W_C contains \mathfrak{T}_n , X_C is contained in \mathfrak{S}_n . This shows that

$$X_C = X_{\bar{C}}^{\bar{n}} = X_{\bar{C}} \cap \mathfrak{S}_n.$$

In particular, X_C contains a unique element of maximal length: this is $\sigma_n \sigma_C$.

Now, let k and l be two non-zero natural numbers such that $k + l = n$. Then $W_{k,l}$ is not a parabolic subgroup of W_n . However, $W_{k,\bar{l}}$ is a standard parabolic subgroup of W_n and $W_{k,\bar{l}} \subset W_{k,l}$. So $X_{k,l} \subset X_{k,\bar{l}}$. So, if $x \in X_{k,l}$ and $w \in W_{k,\bar{l}}$, then

$$(2.10) \quad \ell(xw) = \ell(x) + \ell(w).$$

This applies for instance if $w \in W_k \subset W_{k,\bar{l}}$.

Then, we need to introduce a decomposition of X_C using Proposition 2.8

(b). Write $C = (c_1, \dots, c_r) \models n$. We set

$$X_{C,i} = X_{(|c_1| + \dots + |c_i|, c_{i+1}, \dots, c_r)}^{(|c_1| + \dots + |c_{i-1}|, c_i, \dots, c_r)}.$$

Then the map

$$\begin{aligned} X_{C,r} \times \dots \times X_{C,2} \times X_{C,1} &\longrightarrow X_C \\ (x_r, \dots, x_2, x_1) &\longmapsto x_r \dots x_2 x_1 \end{aligned}$$

is bijective by Proposition 2.8 (b). Moreover, by (2.10), we have

$$(2.11) \quad \ell(x_r \dots x_2 x_1) = \ell(x_r) + \dots + \ell(x_2) + \ell(x_1)$$

for every $(x_r, \dots, x_2, x_1) \in X_{C,r} \times \dots \times X_{C,2} \times X_{C,1}$. For every $i \in [1, r]$, $X_{C,i}$ contains a unique element of maximal length (see (1)-(2) above). Let us denote it by $\eta_{C,i}$. We set:

$$\eta_C = \eta_{C,r} \dots \eta_{C,2} \eta_{C,1}.$$

Then, by (2.11), we have

PROPOSITION 2.12. — *Let $C \models n$, then η_C is the unique element of X_C of maximal length.*

2.7. Double cosets representatives

If C and D are two signed compositions of n , we set

$$X_{CD} = X_C^{-1} \cap X_D.$$

PROPOSITION 2.13. — *Let C and D be two signed composition of n and let $d \in X_{CD}$. Then:*

- (a) *There exists a unique signed composition E of n such that $S'_E = S'_C \cap {}^d S'_D$. It will be denoted by $C \cap {}^d D$ or ${}^d D \cap C$. We have $(C \cap {}^d D)^- = C^- \cap {}^d D^-$.*
- (b) *$W_C \cap {}^d W_D = W_{C \cap {}^d D}$ and $W_C \cap {}^d S'_D = S'_C \cap {}^d W_D = S'_{C \cap {}^d D}$.*
- (c) *If $w \in W_{C \cap {}^d D}$, then $\ell_t(w) = \ell_t(d^{-1}wd)$.*
- (d) *If $w \in W_C d W_D$, then there exists a unique pair $(x, y) \in X_{C \cap {}^d D}^C \times W_D$ such that $w = xdy$.*
- (e) *Let $(x, y) \in X_{C \cap {}^d D}^C \times W_D$, then $\ell(xdy) \geq \ell(x_S) + \ell_t(x) + \ell(d) + \ell(y_S) + \ell_t(y)$.*
- (f) *d is the unique element of $W_C d W_D$ of minimal length.*

Proof. — (a) follows immediately from Lemma 2.5 (equivalence between (3) and (4)).

(b) It is clear that $W_E \subset W_C \cap {}^d W_D$. Let us show the reverse inclusion. Let $w \in W_C \cap {}^d W_D$. We will show by induction on $\ell_t(w)$ that $w \in W_E$. If $\ell_t(w) = 0$, then we see from Proposition 2.8 (d) that $w \in \mathfrak{S}_{C^+} \cap {}^d \mathfrak{S}_{D^+} = \mathfrak{S}_{E^+}$ by definition of E^+ .

Assume now that $\ell_t(w) > 0$ and that, if $w' \in W_C \cap {}^d W_D$ is such that $\ell_t(w') < \ell_t(w)$, then $w' \in W_E$. Since $\ell_t(w) > 0$, there exists $i \in [1, n]$ such that $w(i) < 0$. In particular, $t_i \in \mathfrak{T}_C$. By the same argument as in the proof of Proposition 2.8 (d), we have that $t_i \in {}^d W_D$. So, $t_i \in T_C \cap {}^d T_D = T_E$. Now, let $w' = wt_i$. Then $t_i \in W_E$, $w' \in W_C \cap {}^d W_D$ and $\ell_t(w') = \ell_t(w) - 1$. So, by the induction hypothesis, $w' \in W_E$, so $w \in W_E$.

The other assertions of (b) follow easily.

(c) Let $w = \sigma_1 \dots \sigma_l$ be a reduced decomposition of w with respect to S_C . Then $d^{-1}wd = (d^{-1}\sigma_1 d) \dots (d^{-1}\sigma_l d)$. But $d^{-1}\sigma_i d \in d^{-1}(S'_C \cap {}^d S'_D) = S'_{d^{-1}C \cap D}$, so $\ell_t(d^{-1}\sigma_i d) = \ell_t(\sigma_i)$. Since $\ell_t(w) = \ell_t(\sigma_1) + \dots + \ell_t(\sigma_l)$, we see that $\ell_t(w) \geq \ell_t(d^{-1}wd)$. By symmetry, we obtain the reverse inequality.

(d) Let $w \in W_C d W_D$. Let us write $w = adb$, with $a \in W_C$ and $b \in W_D$. We then write $a = xa'$ with $x \in X_{C \cap {}^d D}^C$ and $a' \in W_{C \cap {}^d D}$. Then $d^{-1}a'd \in$

$W_{d^{-1}C \cap D} \subset W_D$. Write $y = (d^{-1}a'd)b$. Then $(x, y) \in X_{C \cap aD}^C \times W_D$ and $w = xdy$.

Now let $(x', y') \in X_{C \cap aD}^C \times W_D$ such that $w = x'dy'$. Then $x'^{-1}x = d(yy'^{-1})d^{-1}$. So $x'^{-1}x \in W_{C \cap aD}$, that is $xW_{C \cap aD} = x'W_{C \cap aD}$. So $x = x'$ and $y = y'$.

(e) Let $(x, y) \in X_{C \cap aD}^C \times W_D$. We will show by induction on $\ell_t(x) + \ell_t(y)$ that

$$\ell(xdy) \geq \ell(x_S) + \ell_t(x) + \ell(d) + \ell(y_S) + \ell_t(y).$$

If $\ell_t(x) = \ell_t(y) = 0$, then $x \in X_{C^- \cap a(D^-)}$, $y \in \mathfrak{S}_{D^+}$ and $d \in X_{C^-, D^-}$. So, by [8, Proposition 2.1.7], we have $\ell(xdy) = \ell(x_S) + \ell(d) + \ell(y_S)$, as desired.

Now, let us assume that $\ell_t(x) + \ell_t(y) > 0$ and that the result holds for every pair $(x', y') \in X_{C \cap aD}^C \times W_D$ such that $\ell_t(x') + \ell_t(y') < \ell_t(x) + \ell_t(y)$. By symmetry, and using (c), we can assume that $\ell_t(y) > 0$. So there exists $i \in I_n$ such that $y(i) < 0$. Let $y' = yt_i$. Then $t_i \in T_D$, $\ell(y_S) = \ell(y'_S)$, $\ell_t(y') = \ell_t(y) - 1$. Therefore, by induction hypothesis, we have

$$\ell(xdy') \geq \ell(x_S) + \ell_t(x) + \ell(d) + \ell(y_S) + \ell_t(y) - 1.$$

It is now enough to show that $\ell(xdy't_i) > \ell(xdy')$, that is $x dy'(i) > 0$. Note that $y'(i) > 0$ and that $t_{y'(i)} = y't_i y'^{-1} \in W_D$. So the result follows from the following lemma:

LEMMA 2.14. — *If $d \in X_{CD}$, if $x \in X_{C \cap aD}^D$ and if $j \in [1, n]$ is such that $t_j \in T_D$, then $xd(j) > 0$.*

Proof. — Since $t_j \in W_D$ and $d \in X_D$, we have $d(j) > 0$. Two cases may occur. If $t_{d(j)} \in T_C$, then $t_{d(j)} = dt_j d^{-1} \in T_{C \cap aD}$. Therefore, $x(d(j)) > 0$ since $x \in X_{C \cap aD}^C$. If $t_{d(j)} \notin T_C$, then $x(d(j)) > 0$ since $x \in W_C = \mathfrak{S}_{C^+} \times \mathfrak{T}_C$. □

(f) follows immediately from (e). □

Remark 2.15. — Let C and D be two signed compositions of n and let $d \in X_{CD}$. Then $d^{-1} \in X_{DC}$ and, by Proposition 2.9, we have that

$$X_{C \cap aD} d = X_{a^{-1}C \cap D}.$$

COROLLARY 2.16. — *The map $X_{CD} \rightarrow W_C \backslash W_n / W_D$ is bijective.*

Proof. — The Proposition 2.13 (f) shows that the map is injective. The surjectivity follows from the fact that, if $w \in W_n$ is an element of minimal length in $W_C w W_D$, then $w \in X_{CD}$. □

COROLLARY 2.17. — *If C is parabolic or if D is semi-positive, then*

$$X_D = \coprod_{d \in X_{CD}} X_{C \cap aD}^C d.$$

Proof. — It follows from Corollary 2.16 that

$$|X_D| = |W_n/W_D| = \sum_{d \in X_{CD}} |W_C d W_D/W_D| = \sum_{d \in X_{CD}} |X_{C \cap {}^d D}^C|,$$

the last equality following from Proposition 2.13 (d). So, it remains to show that, if $d \in X_{CD}$ and if $x \in X_{C \cap {}^d D}^C$, then $xd \in X_D$.

Assume that we have found $s \in S_D$ such that $\ell(xds) < \ell(xd)$. If $s \in T_D$, then $s = t_i$ for some $i \in I_n$. But, by Lemma 2.14, $xd(i) > 0$, so $\ell(xdt_i) > \ell(xd)$, contradicting our hypothesis. Therefore, $s \in S_{D^-}$, that is $s = s_i$ for some $i \in [1, n - 1]$. If C is parabolic, $C \cap {}^d D$ is also parabolic. Therefore, $\ell(xds) > \ell(xd)$ which is a contradiction, so D is semi-positive. Therefore, we have that t_i and t_{i+1} belong to T_D . Thus, by Lemma 2.14, we have $xd(i) > 0$ and $xd(i + 1) > 0$. Moreover, since $\ell(xds_i) < \ell(xd)$, we have

$$(*) \quad 0 < xd(i + 1) < xd(i).$$

But, since $d \in X_D$, we have $d(i + 1) > d(i)$. So, by Proposition 2.13 (b), we have that $ds_i d^{-1} \in S_{C \cap {}^d D}$. Thus $\ell(x(ds_i d^{-1})) > \ell(x)$ because $x \in X_{C \cap {}^d D}^C$. In other words, $xd(i + 1) > xd(i)$. This contradicts (*). \square

If E is a signed composition of n such that $C \subset E$ and $D \subset E$, we set $X_{CD}^E = X_{CD} \cap W_E$.

Example. — It is not true in general that $X_D = \coprod_{d \in X_{CD}} X_{C \cap {}^d D}^C d$. This is false, if $n = k + l$ with $k, l \geq 1$, $C = (\bar{k}, \bar{l})$ and $D = (n)$. See Example 2.25 for precisions.

2.8. A partition of W_n

If $C = (c_1, \dots, c_r)$ is a signed composition of n , we set

$$A_C = \{s_{|c_1|+\dots+|c_i|} \mid i \in [1, r] \text{ and } c_i < 0 \text{ and } c_{i+1} > 0\}$$

and

$$\mathcal{A}_C = S'_C \coprod A_C.$$

As example, $A_{(1, \bar{3}, \bar{1}, 2, \bar{1}, 1)} = \{s_5, s_8\}$. Note that $\mathcal{A}_C = \mathcal{A}_D$ if and only if $C = D$. If $w \in W_n$, then we define the ascent set of w :

$$\mathcal{U}'_n(w) = \{s \in S'_n \mid \ell(ws) > \ell(w)\}.$$

Finally, following Mantaci-Reutenauer, we associate to each element $w \in W_n$ a signed composition $\mathbf{C}(w)$ as follows. First, let $\mathbf{C}^+(w) = (c_1^+, \dots, c_r^+)$ denote the biggest composition (for the order \subset) of n such that, for every $1 \leq i \leq r$, the map $w : I_{\mathbf{C}^+(w), +}^{(i)} \rightarrow I_n$ is increasing and has constant sign.

Now, we define $\nu_i = \text{sign}(w(j))$ for $j \in I_{\mathcal{C}^+}^{(i)}(w)$. The descent composition of w is $\mathcal{C}(w) = (\nu_1 c_1^+, \dots, \nu_r c_r^+)$.

Example. — $\mathcal{C}(\underbrace{9.\bar{3}\bar{2}\bar{1}.\bar{4}.58.\bar{6}.\bar{7}}_{\in W_9}) = (1, \bar{3}, \bar{1}, 2, \bar{1}, 1) \Vdash 9$.

The following proposition is easy to check (see Remark 2.1):

PROPOSITION 2.18. — *If $w \in W_n$, then $\mathcal{U}'_n(w) = \mathcal{A}_{\mathcal{C}(w)}$.*

Remark. — Mantaci and Reutenauer have defined the descent shape of a signed permutation [16]. It is a signed composition defined similarly than descent composition except that the absolute value of the letters in u_i must be in increasing order. For instance, the descent shape of $9.\bar{3}.\bar{2}.\bar{1}\bar{4}.58.\bar{6}.\bar{7}$ is $(1, \bar{1}, \bar{1}, \bar{2}, 2, \bar{1}, 1)$.

Example 2.19. — Let n' be a non-zero natural number, $n' < n$ and let $c \in \mathbf{Z}$ such that $n - n' = |c|$. Let $w \in W_{n'} \subset W_n$ and write $\mathcal{C}(w) = (c_1, \dots, c_r) \Vdash n'$. Then $\mathcal{C}(\eta_{(n',c)}w) = (c_1, \dots, c_r, c)$. Consequently, if $C \Vdash n$, an easy induction argument shows that $\mathcal{C}(\eta_C) = C$.

We have then defined a surjective map

$$\mathcal{C} : W_n \longrightarrow \text{Comp}(n)$$

whose fibers are equal to those of the application $\mathcal{U}'_n : W_n \rightarrow \mathcal{P}(S'_n)$. The surjectivity follows from Example 2.19. If $C \Vdash n$, we define

$$Y_C = \{w \in W_n \mid \mathcal{C}(w) = C\}.$$

Then

$$W_n = \coprod_{C \Vdash n} Y_C.$$

Example 2.20. — We have $Y_n = \{1_n\}$, $Y_{\bar{n}} = \{\sigma_n w_n\}$, $Y_{(1, \dots, 1)} = \{\sigma_n\}$ and $Y_{(\bar{1}, \dots, \bar{1})} = \{w_n\}$.

First, note the following elementary facts.

LEMMA 2.21. — *Let C and D be two signed compositions of n . Then:*

- (a) *If $Y_C \cap X_D \neq \emptyset$, then $Y_C \subset X_D$.*
- (b) *$\eta_C \in Y_C$ and $Y_C \subset X_C$.*

Proof. — (a) If $w \in W_n$, then $w \in X_D$ if and only if $\mathcal{U}'_n(w)$ contains S'_D . Since the map $w \mapsto \mathcal{U}'_n(w)$ is constant on Y_C (see Proposition 2.18), (a) follows.

(b) By Example 2.19, we have $\eta_C \in Y_C \cap X_C$. Therefore, by (a), $Y_C \subset X_C$. □

We then define a relation \leftarrow between signed composition of n as follow. If $C, D \models n$, we write $C \leftarrow D$ if $Y_D \subset X_C$. We denote by \preceq the transitive closure of the relation \leftarrow . It follows from Lemma 2.21 (a) that

$$(2.22) \quad X_C = \coprod_{C \leftarrow D} Y_D.$$

Example 2.23. — Let $w \in W_n$. By Remark 2.1, $w \in X_{\bar{n}}$ if and only if the sequence $(w(1), w(2), \dots, w(n))$ of elements of I_n is strictly increasing (see Remark 2.1). So there exists a unique $k \in \{0, 1, 2, \dots, n\}$ such that $w(i) > 0$ if and only if $i > k$. Note that $k = \ell_t(w)$. Let $i_1 < \dots < i_k$ be the sequence of elements of I_n such that $(w(1), \dots, w(k)) = (\bar{i}_k, \dots, \bar{i}_1)$. Then $w = r_{i_1} r_{i_2} \dots r_{i_k}$ where, if $1 \leq i \leq n$, we set $r_i = s_{i-1} \dots s_2 s_1 t$. Note that $C(w) = (\bar{k}, n - k)$. Therefore,

$$X_{\bar{n}} = \{r_{i_1} r_{i_2} \dots r_{i_k} \mid 0 \leq k \leq n \text{ and } 1 \leq i_1 < i_2 < \dots < i_k \leq n\}.$$

Note that $\ell(r_{i_1} r_{i_2} \dots r_{i_k}) = i_1 + i_2 + \dots + i_k$ and $\ell_t(r_{i_1} r_{i_2} \dots r_{i_k}) = k$. We get

$$X_{\bar{n}} = \coprod_{0 \leq k \leq n} Y_{(\bar{k}, n - k)},$$

and, for every $k \in \{0, 1, 2, \dots, n\}$, we have

$$Y_{(\bar{k}, n - k)} = \{r_{i_1} r_{i_2} \dots r_{i_k} \mid 1 \leq i_1 < i_2 < \dots < i_k \leq n\}.$$

This shows that $(\bar{n}) \leftarrow (\bar{k}, n - k)$.

PROPOSITION 2.24. — *Let C and D be two signed compositions of n . Then:*

- (a) $C \leftarrow C$.
- (b) If $C \subset D$, then $C \leftarrow D$.
- (c) \preceq is an order on $\text{Comp}(n)$.

Proof. — (a) follows immediately from Lemma 2.21 (b).

(b) If $C \subset D$, then $X_D \subset X_C$. But, by Lemma 2.21 (b), we have $Y_D \subset X_D$. So $C \leftarrow D$.

(c) Let $a_C = \ell(\eta_C)$. By (a), \preceq is reflexive. By definition, it is transitive. So it is sufficient to show that it is antisymmetric. But it follows from Lemma 2.21 (b) that:

- If $C \leftarrow D$, then $a_D \leq a_C$.
- If $C \leftarrow D$ and if $a_C = a_D$, then $C = D$.

The assertion (c) now follows easily from these two remarks. □

A precise description of the relation \leftarrow will be given in Theorem 3.15.

Example 2.25. — If $C = (c_1, \dots, c_r)$ is a composition of n (not a signed composition), we will prove that

$$X_{\bar{n}} = \prod_{\substack{0 \leq m_2 \leq c_2 \\ 0 \leq m_3 \leq c_3 \\ \dots \\ 0 \leq m_r \leq c_r}} X_{(\bar{c}_1, m_2, c_2 - m_2, \dots, m_r, c_r - m_r)}^C \times Y_{(\bar{c}_1, \bar{m}_2, c_2 - m_2, \dots, \bar{m}_r, c_r - m_r)}^{(c_1, m_2, c_2 - m_2, \dots, m_r, c_r - m_r)} \sigma_{C, m_2, \dots, m_r}^{-1},$$

where $\sigma_{C, m_2, \dots, m_r} \in \mathfrak{S}_n$ satisfies

$$\sigma_{C, m_2, \dots, m_r} (S'_{(c_1, m_2, c_2 - m_2, \dots, m_r, c_r - m_r)}) \subset S'_n$$

and

$$\sigma_{C, m_2, \dots, m_r} \in X_{(c_1, m_2, c_2 - m_2, \dots, m_r, c_r - m_r)}.$$

By an easy induction argument, it is sufficient to prove it whenever $r = 2$. In other words, we want to prove that, if $k + l = n$ with $k, l \geq 0$, then

$$(*) \quad X_{\bar{n}} = \prod_{0 \leq m \leq l} X_{(\bar{k}, \bar{l})}^{(k, m, l - m)} Y_{(k, \bar{m}, l - m)}^{(k, m, l - m)} \sigma_{k, l, m}^{-1},$$

where $\sigma_{k, l, m} \in \mathfrak{S}_n$ satisfies $\sigma_{k, l, m} (S'_{(k, m, l - m)}) \subset S'_n$ and $\sigma_{k, l, m} \in X_{(k, m, l - m)}$. But, if $0 \leq m \leq l$, we set

$$\sigma_{k, l, m}(i) = \begin{cases} m + i & \text{if } 1 \leq i \leq k, \\ i - k & \text{if } k + 1 \leq i \leq k + m, \\ i & \text{if } k + m + 1 \leq i \leq n, \end{cases}$$

and one can easily check that $(*)$ holds. Moreover, since $S'_{k, m, l - m} = S'_n \setminus \{s_k, s_{k+m}\}$, we get that $\sigma_{k, l, m} (S'_{(k, m, l - m)}) \subset S'_n$ and $\sigma_{k, l, m} \in X_{(k, m, l - m)}$.

3. Generalized descent algebra

3.1. Definition

If C and D are two signed compositions of n such that $C \subset D$, we set

$$x_C^D = \sum_{w \in X_C^D} w \in \mathbf{Z}W_D$$

and

$$y_C^D = \sum_{w \in Y_C^D} w \in \mathbf{Z}W_D.$$

Now, let

$$\Sigma'(W_D) = \bigoplus_{C \subset D} \mathbf{Z}y_C^D \subset \mathbf{Z}W_D.$$

Note that

$$\Sigma'(W_D) = \bigoplus_{C \subset D} \mathbf{Z}x_C^D$$

by (2.22) and Proposition 2.24. We define

$$\theta_D : \Sigma'(W_D) \longrightarrow \mathbf{Z} \text{Irr } W_D$$

as the unique \mathbf{Z} -linear map such that

$$\theta_D(x_C^D) = \text{Ind}_{W_C}^{W_D} 1_C$$

for every $C \subset D$. Here, 1_C is the trivial character of W_C . We denote by ε_D the sign character of W_D .

Notation. — If $D = (n)$, we set $x_C^D = x_C$, $y_C^D = y_C$ for simplification. If E is \mathbf{Z} -module, we denote by $\mathbf{Q}E$ the \mathbf{Q} -vector space $\mathbf{Q} \otimes_{\mathbf{Z}} E$. We denote by $\theta_{D, \mathbf{Q}}$ the extension of θ_D to $\mathbf{Q}\Sigma'(W_D)$ by \mathbf{Q} -linearity.

Remark. — $\Sigma'(W_n)$ contains the Solomon descent algebras of W_n and \mathfrak{S}_n . Moreover, $\Sigma'(W_n)$ is precisely the *Mantaci-Reutenauer algebra* which is, by definition, generated by $y_D = y_D^{(n)}$, for all $D \Vdash n$.

3.2. First properties of θ_D

By the Mackey formula for the tensor product of two induced characters and by Proposition 2.13, we have that

$$(3.1) \quad \theta_n(x_C)\theta_n(x_D) = \sum_{d \in X_{CD}} \theta_n(x_{a^{-1}C \cap D}).$$

Example 3.2. — If C is parabolic or D is semi-positive, then, by Corollary 2.17, we have

$$x_D = \sum_{d \in X_{CD}} x_{C \cap aD}^C.$$

Therefore, by Proposition 2.8 (b) and Remark 2.15, we get

$$x_C x_D = \sum_{d \in X_{CD}} x_{a^{-1}C \cap D}.$$

So $x_C x_D \in \Sigma'(W_n)$ and, by (3.1), $\theta_n(x_C x_D) = \theta_n(x_C)\theta_n(x_D)$.

Before starting the proof of the fact that $\Sigma'(W_D)$ is a subalgebra of $\mathbf{Z}W_D$ and that θ_D is a morphism of algebras, we need the following result, which will be useful for arguing by induction. If $C \subset D$, the transitivity of induction and Proposition 2.8 (b) show that the diagram

$$(3.3) \quad \begin{array}{ccc} \Sigma'(W_C) & \xrightarrow{x_C^D} & \Sigma'(W_D) \\ \theta_C \downarrow & & \downarrow \theta_D \\ \mathbf{Z} \text{Irr } W_C & \xrightarrow{\text{Ind}_{W_C}^{W_D}} & \mathbf{Z} \text{Irr } W_D \end{array}$$

is commutative.

Now, let $p_D : W_D \rightarrow \mathfrak{S}_{D+}$ be the canonical projection. It induces an injective morphism of \mathbf{Z} -algebras $p_D^* : \mathbf{Z} \text{Irr } \mathfrak{S}_{D+} \rightarrow \mathbf{Z} \text{Irr } W_D$. Moreover, the algebra $\Sigma'(\mathfrak{S}_{D+})$ coincides with the usual descent algebra in symmetric groups and is contained in $\Sigma'(W_D)$. Also, the diagram

$$(3.4) \quad \begin{array}{ccc} \Sigma'(\mathfrak{S}_{D+}) \hookrightarrow & \longrightarrow & \Sigma'(W_D) \\ \theta_{D-} \downarrow & & \downarrow \theta_D \\ \mathbf{Z} \text{Irr } \mathfrak{S}_{D+} \hookrightarrow & \xrightarrow{p_D^*} & \mathbf{Z} \text{Irr } W_D \end{array}$$

is commutative.

Example 3.5. — We have $y_{(\bar{1}, \dots, \bar{1})} = w_n$, $y_{\bar{n}} = w_n \sigma_n = \sigma_n w_n$, $y_n = 1$ and $y_{(1, \dots, 1)} = \sigma_n$. It is well-known [18] that $y_{(\bar{1}, \dots, \bar{1})}$ belongs to the classical descent algebra of W_n and that

$$(a) \quad \theta_n(w_n) = \varepsilon_n.$$

On the other hand,

$$(b) \quad \theta_n(1_n) = 1_{(n)}.$$

Also, by the commutativity of the diagram (3.4) and as above, we have

$$(c) \quad \theta_n(\sigma_n) = \gamma_n,$$

where $\gamma_n = p_n^* \varepsilon_{\bar{n}}$. Finally, w_n is a \mathbf{Z} -linear combination of x_C , where C runs over the parabolic compositions of n . Therefore, by Example 3.2, we have, for every $x \in \Sigma'(W_n)$,

$$(d) \quad \theta_n(w_n x) = \theta_n(w_n) \theta_n(x) = \varepsilon_n \theta_n(x).$$

In particular,

$$(e) \quad \theta_n(y_{\bar{n}}) = \theta_n(w_n \sigma_n) = \varepsilon_n \gamma_n.$$

So we have obtained the four linear characters of W_n as images by θ_n of explicit elements of $\Sigma'(W_n)$.

Let $\text{deg}_D : \mathbf{Z} \text{Irr } W_D \rightarrow \mathbf{Z}$ be the \mathbf{Z} -linear map sending an irreducible character of W_D to its degree. It is a morphism of \mathbf{Z} -algebras. Let $\text{aug}_D : \mathbf{Z}W_D \rightarrow \mathbf{Z}$ denote the augmentation morphism. Then the diagram

$$(3.6) \quad \begin{array}{ccc} \Sigma'(W_D) & \xrightarrow{\theta_D} & \mathbf{Z} \text{Irr } W_D \\ & \searrow \text{aug}_D & \downarrow \text{deg}_D \\ & & \mathbf{Z} \end{array}$$

is commutative.

3.3. Main result

We are now ready to prove that $\Sigma'(W_D)$ is a \mathbf{Z} -subalgebra of $\mathbf{Z}W_D$ and that θ_D is a surjective morphism of algebras.

THEOREM 3.7. — *Let D be a signed composition of n , then:*

- (a) $\Sigma'(W_D)$ is a \mathbf{Z} -subalgebra of $\mathbf{Z}W_D$;
- (b) θ_D is a morphism of algebra;
- (c) θ_D is surjective and $\text{Ker } \theta_D = \sum_{\substack{C, C' \subset D \\ C \equiv_D C'}} \mathbf{Z}(x_C^D - x_{C'}^D)$;
- (d) $\text{Ker } \theta_{D, \mathbf{Q}}$ is the radical of the algebra $\mathbf{Q}\Sigma'(W_D)$.

Moreover, $\mathbf{Q}\Sigma'(W_D)$ is a split algebra whose largest semisimple quotient is commutative. In particular, all its simple modules are of dimension 1.

Proof. — We want to prove the theorem by induction on $|W_D|$. By taking direct products, we may therefore assume that $D = (n)$ or $D = (\bar{n})$. If $D = (\bar{n})$, then it is well-known that (a), (b), (c) and (d) hold. So we may assume that $D = (n)$ and that (a), (b), (c) and (d) hold for every signed composition D' of n different from (n) .

(a) and (b): Let A and B be two signed compositions of n . We want to prove that $x_A x_B \in \Sigma'(W_n)$ and that $\theta_n(x_A x_B) = \theta_n(x_A) \theta_n(x_B)$. If A is

parabolic or B is semi-positive, then this is just Example 3.2. So we may assume that A is not parabolic and B is not semi-positive.

First, note that $B \subset B^+$ and that B^+ is semi-positive. Therefore, by Proposition 2.8(b) and Example 3.2, we have

$$\begin{aligned} x_A x_B &= x_A x_{B^+} x_B^{B^+} = \sum_{d \in X_{A, B^+}} x_{d^{-1}A \cap B^+} x_B^{B^+} \\ &= x_{B^+} \sum_{d \in X_{A, B^+}} x_{d^{-1}A \cap B^+}^{B^+} x_B^{B^+}. \end{aligned}$$

Assume first that $B^+ \neq (n)$. Then, by induction hypothesis,

$$\sum_{d \in X_{A, B^+}} x_{d^{-1}A \cap B^+}^{B^+} x_B^{B^+} \in \Sigma'(\mathfrak{S}_{B^+})$$

and

$$\theta_{B^+} \left(\sum_{d \in X_{A, B^+}} x_{d^{-1}A \cap B^+}^{B^+} x_B^{B^+} \right) = \sum_{d \in X_{A, B^+}} \theta_{B^+}(x_{d^{-1}A \cap B^+}^{B^+}) \theta_{B^+}(x_B^{B^+}).$$

Therefore, by (3.3) and (3.4), $x_A x_B \in x_{B^+} \Sigma'(\mathfrak{S}_{B^+}) \subset \Sigma'(\mathfrak{S}_n) \subset \Sigma'(W_n)$ and, by (3.3) and by the Mackey formula for tensor product, we get

$$\begin{aligned} \theta_n(x_A x_B) &= \text{Ind}_{W_{B^+}}^{W_n} \left(\sum_{d \in X_{A, B^+}} \theta_{B^+}(x_{d^{-1}A \cap B^+}^{B^+}) \theta_{B^+}(x_B^{B^+}) \right) \\ &= \theta_n(x_A) \text{Ind}_{W_{B^+}}^{W_n} \theta_{B^+}(x_B^{B^+}) \\ &= \theta_n(x_A) \theta_n(x_B), \end{aligned}$$

as desired.

Therefore, it remains to consider the case where $B^+ = (n)$. In particular, $B = (n)$ or (\bar{n}) . Since B is not semi-positive, we have $B = (\bar{n})$. By Example 2.25, we have

$$x_{\bar{n}} = x_{A^-}^{A^+} + \sum_{D \subset A^+} a_D x_D^{A^+} (\sigma_D^{-1} - 1)$$

where $a_D \in \mathbf{Z}$ and $\sigma_D(S'_D) \subset S'_n$ and $\sigma_D \in X_D$ for every $D \subset A^+$. Therefore,

$$x_A x_B = x_A x_{\bar{n}} = x_{A^+} \left(x_A^{A^+} x_{A^-}^{A^+} + \sum_{D \subset A^+} a_D x_A^{A^+} x_D^{A^+} (\sigma_D^{-1} - 1) \right).$$

Now, W_A is a standard parabolic subgroup of W_{A^+} . So, by Example 3.2, we have

$$x_A x_B = \sum_{d \in X_{A, A^+}^{A^+}} x_{d^{-1}A \cap (A^-)} + \sum_{D \subset A^+} \left(a_D \sum_{d \in X_{A, D}^{A^+}} x_{d^{-1}A \cap D} (\sigma_D^{-1} - 1) \right).$$

Therefore, since $\sigma_D(S'_D) \subset S'_n$ and $\sigma_D \in X_D$, we have that $x_{a^{-1}A \cap D} \sigma_D^{-1} = x_{\sigma_D(a^{-1}A \cap D)}$. So $x_A x_B \in \Sigma'(W_n)$ and $\theta_n(x_A x_B) = \theta_n(x_A) \theta_n(x_B)$ by the Mackey formula for tensor product of induced characters. This concludes the proof of (a) and (b).

(c) First, let us show that θ_n is surjective. Using the induction hypothesis, the commutativity of the diagram (3.3), and the classical description of irreducible characters of W_n , we are reduced to prove that, for every $\chi \in \text{Irr } \mathfrak{S}_n$, $p_n^*(\chi)$ and $p_n^*(\chi)\varepsilon_n$ lie in the image of θ_n . But it is well-known that $\theta_{\bar{n}}$ is surjective. So the result follows from the commutativity of the diagram (3.4) and from Example 3.5 (d).

Now, let

$$I = \sum_{\substack{C, C' \models n \\ C \equiv_n C'}} \mathbf{Z}(x_C - x_{C'}).$$

Then it is clear that $I \subset \text{Ker } \theta_n$. Let $J = \bigoplus_{\lambda \in \text{Bip}(n)} \mathbf{Z}x_\lambda$. Then $\Sigma'(W_n) = I \oplus J$ and the map $\theta_n : J \rightarrow \mathbf{Z} \text{Irr } W_n$ is surjective. Since J and $\mathbf{Z} \text{Irr } W_n$ have the same rank (equal to $|\text{Bip}(n)|$), we get that $J \cap \text{Ker } \theta_n = 0$. So $I = \text{Ker } \theta_n$.

(d) Let $R = \text{Rad}(\mathbf{Q}\Sigma'(W_n))$ and $K = \text{Ker } \theta_{n, \mathbf{Q}}$. Since $\text{Im}(\theta_{n, \mathbf{Q}}) = \mathbf{Q} \text{Irr } W_n$ is a semisimple algebra, we get that $R \subset K$.

Now, let $\chi : \mathbf{Q}W_n \rightarrow \mathbf{Q}$ be the character of the $\mathbf{Q}W_n$ -module $\mathbf{Q}W_n$ (the regular representation). Then, $\chi(w) = 0$ for every $w \neq 1$. Let χ' denote the restriction of χ to $\Sigma'(W_n)$. We have $\chi'(x_C) = \chi(1)$ for every $C \models n$. Therefore, $\chi'(x) = 0$ for every $x \in K$ by (c). We fix now $x \in K$. Then, for every $y \in \mathbf{Q}\Sigma'(W_n)$, we have $\chi'(xy) = 0$ because $xy \in K$ by (b). Since the $\mathbf{Q}\Sigma'(W_n)$ -module $\mathbf{Q}W_n$ is faithful, this implies that $x \in R$. So $K \subset R$. \square

Remark. — $\Sigma'(W_C) \simeq \Sigma'(W_{c_1}) \otimes \Sigma'(W_{c_2}) \otimes \cdots \otimes \Sigma'(W_{c_r})$.

3.4. Further properties of θ_D

Let $\tau_D : \mathbf{Z}W_D \rightarrow \mathbf{Z}$ be the unique linear map such that $\tau_D(w) = 0$ if $w \neq 1$ and $\tau_D(1) = 1$. Then τ_D is the canonical symmetrizing form on $\mathbf{Z}W_D$: in particular, the map $\mathbf{Z}W_D \times \mathbf{Z}W_D \rightarrow \mathbf{Z}$, $(x, y) \mapsto \tau_D(xy)$ is a non-degenerate symmetric bilinear form on $\mathbf{Z}W_D$. We denote by $\langle \cdot, \cdot \rangle_D$ the scalar product on $\mathbf{Z} \text{Irr } W_D$ such that $\text{Irr } W_D$ is an orthonormal basis. The following property is a kind of “isometry property” for the morphism θ_D .

PROPOSITION 3.8. — *If $x, y \in \Sigma'(W_D)$, then*

$$\tau_D(xy) = \langle \theta_D(x), \theta_D(y) \rangle_D.$$

Proof. — Let C and C' be two signed compositions of n such that $C, C' \subset D$. Then $\tau_D(x_C^D x_{C'}^D) = |X_{CC'}^D|$ by definition of τ_D . Moreover, since $\theta_D(x_C)$ and $\theta_D(x_{C'})$ take only rational values, we have

$$\langle \theta_D(x_C^D), \theta_D(x_{C'}^D) \rangle_D = \langle \theta_D(x_C^D) \theta_D(x_{C'}^D), 1_{W_D} \rangle_D.$$

But, by (3.1) and by Frobenius reciprocity, we have

$$\langle \theta_D(x_C^D) \theta_D(x_{C'}^D), 1_{W_D} \rangle_D = |X_{CC'}^D|.$$

So the proposition follows now from the fact that $(x_C^D)_{C \subset D}$ generates $\Sigma'(W_D)$. □

COROLLARY 3.9. — *We have*

$$\text{Ker } \theta_D = \{x \in \Sigma'(W_D) \mid \forall y \in \Sigma'(W_D), \tau_D(xy) = 0\}.$$

Proof. — Since $\langle \cdot, \cdot \rangle_D$ is non-degenerate on $\mathbf{Z} \text{Irr } W_D$, this follows from Proposition 3.8. □

Write $D = (d_1, \dots, d_r)$ and let $\text{Bip}(D)$ denote the set of r -tuples $(\lambda_{(1)}, \dots, \lambda_{(r)})$ of bipartitions $\lambda_{(i)} = (\lambda_{(i)}^+, \lambda_{(i)}^-)$ such that $\lambda_{(i)}^- = \emptyset$ if $d_i < 0$ and $|\lambda_{(i)}| = |d_i|$ for every $i \in [1, r]$. If $\lambda \in \text{Bip}(D)$, we denote by \mathcal{C}_λ^D the conjugacy class in W_D of a Coxeter element of $W_{\hat{\lambda}}$ (with respect to $S_{\hat{\lambda}}$). Let f_λ^D denote the characteristic function of \mathcal{C}_λ^D . Then f_λ^D is a primitive idempotent of $\mathbf{Q} \text{Irr } W_D$. Moreover, $(f_\lambda^D)_{\lambda \in \text{Bip}(D)}$ is a complete family of orthogonal primitive idempotents of $\mathbf{Q} \text{Irr } W_D$. Since θ_D is surjective, there exists a family of idempotents $(E_\lambda^D)_{\lambda \in \text{Bip}(D)}$ of $\mathbf{Q} \Sigma'(W_D)$ such that

- (1) $\forall \lambda \in \text{Bip}(D), \theta_D(E_\lambda^D) = f_\lambda^D.$
- (2) $\forall \lambda, \mu \in \text{Bip}(D), \lambda \neq \mu \Rightarrow E_\lambda^D E_\mu^D = E_\mu^D E_\lambda^D = 0.$
- (3) $\sum_{\lambda \in \text{Bip}(D)} E_\lambda^D = 1.$

PROPOSITION 3.10. — *If $x \in \Sigma'(W_D)$, then*

$$\theta_D(x) = |W_D| \sum_{\lambda \in \text{Irr } D} \frac{\tau_D(x E_\lambda^D)}{|\mathcal{C}_\lambda^D|} f_\lambda^D \in \mathbf{Z} \text{Irr } W_D.$$

Proof. — If $f \in \mathbf{Q} \text{Irr } W_D$, then

$$f = |W_D| \sum_{\lambda \in \text{Bip}(D)} \frac{\langle f, f_\lambda^D \rangle_D}{|\mathcal{C}_\lambda^D|} f_\lambda^D \in \mathbf{Z} \text{Irr } W_D.$$

If $f = \theta_D(x)$ with $x \in \Sigma'(W_D)$, then we get the desired formula just by applying Proposition 3.8 and the property (1) above. □

3.5. Character table

Since all irreducible characters of W_D have rational values, the algebra $\mathbf{Q} \text{Irr } W_D$ may be identified with the \mathbf{Q} -algebra of central functions $W_D \rightarrow \mathbf{Q}$. If $\lambda \in \text{Bip}(D)$, we denote by $\text{ev}_\lambda^D : \mathbf{Q} \text{Irr } W_D \rightarrow \mathbf{Q}$, $\chi \mapsto \chi(c_\lambda^D)$, where c_λ^D is some element of \mathcal{C}_λ^D (for instance, a Coxeter element of $W_{\hat{\lambda}}$). Then ev_λ^D is a morphism of algebras: it is an irreducible representation of $\mathbf{Q} \text{Irr } W_D$. Moreover, $\{\text{ev}_\lambda^D \mid \lambda \in \text{Bip}(D)\}$ is a complete set of representatives of isomorphy classes of irreducible representations of $\mathbf{Q} \text{Irr } W_D$. Now, let \mathbf{Q}_λ^D denote the $\mathbf{Q}\Sigma'(W_D)$ -module whose underlying vector space is \mathbf{Q} and on which an element $x \in \mathbf{Q}\Sigma'(W_D)$ acts by multiplication by $\pi_\lambda^D(x) = (\text{ev}_\lambda^D \circ \theta_D)(x)$.

Then, by Theorem 3.7, we get:

PROPOSITION 3.11. — $\{\mathbf{Q}_\lambda^D \mid \lambda \in \text{Bip}(D)\}$ is a complete set of isomorphy classes of simple $\mathbf{Q}\Sigma'(W_D)$ -modules. We have

$$\text{Irr}(\mathbf{Q}\Sigma'(W_D)) = \{\pi_\lambda^D \mid \lambda \in \text{Bip}(D)\}.$$

The character table of $\mathbf{Q}\Sigma'(W_D)$ is the square matrix whose rows and the columns are indexed by $\text{Bip}(D)$ and whose (λ, μ) -entry is the value of the irreducible character $\pi_\lambda^D(x_\mu^D)$. Note that

$$\pi_\lambda^D(x_\mu^D) = \left(\text{Ind}_{W_{\hat{\mu}}}^{W_D} 1_{\hat{\mu}} \right) (c_\lambda^D).$$

Notation. — If $D = (n)$, we denote \mathcal{C}_λ^D , f_λ^D , E_λ^D , c_λ^D , ev_λ^D , \mathbf{Q}_λ^D and π_λ^D by \mathcal{C}_λ , f_λ , E_λ , c_λ , ev_λ , \mathbf{Q}_λ and π_λ respectively.

Now, if $\lambda, \mu \in \text{Bip}(D)$, we write $\lambda \subset \mu$ if there exists some $w \in W_D$ such that $W_{\hat{\lambda}} \subset {}^w W_{\hat{\mu}}$. By Proposition 2.7, \subset is a partial order on $\text{Bip}(D)$. For this partial order, the character table of $\mathbf{Q}\Sigma'(W_D)$ is triangular :

PROPOSITION 3.12. — If $\pi_\lambda^D(x_\mu^D) \neq 0$, then $\lambda \subset \mu$.

Proof. — We may, and we will, assume that $D = (n)$. If $\pi_\lambda(x_\mu) \neq 0$, then there exists $w \in W_n$ such that $wc_\lambda w^{-1} \in W_{\hat{\mu}}$. Therefore, there exists $\nu \in \text{Bip}(\hat{\mu})$ and $w' \in W_{\hat{\mu}}$ such that $w'wc_\lambda w'^{-1}$ is a Coxeter element of $W_{\hat{\nu}}$. Let C denote the unique signed composition of n such that $W_{\hat{\nu}} = W_C$ and let $\lambda' = \boldsymbol{\lambda}(C)$. Then $w'wc_\lambda w'^{-1}$ is conjugate to $c_{\lambda'}$. Therefore, $\lambda = \lambda'$. This completes the proof of the proposition. \square

In the last section of this paper, we will give the character table of $\Sigma'(W_2)$.

3.6. Combinatorial description

In \mathfrak{S}_n , the refinement of compositions is useful to construct X_C from Y_D without considering subsets of S'_n . The aim of this subsection is to describe such a procedure in our case. Let us start with an example. Consider $C = (\bar{2}, 1)$, then the subsets of S'_3 containing $S_C = \{s_1, t_3\}$ are $\{s_1, s_2, t_3\} = \mathcal{A}_{(\bar{2}, 1)}$; $\{s_1, t_2, t_3\} = \mathcal{A}_{(\bar{1}, 1, 1)}$; $\{s_1, t_1, t_2, t_3\} = \mathcal{A}_{(2, 1)}$, $\{s_1, s_2, t_2, t_3\} = \mathcal{A}_{(\bar{1}, 2)}$ and $S'_3 = \mathcal{A}_{(3)}$. Observe that $(1, 2)$ (which corresponds to $\{s_2, t_1, t_2, t_3\} \not\subseteq S_C$) is not obtained. Here, we define a procedure which give $(\bar{2}, 1)$, $(\bar{1}, 1, 1)$, $(\bar{1}, 2)$ and (3) from $(\bar{2}, 1)$, without obtaining $(1, 2)$.

Let $C = (c_1, \dots, c_k) \models n$, we write:

- $C \xleftarrow{B} D$ if $D = (a_1, b_1, a_2, b_2, \dots, a_k, b_k) \models n$ is such that for all $i \in [1, k]$ we have $|a_i| + |b_i| = |c_i|$; $a_i = c_i$ (hence $b_i = 0$) if $c_i > 0$; $a_i \leq 0 \leq b_i$ if $c_i < 0$ (remove the 0 from the list $(a_1, b_1, a_2, b_2, \dots, a_k, b_k)$). That is, D is obtained from C by *breaking negative parts operations*.
- $C \xleftarrow{R} D$ if C is finer than $D \models n$, that is, D can be obtained from C by summing consecutive parts of C having the same sign (*refinement operations*).

Example 3.13. — Let $C = (1, \bar{2}, \bar{1})$, then

$$\left\{ D \models 4 \mid C \xleftarrow{B} D \right\} = \left\{ (1, \bar{2}, \bar{1}), (1, \bar{1}, 1, \bar{1}), (1, \bar{1}, 1, 1), (1, 2, \bar{1}), (1, \bar{2}, 1), (1, 2, 1) \right\}.$$

Remark 3.14. — Let $C, D \models n$, then we have $C \leftarrow D$ if and only if $S_C \subset \mathcal{A}_D$. We deduce easily from definitions, Lemma 2.21 and Example 2.23 the following properties for any $i \in [1, k - 1]$:

- if $\text{sign } c_i = \text{sign } c_{i+1}$, then

$$C = (c_1, \dots, c_i, c_{i+1}, \dots, c_k) \xleftarrow{R} (c_1, \dots, c_i + c_{i+1}, \dots, c_k) = D,$$

and this means that $\mathcal{A}_D = \mathcal{A}_C \uplus \{s_{|c_1| + \dots + |c_i|}\}$;

- if $c_i, c_{i+1} < 0$, then

$$C = (c_1, \dots, c_i, c_{i+1}, \dots, c_k) \xleftarrow{B} (c_1, \dots, c_i + 1, 1, c_{i+1}, \dots, c_k) = D$$

(remove the 0 from the list), and this means that

$$\mathcal{A}_D = \mathcal{A}_C \uplus \{t_{|c_1| + \dots + |c_i|}\};$$

- if $c_i < 0$ and $c_{i+1} > 0$, then

$$C = (c_1, \dots, c_i, c_{i+1}, \dots, c_k) \xleftarrow{B} (c_1, \dots, c_i + 1, 1, c_{i+1}, \dots, c_k) = D$$

(remove the 0 from the list), and this means that

$$\mathcal{A}_D \uplus \{s_{|c_1|+\dots+|c_i|}\} = \mathcal{A}_C \uplus \{t_{|c_1|+\dots+|c_i|}\}.$$

Moreover, as $s_{|c_1|+\dots+|c_i|} \notin S_C$, we have $S_C \subset \mathcal{A}_D$, that is, $C \leftarrow D$;

- finally, if $c_i < 0$, then $C \xleftarrow{B} (c_1, \dots, c_i + 1, 1, c_{i+1}, \dots, c_k) = D$ and

$$C \xleftarrow{B} (c_1, \dots, c_i + 2, 2, c_{i+1}, \dots, c_k) = D'$$

(remove the 0 from the list), and this means that

$$\mathcal{A}_{D'} = \mathcal{A}_D \uplus \{t_{|c_1|+\dots+|c_i|}\}.$$

Hence $S_C \subset \mathcal{A}_D \subset \mathcal{A}_{D'}$.

In all these cases, we have $C \leftarrow D$.

THEOREM 3.15. — *Let $C, D \Vdash n$, then $C \leftarrow D$ if and only if there is $E \Vdash n$ such that $C \xleftarrow{B} E \xleftarrow{R} D$. Moreover, E is uniquely determined.*

Proof. — Suppose that E exists, then it is easy to check (using Remark 3.14 and induction) that $S_C \subset \mathcal{A}_E \subset \mathcal{A}_D$, which implies $C \leftarrow D$.

Now, suppose that $C \leftarrow D$. As $S_C \subset \mathcal{A}_D$, it is easy to construct a unique $E \Vdash n$ such that $\mathcal{A}_E \cap T_n = \mathcal{A}_D \cap T_n$ and $C \xleftarrow{B} E$ (hence $C \leftarrow B$). It remains to show that $E \xleftarrow{R} D$, that is, to show that $\mathcal{A}_E \cap S_{\bar{n}} \subset \mathcal{A}_D \cap S_{\bar{n}}$. Let $s_j \in \mathcal{A}_E \cap S_{\bar{n}}$, then either $j \in [|c_1| + \dots + |c_{i-1}| + 1, \dots, |c_1| + \dots + |c_i| - 1]$ hence $s_j \in S_C \subset \mathcal{A}_D$; or $j = |c_1| + \dots + |c_i|$ and $c_i < 0$ and $c_{i+1} > 0$ by definition. But refinement operations do not act on parts having not the same sign, that is, $s_j \in \mathcal{A}_D$. □

Example 3.16. — Consider the signed composition $C = (1, \bar{2}, \bar{1})$. Then we obtain from Theorem 3.15 and Example 3.13

$$\begin{aligned} X_{(1, \bar{2}, \bar{1})} = & Y_{(1, \bar{2}, \bar{1})} \cup Y_{(1, \bar{3})} \cup Y_{(1, \bar{1}, 1, \bar{1})} \cup Y_{(1, \bar{1}, 1, 1)} \cup Y_{(1, \bar{1}, 2)} \cup Y_{(1, 2, \bar{1})} \cup Y_{(3, \bar{1})} \\ & \cup Y_{(1, \bar{2}, 1)} \cup Y_{(1, 2, 1)} \cup Y_{(3, 1)} \cup Y_{(1, 3)} \cup Y_{(4)}. \end{aligned}$$

4. Coplactic space

4.1. Robinson-Schensted correspondence for W_D

In [20], the author defined a bijection between W_n and a certain set of bitableaux, which sounds like a Robinson-Schensted correspondence. Let

us recall here some of his results. A *bitableau* is a pair $T = (T^+, T^-)$ of tableaux. The *shape* of T is the bipartition (λ^+, λ^-) , where λ^+ is the shape of T^+ and λ^- is the shape of T^- : it is denoted by $\text{sh} T$. We note $|T| = |\text{sh} T|$. The bitableau T is said to be *standard* if the set of numbers in T^+ and T^- is $[1, m]$, where $m = |T|$, and if the fillings of T^+ and T^- are increasing in rows and in column.

Let $D \models n$. Write $D = (d_1, \dots, d_r)$ and denote by $\mathcal{SBT}(D)$ the set of r -tuples $T = (T_1, \dots, T_r)$ of bitableaux $T_i = (T_i^+, T_i^-)$ such that $|T_i| = |d_i|$, $T_i^- = \emptyset$ if $d_i < 0$, T_i^+ and T_i^- are standard and the fillings of T_i^+ and T_i^- are exactly the numbers in $I_{D,+}^{(i)} = [|d_1| + \dots + |d_{i-1}| + 1, |d_1| + \dots + |d_i|]$. The *shape* of T , denoted by $\text{sh} T$, is the r -tuple of bipartitions $(\text{sh} T_1, \dots, \text{sh} T_r)$. If $T \in \mathcal{SBT}(D)$, then $\text{sh} T \in \text{Bip}(D)$. If $\lambda \in \text{Bip}(D)$, we denote by \mathcal{SBT}_λ^D the set of elements $T \in \mathcal{SBT}(D)$ such that $\text{sh} T = \lambda$. In [20], the author defined a bijection (which we call *generalized Robinson-Schensted correspondence*)

$$\begin{aligned} \pi_D : W_D &\longrightarrow \{(P, Q) \in \mathcal{SBT}(D) \times \mathcal{SBT}(D) \mid \text{sh} P = \text{sh} Q\} \\ w &\longmapsto (\mathbf{P}_D(w), \mathbf{Q}_D(w)). \end{aligned}$$

Note that, in [20] (see also [4, Section 3]), the bijection has been defined only for $D = (n)$. It is not difficult to deduce from this the bijection π_D for general D . To this bijection is associated a partition of W_n as follows: if $Q \in \mathcal{SBT}(D)$, we set

$$Z_Q^D = \{w \in W_D \mid \mathbf{Q}_D(w) = Q\}.$$

Then

$$W_D = \coprod_{Q \in \mathcal{SBT}(D)} Z_Q^D.$$

4.2. Properties

First, note that the bijection π_D satisfies the following property: if $w \in W_n$, then

$$(4.1) \quad \pi_D(w^{-1}) = (\mathbf{Q}_D(w), \mathbf{P}_D(w)).$$

In particular, if Q and Q' are two elements of $\mathcal{SBT}(D)$, then

$$(4.2) \quad |Z_Q^D \cap (Z_{Q'}^D)^{-1}| = \begin{cases} 1 & \text{if } \text{sh} Q = \text{sh} Q', \\ 0 & \text{otherwise.} \end{cases}$$

Remark. — $\pi_{\bar{n}}$ is the usual Robinson-Schensted correspondence. For simplification, we denote by $Z_Q = Z_Q^{(n)}$ if $Q \in \mathcal{SBT}(n)$.

In [4, Section 3], the authors give another way to define the equivalence relation associated to this partition which looks like coplactic equivalence or dual-Knuth equivalence. If $w \in W_D$, let $\mathcal{D}'_D(w)$ denote the set $\{s \in S'_D \mid \ell(ws) < \ell(w)\}$. If $w, w' \in W_D$, we write $w \smile_D w'$ if $w'w^{-1} \in S_{D-} \subset S_{\bar{n}} = \{s_1, \dots, s_{n-1}\}$ and $\mathcal{D}'_D(w^{-1}) \not\subset \mathcal{D}'_D(w'^{-1})$ and $\mathcal{D}'_D(w'^{-1}) \not\subset \mathcal{D}'_D(w^{-1})$. Note that the relation \smile_D is symmetric. We denote by \sim_D the reflexive and transitive closure of \smile_D . It is an equivalence relation, called the *coplactic equivalence relation*. The equivalence classes for this relation are called the *coplactic classes* of W_D . We denote by $\text{Cop}(W_D)$ the set of coplactic classes for the relation \sim_D .

By [4, Proposition 3.8], we have, for every $w, w' \in W_D$,

$$(4.3) \quad w \sim_D w' \iff \mathbf{Q}_D(w) = \mathbf{Q}_D(w').$$

So $\text{Cop}(W_D) = \{Z_Q^D \mid Q \in \mathcal{SBT}(D)\}$.

Remark 4.4. — The relation \smile_D has a useful combinatorial interpretation (see [4, Proof of Proposition 3.8]): $w \smile_D s_i w$ ($s_i \in S_{D-}$) if and only if:

- either $\text{sign}(w(i)) \neq \text{sign}(w(i+1))$;
- or $\text{sign}(w(i)) = \text{sign}(w(i+1))$, then $s_i w$ is obtained from w by a classical dual-Knuth transformation; that is, $w^{-1}(i-1)$ or $w^{-1}(i+2)$ lie between $w^{-1}(i)$ and $w^{-1}(i+1)$.

PROPOSITION 4.5. — *Let $w, w' \in W_D$, then*

$$w \sim_D w' \Rightarrow \mathcal{D}'_D(w) = \mathcal{D}'_D(w').$$

Proof. — We may, and we will, assume that $D = (n)$. If T_0 is a Young tableau, let $\mathcal{D}(T_0) = \{s_p \in S_{\bar{n}} \mid p+1 \text{ lies in a row above the row containing } p\}$. Let tT_0 denote the transposed tableau of T . If $T = (T^+, T^-)$ is a standard bitableau, we set

$$\mathcal{D}'(T) = \{t_p \mid p \in T^-\} \uplus \{s_p \mid p \in T^+ \text{ and } p+1 \in T^-\} \uplus \mathcal{D}(T^+) \uplus \mathcal{D}({}^tT^-).$$

Then it is easy to check that $\mathcal{D}'_n(w) = \mathcal{D}'(\mathbf{Q}(w))$. This completes the proof of the proposition. □

Example 4.6. — Let

$$T = \left(\begin{array}{|c|c|} \hline 1 & 7 \\ \hline 6 & 9 \\ \hline 8 & \\ \hline \end{array} , \begin{array}{|c|c|c|} \hline 2 & 3 & 5 \\ \hline 4 & & \\ \hline \end{array} \right) \in \mathcal{SBT}(9).$$

Then

$$\mathcal{D}'(T) = \{s_1, s_3, s_6, s_8, t_2, t_3, t_4, t_5\}.$$

Remark 4.7. — Using Proposition 4.5, we may assign a signed composition $\mathbf{C}(Q) \models n$ to any standard bitableau $Q \in \mathcal{SBT}(n)$ by setting $\mathbf{C}(Q) = \mathbf{C}(w)$ for any $w \in W_n$ such that $Q(w) = Q$. One can determine $\mathbf{C}(Q)$ directly from Q thanks to the following procedure, which is a combinatorial translation of the proof of Proposition 4.5. First one looks for maximal subwords $j j + 1 j + 2 \dots k$ of $1 2 3 \dots n$ such that

- either the numbers $j, j + 1, j + 2, \dots, k$ can be found in this order in Q^+ when one goes from left to right (changes of rows are allowed)
- or they can be found in this order in Q^- when one goes from top to bottom (changes of column are allowed).

The word $1 2 3 \dots n$ is then the concatenation of these maximal subwords, and the signed composition $\mathbf{C}(Q)$ is the sequence of the lengths of these subwords, adorned with a minus sign if the letters of the subword can be found in Q^- . As an example, consider $Q = (Q^+, Q^-)$ with

$$Q^+ = \begin{array}{|c|c|c|c|c|} \hline 1 & 2 & 6 & 7 & 8 & 13 \\ \hline 9 & 11 & 12 & & & \\ \hline 10 & & & & & \\ \hline \end{array} \quad \text{and} \quad Q^- = \begin{array}{|c|c|} \hline 3 & 14 \\ \hline 4 & \\ \hline 5 & \\ \hline 15 & \\ \hline \end{array}.$$

The partition of $1 2 \dots 14 15$ in maximal subwords is $1 2 \mid 3 4 5 \mid 6 7 8 \mid 9 \mid 10 11 12 13 \mid 14 15$, from what we can deduce that $\mathbf{C}(Q) = (2, \bar{3}, 3, 1, 4, \bar{2})$.

Therefore, we have by definitions

$$X_C = \coprod_{C \leftarrow \mathbf{C}(Q)} Z_Q.$$

PROPOSITION 4.8. — *Let $C, D \models n$ such that $C \subset D$. Let $w, w' \in W_C$ and $x, x' \in X_C^D$, then:*

- (a) *If $w \sim_C w'$, then $wx^{-1} \sim_D w'x^{-1}$.*
- (b) *If $xw \sim_D x'w'$, then $w \sim_C w'$.*
- (c) *If $w \sim_C w'$, then $w_C w \sim_C w_C w'$ and $w w_C \sim_C w' w_C$.*

Proof. — (c) is clear. Let us now prove (a). We may assume that $w \smile_C w'$. But $\mathcal{D}_C(w^{-1}) \subset \mathcal{D}_D(xw^{-1})$ and $\mathcal{D}_C(w'^{-1}) \subset \mathcal{D}_D(xw'^{-1})$. So $wx^{-1} \smile_D w'x^{-1}$.

We now prove (b). If W_C is a standard parabolic subgroup of W_D , and using the fact that coplactic classes are left cells for a particular choice of parameters [4, Theorem 7.7], then (b) follows from [6]. Therefore, by taking

direct products and by arguing by induction on $|X_C^D|$, we may now assume that $D = (n)$ and $C = (k, l)$ with $k, l \geq 1$ and $k + l = n$.

Let us start by proving (a). We may assume that $w \smile_C w'$. But $\mathcal{D}_C(w^{-1}) \subset \mathcal{D}_D(xw^{-1})$ and $\mathcal{D}_C(w'^{-1}) \subset \mathcal{D}_D(xw'^{-1})$. So $wx^{-1} \smile_D w'x^{-1}$.

Let us now prove (b). We may assume that $xw \smile_D x'w'$. Let $Q = \mathcal{Q}_C(w) = \mathcal{Q}_C(w')$. From Remark 4.4, we have two cases: either $x'w'$ is obtained from xw by a dual-Knuth relation, or $x'w' = s_i xw$ and $\text{sign}(xw(i)) \neq \text{sign}(xw(i + 1))$. In the first case, observe that, for any $i \in [1, k - 1]$ and $i \in [k + 1, k + l - 1]$, $xw(k) < xw(k + 1)$ if and only if $w(k) < w(k + 1)$, since $x \in X_{(k,l)} = X_{(\bar{k}, \bar{l})}^{(\bar{n})} \subset W_{\bar{n}}$. Then we conclude by Remark 4.4 (which is exactly the result of Lascoux and Schützenberger on the shuffle of plactic classes [12]).

In the second case, observe that, for any $k \in [1, n]$,

$$(\star) \quad \text{sign}(w(k)) = \text{sign}(xw(k)) = \text{sign}(s_i xw(k))$$

since $X_{(k,l)} = X_{(\bar{k}, \bar{l})}^{(\bar{n})} \subset W_{\bar{n}}$ and $s_i \in S_{\bar{n}}$. If $s_i x = x'$, then $w = w'$ and the result follows. If $s_i x = x s_j$, with $s_j \in S_{(\bar{k}, \bar{l})}$ (by Deodhar's Lemma), then $x' = x$. Therefore $w' = s_j w$, by (\star) and Remark 4.4. So $w \smile_C w'$. \square

4.3. Coplactic space

Let $D \Vdash n$. If $Q \in \mathcal{SBT}(D)$, we set

$$z_Q^D = \sum_{w \in Z_Q^D} w \quad \in \mathbf{Z}W_D.$$

Now, let

$$\mathcal{Q}_D = \bigoplus_{Q \in \mathcal{SBT}(D)} \mathbf{Z}z_Q^D \quad \subset \mathbf{Z}W_D$$

and

$$\mathcal{Q}_D^\perp = \bigoplus_{\substack{Q, Q' \in \mathcal{SBT}(D) \\ \text{sh } Q = \text{sh } Q'}} \mathbf{Z}(z_Q^D - z_{Q'}^D) \quad \subset \mathcal{Q}_D.$$

Then, by Proposition 4.5, we have

$$(4.9) \quad \Sigma'(W_D) \subset \mathcal{Q}_D.$$

The next proposition justifies the notation \mathcal{Q}_D^\perp :

PROPOSITION 4.10. — $\mathcal{Q}_D^\perp = \{x \in \mathcal{Q}_D \mid \forall y \in \mathcal{Q}_D, \tau_D(xy) = 0\}$.

Proof. — Let $\mathcal{Q}'_D = \{x \in \mathcal{Q}_D \mid \forall y \in \mathcal{Q}_D, \tau_D(xy) = 0\}$. Let Q and Q' be elements of $\mathcal{SBT}(D)$. Then, by (4.2), we have

$$(4.11) \quad \tau_D(z_Q^D z_{Q'}^D) = \begin{cases} 1 & \text{if } \text{sh } Q = \text{sh } Q', \\ 0 & \text{otherwise.} \end{cases}$$

This shows in particular that $\mathcal{Q}_D^\perp \subset \mathcal{Q}'_D$.

Let us now prove that $\mathcal{Q}'_D \subset \mathcal{Q}_D^\perp$. Now, since $\mathcal{Q}_D/\mathcal{Q}_D^\perp$ is torsion free, it is sufficient to prove that $\dim_{\mathbb{Q}} \mathbb{Q}\mathcal{Q}'_D \leq \dim_{\mathbb{Q}} \mathbb{Q}\mathcal{Q}_D^\perp$. But, by construction, we have $\dim_{\mathbb{Q}} \mathbb{Q}\mathcal{Q}_D - \dim_{\mathbb{Q}} \mathbb{Q}\mathcal{Q}_D^\perp = |\text{Bip}(D)|$. Moreover, by Proposition 3.8, we have $\dim_{\mathbb{Q}} \mathbb{Q}\mathcal{Q}_D - \dim_{\mathbb{Q}} \mathbb{Q}\mathcal{Q}'_D \geq |\text{Irr } W_D| = |\text{Bip}(D)|$. \square

The next lemma is a generalization to our case of a result of Blessenohl and Schocker concerning the symmetric group [3].

PROPOSITION 4.12. — *We have $\mathcal{Q}_D = \Sigma'(W_D) + \mathcal{Q}_D^\perp$ and $\Sigma'(W_D) \cap \mathcal{Q}_D^\perp = \text{Ker } \theta_D$.*

Proof. — Let us first prove that $\mathcal{Q}_D = \Sigma'(W_D) + \mathcal{Q}_D^\perp$. For this, we may, and we will, assume that $D = (n)$. We first need to introduce an order on bipartitions of n . We denote by \leq_{sl} the lexicographic order on $\text{Bip}(n)$ induced by the following order on I_n :

$$\bar{1} <_{\text{sl}} \bar{2} <_{\text{sl}} \cdots <_{\text{sl}} \bar{n} <_{\text{sl}} 1 <_{\text{sl}} 2 <_{\text{sl}} \cdots <_{\text{sl}} n.$$

If λ is a bipartition of n , we denote by $Q_\lambda = Q(\eta_\lambda)$. If $\lambda = (\lambda^+, \lambda^-)$, then it is easy to check that $\text{sh } Q_\lambda = (\lambda^+, {}^t\lambda^-) = \lambda^*$, where ${}^t\lambda^-$ is the transpose of the partition λ^- , and, using Remark 4.7, that Q_λ is obtained by numbered Q_λ^+ (resp. ${}^tQ_\lambda^-$) the first column first, then the second one and so on. Now, let $Q \in \mathcal{SBT}(n)$. Then:

LEMMA 4.13. — *Assume that $Z_Q \subset X_{\bar{\lambda}}$, then $\lambda \leq_{\text{sl}} (\text{sh } Q)^*$. Moreover, if $\text{sh } Q = \lambda^*$, then $Q = Q_\lambda$.*

Proof. — First, we easily check (using Remark 4.7), that $\lambda(\mathbf{C}(Q)) \leq_{\text{sl}} (\text{sh } Q)^*$ with equality if and only if $Q = Q_\lambda$.

Then, observe (using Theorem 3.15), that $\lambda \leq_{\text{sl}} \lambda(\mathbf{C}(Q))$ with equality if and only if $\mathbf{C}(Q) = \hat{\lambda}$. This conclude the proof. \square

We are now ready to prove by descending induction on $(\text{sh } Q)^*$ that $z_Q \in \Sigma'(W_n) + \mathcal{Q}_n^\perp$. If $(\text{sh } Q)^* = (n, \emptyset)$, then $Z_Q = \{1\} = Y_n$. So $z_Q = y_n \in \Sigma'(W_n)$.

Now, assume that $(\text{sh } Q)^* <_{\text{sl}} (n, \emptyset)$ and that $z_{Q'} \in \Sigma'(W_n) + \mathcal{Q}_n^\perp$ for every $Q' \in \mathcal{SBT}(n)$ such that $(\text{sh } Q)^* <_{\text{sl}} (\text{sh } Q')^*$. Let $\lambda = (\text{sh } Q)^*$. Then $z_Q = z_{Q_\lambda} + (z_Q - z_{Q_\lambda}) \in z_{Q_\lambda} + \mathcal{Q}_n^\perp$. So it is sufficient to prove that

$z_{Q_\lambda} \in \Sigma'(W_n) + \mathcal{Q}_n^\perp$. But, by Lemma 4.13 $x_\lambda - z_{Q_\lambda}$ is a sum of $z_{Q'}$ with $\lambda <_{\text{lex}} (\text{sh } Q)^*$. Hence, by the induction hypothesis, we have $x_\lambda - z_{Q_\lambda} \in \Sigma'(W_n) + \mathcal{Q}_n^\perp$, as desired.

Now, let us prove that $\Sigma'(W_D) \cap \mathcal{Q}_D^\perp = \text{Ker } \theta_D$. The natural map $\Sigma'(W_D) \rightarrow \mathcal{Q}_D/\mathcal{Q}_D^\perp$ is surjective, so $\text{rank}_{\mathbf{Z}} \Sigma'(W_D) \cap \mathcal{Q}_D^\perp = \text{rank}_{\mathbf{Z}} \text{Ker } \theta_D$. Since the \mathbf{Z} -modules $\Sigma'(W_D)/(\Sigma'(W_D) \cap \mathcal{Q}_D^\perp)$ and $\Sigma'(W_D)/\text{Ker } \theta_D$ are torsion free, it is sufficient to prove that $\Sigma'(W_D) \cap \mathcal{Q}_D^\perp$ is contained in $\text{Ker } \theta_D$. But this follows from Proposition 4.10 and Corollary 3.9. \square

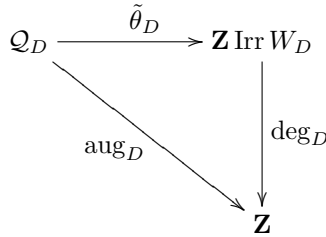
Using Proposition 4.12, we can easily extend the linear map θ_D to a linear map $\tilde{\theta}_D : \mathcal{Q}_D \rightarrow \mathbf{Z} \text{Irr } W_D$. If $x \in \mathcal{Q}_D$, write $x = a + b$ with $a \in \Sigma'(W_D)$ and $b \in \mathcal{Q}_D^\perp$ and set

$$\tilde{\theta}_D(x) = \theta_D(a).$$

Then Proposition 4.12 shows that $\tilde{\theta}_D$ is well-defined (that is, $\theta_D(a)$ does not depend on the choice of a and b).

THEOREM 4.14. — *Let $D \models n$. Then:*

- (a) $\tilde{\theta}_D$ is an extension of θ_D to \mathcal{Q}_D ;
- (b) $\text{Ker } \tilde{\theta}_D = \mathcal{Q}_D^\perp$;
- (c) if x and y are two elements of \mathcal{Q}_D , then $\tau_D(xy) = \langle \tilde{\theta}_D(x), \tilde{\theta}_D(y) \rangle_D$;
- (d) the diagram



is commutative;

- (e) if $x \in \mathcal{Q}_D$, then

$$\tilde{\theta}_D(x) = |W_D| \sum_{\lambda \in \text{Bip}(D)} \frac{\tau_D(x E_\lambda^D)}{|\mathcal{C}_\lambda^D|} f_\lambda^D.$$

Proof. — (a) and (b) are easy. (c) follows from Proposition 3.8 and Proposition 4.10. (d) follows from the commutativity of the diagram (3.6) and from the fact that $\text{aug}_D(\mathcal{Q}_D^\perp) = 0$ (indeed, if Q and Q' are two elements of $\mathcal{SBT}(D)$ of the same shape, then $|Z_Q^D| = |Z_{Q'}^D|$). Using Proposition 4.12, it is sufficient to prove (e) for $x \in \Sigma'(W_D)$ or $x \in \mathcal{Q}_D^\perp$. If $x \in \Sigma'(W_D)$, this follows from Proposition 3.10. If $x \in \mathcal{Q}_D^\perp$, this follows from Proposition 4.10. \square

Remark. — In the theorem, the case $D = (\bar{n})$ is precisely the symmetric group case.

COROLLARY 4.15. — *If $\tilde{\theta}$ is an extension of θ_D to the \mathcal{Q}_D such that, for all x and y in \mathcal{Q}_D , $\tau_D(xy) = \langle \tilde{\theta}(x), \tilde{\theta}(y) \rangle_D$, then $\tilde{\theta} = \tilde{\theta}_D$.*

Proof. — Assume that $\tilde{\theta}$ is an extension of θ_D to \mathcal{Q}_D such that $\tau_D(xy) = \langle \tilde{\theta}(x), \tilde{\theta}(y) \rangle_D$ for all x and y in \mathcal{Q}_D . Then, if $x \in \mathcal{Q}_D^\perp$ and $\chi \in \mathbf{Z} \text{Irr } W_D$, then there exists $y \in \mathcal{Q}_D$ such that $\tilde{\theta}_D(y) = \chi$. So

$$\langle \chi, \tilde{\theta}(x) \rangle_D = \langle \tilde{\theta}(y), \tilde{\theta}(x) \rangle_D = \tau_D(xy) = 0$$

by hypothesis and by Proposition 4.10. Since $\langle \cdot, \cdot \rangle_D$ is a perfect pairing on $\mathbf{Z} \text{Irr } W_D$, we get that $\tilde{\theta}(x) = 0$. So $\tilde{\theta}$ coincides with $\tilde{\theta}_D$ on $\Sigma'(W_D)$ and on \mathcal{Q}_D^\perp , so $\tilde{\theta} = \tilde{\theta}_D$ by Proposition 4.12. \square

Let $\lambda \in \text{Bip}(D)$. Let $Q \in \mathcal{SBT}(D)$ be of shape λ . Now, let

$$\xi_\lambda = \tilde{\theta}_D(z_Q).$$

Then ξ_λ depends only on λ and not on the choice of Q . Moreover, $\xi_\lambda \in \mathbf{Z} \text{Irr } W_D$, $\deg_D \xi_\lambda = |Z_Q| > 0$ (see Theorem 4.14 (d)) and, by Theorem 4.14 (c) and (4.11), we have $\langle \xi_\lambda, \xi_\lambda \rangle_D = 1$. This shows that $\xi_\lambda \in \text{Irr } W_D$. Moreover, if $\lambda \neq \mu$, it also follows from Theorem 4.14 (c) and (4.11) that $\langle \xi_\lambda, \xi_\mu \rangle_D = 0$. So we have proved the following proposition:

PROPOSITION 4.16. — *The map $\text{Bip}(D) \rightarrow \text{Irr } W_D$, $\lambda \mapsto \xi_\lambda$ is well-defined and bijective.*

Remark 4.17. — If $T = (T^+, T^-) \in \mathcal{SBT}(n)$, we denote by T^\vee the standard bitableau (T^-, T^+) . If $\lambda = (\lambda^+, \lambda^-) \in \text{Bip}(n)$, we set $\lambda^\vee = (\lambda^-, \lambda^+) \in \text{Bip}(n)$. In particular, $\text{sh } T^\vee = (\text{sh } T)^\vee$.

Now, let $w \in W_n$. Then $\pi_n(w_n w) = (\mathbf{P}(w)^\vee, \mathbf{Q}(w)^\vee)$. Therefore, if $Q \in \mathcal{SBT}(n)$ then $w_n Z_Q = Z_{Q^\vee}$. This shows in particular that $w_n \mathcal{Q}_n = \mathcal{Q}_n$ and that $w_n \mathcal{Q}_n^\perp = \mathcal{Q}_n^\perp$. Moreover,

$$(4.18) \quad \tilde{\theta}_n(w_n z) = \varepsilon_n \tilde{\theta}_n(z)$$

for all $z \in \mathcal{Q}_n$. Indeed, this equality is true if $z \in \Sigma'(W_n)$ by Theorem 3.7 and it is obviously true if $z \in \mathcal{Q}_n^\perp$. So we can conclude using Proposition 4.12. In particular, if $\lambda \in \text{Bip}(n)$, then

$$(4.19) \quad \xi_{\lambda^\vee} = \varepsilon_n \xi_\lambda.$$

Remark 4.20. — Let $Q \in \mathcal{SBT}(n)$ be such that $Q^- = \emptyset$. Then $z_Q \in \mathcal{Q}_{\bar{n}}$. Therefore, $\mathcal{Q}_{\bar{n}} \subset \mathcal{Q}_n$. Moreover, $\mathcal{Q}_{\bar{n}}^\perp = \mathcal{Q}_n^\perp \cap \mathcal{Q}_{\bar{n}}$. Therefore, it follows from the commutativity of Diagram (3.4) that the diagram

$$(4.21) \quad \begin{array}{ccc} \mathcal{Q}_{\bar{n}} & \hookrightarrow & \mathcal{Q}_n \\ \tilde{\theta}_{\bar{n}} \downarrow & & \downarrow \tilde{\theta}_n \\ \mathbf{Z} \text{ Irr } \mathfrak{S}_n & \xrightarrow{p_n^*} & \mathbf{Z} \text{ Irr } W_n \end{array}$$

is commutative. In particular, if $\lambda = (\lambda^+, \emptyset)$ is the shape of Q , and if we denote by $\chi_{\lambda^+}^{\bar{n}}$ the irreducible character of \mathfrak{S}_n associated to λ^+ (apply Proposition 4.16 with $D = (\bar{n})$), we have

$$(4.22) \quad \xi_\lambda = p_n^* \chi_{\lambda^+}^{\bar{n}}.$$

4.4. Induction

We first start by an easy consequence of Proposition 4.8.

LEMMA 4.23. — *Let $C, D \models n$ be such that $C \subset D$. Let $x \in \mathcal{Q}_C$. Then*

- (a) $x_C^D x \in \mathcal{Q}_D$.
- (b) *If $x \in \mathcal{Q}_C^\perp$, then $x_C^D x \in \mathcal{Q}_D^\perp$.*

Proof. — (a) By linearity, we may assume that $x = z_Q^C$ with $Q \in \mathcal{SBT}(C)$. Then, by Proposition 4.8 (a), we have that $X_C^D \cdot Z_Q^C$ is a union of coplactic classes. So $x_C^D x \in \mathcal{Q}_D$.

(b) By linearity, we may assume that $x = z_Q^C - z_{Q'}^C$, where $Q, Q' \in \mathcal{SBT}(C)$ and $\text{sh}(Q) = \text{sh}(Q')$. We denote by $\psi : Z_Q^C \rightarrow Z_{Q'}^C$, the unique bijection such that $\mathbf{P}_C(\psi(w)) = \mathbf{P}_C(w)$ for every $w \in Z_Q^C$.

Then $x_C^D x = x_C^D \cdot \sum_{w \in Z_Q^C} (w - \psi(w))$. But, if $a \in X_C^D$ and $w \in Z_Q^C$, then $\mathbf{P}_D(aw) = \mathbf{P}_D(a\psi(w))$ by Proposition 4.8 (b) and (4.1). We set $\psi'(aw) = a\psi(w)$, then the map $\psi' : X_C^D \cdot Z_Q^C \rightarrow X_C^D \cdot Z_{Q'}^C$, is bijective and satisfies $\text{sh } \mathbf{Q}_D(\psi'(w)) = \text{sh } \mathbf{Q}_D(w)$ for every $w \in X_C^D \cdot Z_Q^C$.

Now, let $\lambda \in \text{Bip}(D)$ and let \mathcal{E}_λ (resp. \mathcal{E}'_λ) be the set of $w \in X_C^D \cdot Z_Q^C$ (resp. $w \in X_C^D \cdot Z_{Q'}^C$) such that $\text{sh } \mathbf{Q}_D(w) = \lambda$. Then ψ' induces a bijection between \mathcal{E}_λ and \mathcal{E}'_λ . Write $\mathcal{E}_\lambda = \coprod_{i=1}^r Z_{Q_i}^D$ and $\mathcal{E}'_\lambda = \coprod_{i=1}^{r'} Z_{Q'_i}^D$, using (a). Then, since $|Z_{Q_1}^D| = \dots = |Z_{Q_r}^D| = |Z_{Q'_1}^D| = \dots = |Z_{Q'_{r'}}^D|$ and $|\mathcal{E}_\lambda| = |\mathcal{E}'_\lambda|$, we have $r = r'$. This shows that $x_C^D x \in \mathcal{Q}_D^\perp$. □

COROLLARY 4.24. — *Let $C, D \models n$ be such that $C \subset D$. Then the diagram*

$$\begin{array}{ccc}
 \mathcal{Q}_C & \xrightarrow{x_C^D} & \mathcal{Q}_D \\
 \tilde{\theta}_C \downarrow & & \downarrow \tilde{\theta}_D \\
 \mathbf{Z} \text{ Irr } W_C & \xrightarrow{\text{Ind}_{W_C}^{W_D}} & \mathbf{Z} \text{ Irr } W_D
 \end{array}$$

is commutative.

Proof. — This follows immediately from Proposition 4.23 and from the commutativity of the diagram (3.3). □

Now, if $\lambda \in \text{Bip}(n)$, then we denote by λ^* the conjugate bipartition and by χ_λ the irreducible character of W_n associated to λ via Clifford theory (see [8, §5.5]). The link between the two parametrizations (the ξ 's and the χ 's) is given by the following result:

COROLLARY 4.25. — *If λ is a bipartition of n , then $\xi_\lambda = \chi_{\lambda^*}$.*

Proof. — Write $\lambda = (\lambda^+, \lambda^-)$, $k = |\lambda^+|$ and $l = |\lambda^-|$. Let Q^+ be a standard tableau of shape λ^+ filled with $\{l + 1, l + 2, \dots, n\}$ and let Q^- be a standard tableau of shape λ^- filled with $\{1, 2, \dots, l\}$. Then, by [4, Proposition 4.8],

$$Z_Q = X_{l,k}(w_l Z_{Q^-} \times Z_{Q^+}).$$

Therefore, by Corollary 4.24, we have

$$\xi_\lambda = \text{Ind}_{W_{l,k}}^{W_n} (\tilde{\theta}_l(w_l Z_{Q^-}^l) \boxtimes \tilde{\theta}_k(Z_{Q^+}^k)).$$

Here, \boxtimes denotes the (external) tensor product of characters. So, by (4.22) and by Remark 4.17, we have

$$\xi_\lambda = \text{Ind}_{W_{k,l}}^{W_n} (p_k^* \chi_{\lambda^+}^{\bar{k}} \boxtimes \varepsilon_l(p_l^* \chi_{\lambda^-}^{\bar{l}})).$$

The result now follows from [8, §5.5]. □

5. Related Hopf algebras

5.1. Hopf algebra of signed permutations

Consider the graded \mathbf{Z} -module

$$SP = \bigoplus_{n \geq 0} \mathbf{Z}W_n,$$

where $W_0 = 1$. In [1], Aguiar and Mahajan have shown that \mathcal{SP} has a structure of Hopf algebra which is similar to the structure of the Malvenuto-Reutenauer Hopf algebra on permutations [15]. Moreover, they have shown that

$$\Sigma' = \bigoplus_{n \geq 0} \Sigma'(W_n)$$

is a Hopf subalgebra of \mathcal{SP} . We revise here the definition of the product and the coproduct on \mathcal{SP} with our point of view.

Notation. — If C is a signed composition, then we denote by x_C the element of \mathcal{SP} lying in $\mathbf{Z}W_{|C|}$ corresponding to the x_C defined in §3. Similarly, if Q is a standard bitableau, then $z_Q \in \mathbf{Z}W_{|\text{sh } Q|}$ is viewed as an element of \mathcal{SP} .

Let $(u, v) \in W_n \times W_m$, we denote $u \times v$ the corresponding element of $W_{n,m} \simeq W_n \times W_m$. If $w \in W_{n,m}$, we denote by $(w'_{(n)}, w''_{(m)})$ the corresponding element of $W_n \times W_m$. We now define

$$u * v = x_{n,m}(u \times v) \in \mathbf{Z}W_{n+m}.$$

We extend $*$ by linearity to a bilinear map $\mathcal{SP} \times \mathcal{SP} \rightarrow \mathcal{SP}$.

Now, let $w \in W_n$. Then, for each $i \in [0, n]$, we denote by $\pi_i(w)$ the unique element of $W_{i,n-i}$ such that $w \in \pi_i(w)X_{i,n-i}^{-1}$. We set

$$\Delta(w) = \sum_{i=0}^n \pi_i(w)'_{(i)} \otimes_{\mathbf{Z}} \pi_i(w)''_{(n-i)} \in \mathcal{SP} \otimes_{\mathbf{Z}} \mathcal{SP}.$$

We extend Δ by linearity to a map $\Delta : \mathcal{SP} \rightarrow \mathcal{SP} \otimes_{\mathbf{Z}} \mathcal{SP}$.

Remark 5.1. — Combinatorially, we see this product as follows: let $w = w_1 \dots w_n$ be a word of length n in the alphabet I_n , the *standardsigned permutation* is the unique element $\text{sts}(w) \in W_n$ such that

$$\begin{cases} \text{sts}(w)(i) < \text{sts}(w)(j) \Leftrightarrow (w_i < w_j) & \text{or } (w_i = w_j \text{ and } i < j) \\ \text{and } \text{sign}(\text{sts}(w)(i)) = \text{sign}(w_i). \end{cases}$$

Then

$$u * v = \sum_{w, w'} ww'$$

where ww' is the concatenation of w and w' ; and the sum is taken over all words w, w' on the alphabet I_n such that $\text{sts}(w) = u$, $\text{sts}(w') = v$ and $\text{alph}(u) \uplus \text{alph}(v) = [1, n]$ (where $\text{alph}(u) =$ the set of absolute values of the letters in u). For instance, $\bar{1}2 \times 2\bar{1} = \bar{1}24\bar{3}$ and

$$\begin{aligned} x_{(2,2)} &= y_{(2,2)} + y_{(4)} \\ &= 1234 + 1324 + 1423 + 2314 + 2413 + 3412. \end{aligned}$$

Hence $\bar{1}2*2\bar{1} = \bar{1}24\bar{3} + \bar{1}34\bar{2} + \bar{1}43\bar{2} + \bar{2}34\bar{1} + \bar{2}43\bar{1} + \bar{3}42\bar{1}$.

Remark 5.2. — For $w \in W_n$ seen as a word on the alphabet I_n and $i < j \in [1, n]$, we denote $w[[i, j]]$ the subword obtained by taking only the digits such that their absolute values are in $[i, j]$. Then we see combinatorially the coproduct as

$$\Delta(w) = \sum_{i=0}^n w[[1, i]] \otimes \text{sts}(w[[i + 1, n]]).$$

As example, consider $w = \bar{2}31\bar{4}$, then we have the following decompositions:

$$w^{-1} = 3\bar{1}2\bar{4} = 3124(1 \times \bar{1}2\bar{3}) = 1324(2\bar{1} \times \bar{1}2) = 1234(3\bar{1}2 \times \bar{1}).$$

Hence

$$w = \bar{2}31\bar{4} = (1 \times \bar{1}2\bar{3})2314 = (\bar{2}1 \times \bar{1}2)1324 = (\bar{2}31 \times \bar{1})1234.$$

Thus

$$\Delta(\bar{2}31\bar{4}) = \emptyset \otimes \bar{2}31\bar{4} + 1 \otimes \bar{1}2\bar{3} + \bar{2}1 \otimes \bar{1}2 + \bar{2}31 \otimes \bar{1} + \bar{2}31\bar{4} \otimes \emptyset.$$

Example 5.3. — Let C and D be two signed composition. We denote by $C \sqcup D$ the signed composition obtained by concatenation of C and D . Then

$$x_C * x_D = x_{C \sqcup D}.$$

Example 5.4. — We have

$$\Delta(x_n) = \sum_{i=0}^n x_i \otimes_{\mathbf{Z}} x_{n-i}$$

and

$$\Delta(x_{\bar{n}}) = \sum_{i=0}^n x_{\bar{i}} \otimes_{\mathbf{Z}} x_{\overline{n-i}}.$$

We state here a result of Aguiar and Mahajan [1], with our basis consisting of the x_C .

THEOREM 5.5. — *The graded vector space \mathcal{SP} , with the product $*$ and the coproduct Δ is a connected graded Hopf algebra; and Σ' is a Hopf subalgebra of \mathcal{SP} which is freely generated by elements $(x_n)_{n \in \mathbf{Z} \setminus \{0\}}$ as algebra.*

If $x, y \in \mathcal{SP}$, we define the product $xy \in \mathcal{SP}$ as follows: if $x \in \mathbf{Z}W_n$ and $y \in \mathbf{Z}W_m$, then $xy = 0$ if $m \neq n$ and xy coincides with the usual product xy in $\mathbf{Z}W_n$ if $m = n$. Let $\tau : \mathcal{SP} \rightarrow \mathbf{Z}$ be the unique linear map which

coincides with τ_n on $\mathbf{Z}W_n$. The the map $\mathcal{SP} \times \mathcal{SP} \rightarrow \mathbf{Z}$, $(x, y) \mapsto \tau(xy)$ is a scalar product on \mathcal{SP} . If $x, y \in \mathcal{SP}$, we set

$$\tau_{\otimes}(x \otimes y) = \tau(x)\tau(y).$$

The following proposition is easily checked from definitions:

PROPOSITION 5.6. — \mathcal{SP} is self-dual for τ , that is,

$$\tau_{\otimes}((u \otimes v)\Delta(w)) = \tau((u * v)w)$$

for all $u, v, w \in \mathcal{SP}$.

5.2. The Hopf algebra of characters

We give here a short recall of a result of Geissinger [9]. Consider the graded \mathbf{Z} -module

$$\mathcal{CHAR} = \bigoplus_{n \geq 0} \mathbf{Z} \text{Irr } W_n.$$

If k and l are two natural numbers, we denote by $\iota_{k,l}$ the canonical isomorphism

$$\iota_{k,l} : \mathbf{Z} \text{Irr } W_k \otimes_{\mathbf{Z}} \mathbf{Z} \text{Irr } W_l \xrightarrow{\sim} \mathbf{Z} \text{Irr } W_{k+l}.$$

Let $(\chi, \psi) \in \mathbf{Z} \text{Irr } W_k \times \mathbf{Z} \text{Irr } W_l$. We define

$$\chi \bullet \psi = \text{Ind}_{W_{k,l}}^{W_{k+l}} \iota_{k,l}(\chi \otimes_{\mathbf{Z}} \psi) \in \mathbf{Z} \text{Irr } W_{k+l}.$$

Now, let $\chi \in \mathcal{CL}_{\mathbf{Q}}W_n$. We define

$$\begin{aligned} \text{Res}(\chi) &= \sum_{i=0}^n \iota_{i,n-i}^{-1} \text{Res}_{W_{i,n-i}}^{W_n} \chi \in \bigoplus_{i=0}^n \mathbf{Z} \text{Irr } W_i \otimes_{\mathbf{Z}} \mathbf{Z} \text{Irr } W_{n-i} \\ &\subset \mathcal{CHAR} \otimes_{\mathbf{Z}} \mathcal{CHAR}. \end{aligned}$$

We denote $\langle \cdot, \cdot \rangle$ the unique scalar product on \mathcal{CHAR} which coincides with $\langle \cdot, \cdot \rangle_n$ on $\mathbf{Z} \text{Irr } W_n$ and such that $\mathbf{Z} \text{Irr } W_n$ and $\mathbf{Z} \text{Irr } W_m$ are orthogonal if $m \neq n$. We now define $\langle \cdot, \cdot \rangle_{\otimes}$ on $\mathcal{CHAR} \otimes_{\mathbf{Z}} \mathcal{CHAR}$ as follows: if $\chi, \chi', \psi, \psi' \in \mathcal{CHAR}$, we set

$$\langle \chi \otimes \psi, \chi' \otimes \psi' \rangle_{\otimes} = \langle \chi, \chi' \rangle \langle \psi, \psi' \rangle.$$

Geissinger [9] has shown that \mathcal{CHAR} with product \bullet and coproduct Res is a connected graded Hopf algebra. Moreover, for any $\chi, \psi, \zeta \in \mathcal{CHAR}$, the reciprocity law of Frobenius can be viewed as

$$(5.7) \quad \langle \chi \otimes \psi, \text{Res } \zeta \rangle_{\otimes} = \langle \chi \bullet \psi, \zeta \rangle.$$

5.3. The coplactic algebra and a Hopf epimorphism

Let us introduce

$$\mathcal{Q} = \bigoplus_{n \geq 0} \mathcal{Q}_n.$$

and

$$\mathcal{CHAR} = \bigoplus_{n \geq 0} \mathbf{Z} \text{Irr } W_n.$$

We define $\theta : \Sigma' \rightarrow \mathcal{CHAR}$ and $\tilde{\theta} : \mathcal{Q} \rightarrow \mathcal{CHAR}$ by

$$\theta = \bigoplus_{n \geq 0} \theta_n \quad \text{and} \quad \tilde{\theta} = \bigoplus_{n \geq 0} \tilde{\theta}_n.$$

The first part of the following theorem shows that \mathcal{Q} is a generalization of the Poirier-Reutenauer Hopf algebra of tableaux [17] to our case (see also [3]), and the second part shows that Jöllenbeck’s construction generalizes to our case.

THEOREM 5.8. — *\mathcal{Q} is a Hopf subalgebra of \mathcal{SP} containing Σ' . Moreover, $\theta : \Sigma' \rightarrow \mathcal{CHAR}$ and $\tilde{\theta} : \mathcal{Q} \rightarrow \mathcal{CHAR}$ are surjective Hopf algebra homomorphisms.*

Proof. — The fact that \mathcal{Q} is a subalgebra of \mathcal{SP} follows from Proposition 4.23. To prove that it is a subcoalgebra, we proceed as in the proof of the result of Poirier and Reutenauer [17], using Remark 4.4: let Z be a coplactic class in W_n , $i \in [0, n]$ and $w \in Z$. Write $w = \pi_i(w)x$, where $x^{-1} \in X_{i, n-i}$. Let $u \in W_i$ such that $u \smile_{(i)} \pi_i(w)'_{(i)}$. As $\text{sign}(x^{-1}w^{-1}(k)) = \text{sign}(w^{-1}(k))$ and $x^{-1}(l) < x^{-1}(l + 1)$, for all $l \in [1, i - 1]$ and for all $l \in [i + 1, n - 1]$, we easily check that $(u \times \pi_i(w)''_{(n-i)})x \smile_{(n)} w$, using Remark 4.4. Let $v \in W_{n-i}$ such that $v \smile_{(n-i)} \pi_i(w)''_{(n-i)}$, then $(u \times v)x \smile_{(n)} w$ as above. Therefore

$$\Delta\left(\sum_{w \in Z} w\right) = \sum_{i=0}^n \sum_{Z_i, Z_{n-i}} \left(\sum_{u \in Z_i} u\right) \otimes \left(\sum_{v \in Z_{n-i}} v\right),$$

where Z_i (resp. Z_{n-i}) are coplactic classes in W_i (resp. W_{n-i}).

We now need to prove that $\tilde{\theta}$ is an homomorphism of Hopf algebras. We first need a lemma concerning the symmetric bilinear form $\beta : (\mathcal{Q} \otimes_{\mathbf{Z}} \mathcal{Q}) \times (\mathcal{Q} \otimes_{\mathbf{Z}} \mathcal{Q}) \rightarrow \mathbf{Z}$, $(x, y) \mapsto \tau_{\otimes}(xy)$. Let $\tilde{\theta}_{\otimes} = \tilde{\theta} \otimes_{\mathbf{Z}} \tilde{\theta} : \mathcal{Q} \otimes_{\mathbf{Z}} \mathcal{Q} \rightarrow \mathcal{CHAR} \otimes_{\mathbf{Z}} \mathcal{CHAR}$. Then:

LEMMA 5.9. — *$\text{Ker } \tilde{\theta}_{\otimes} = \mathcal{Q} \otimes_{\mathbf{Z}} \text{Ker } \tilde{\theta} + \text{Ker } \tilde{\theta} \otimes_{\mathbf{Z}} \mathcal{Q}$ is the kernel of β .*

Proof. — By Theorem 4.14 (c), we have

$$\beta(x, y) = \langle \tilde{\theta}_{\otimes}(x), \tilde{\theta}_{\otimes}(y) \rangle_{\otimes}$$

for all $x, y \in \mathcal{Q} \otimes_{\mathbf{Z}} \mathcal{Q}$. This proves the lemma. □

Proposition 5.6 and Lemma 5.9 show that $\text{Ker } \tilde{\theta}$ is an ideal and a coideal of \mathcal{Q} . Since $\mathcal{Q} = \Sigma' + \text{Ker } \tilde{\theta}$, it is sufficient to prove that θ is a bialgebra homomorphism. First, it is clear that $\tilde{\theta}(x_C * x_D) = \tilde{\theta}(x_{C \sqcup D})$. So $\tilde{\theta}$ is an algebra homomorphism. Using this last property and Theorem 5.5, it is sufficient to prove that $\tilde{\theta}_{\otimes}(\Delta(x_n)) = \text{Res}(\tilde{\theta}(x_n))$ and $\tilde{\theta}_{\otimes}(\Delta(x_{\bar{n}})) = \text{Res}(\tilde{\theta}(x_{\bar{n}}))$. But this follows easily from Example 5.4. □

6. The case $n = 2$

In this Section, we will give a complete description of the algebra $\Sigma'(W_2)$. For simplification, we set $s = s_1$. Note that $t_1 = t$ and $t_2 = sts$. In other words, $S'_2 = \{s, t, sts\}$. Table I gives the correspondence between reduced decomposition of elements of W_2 and permutations of I_2 (if $w \in W_2$, we only give the couple $(w(1), w(2))$ since it determines w as a permutation of I_2). It also gives the value of $\mathcal{U}'_2(w)$ and $\mathbf{C}(w)$. Table II gives representatives of the conjugacy classes of W_2 . Table III gives, for each signed composition C of 2, the subgroup W_C of W_2 , the set S_C , the elements x_C and y_C of $\mathbf{Z}W_2$ and also gives the value of \mathcal{A}_C . Table IV provides the decomposition of the induced characters $\text{Ind}_{W_{\lambda}}^{W_2} 1_{\lambda} = \theta_2(x_{\lambda})$ as a combination of the ξ_{μ} , for $\lambda \Vdash 2$. Table V gives the character table of $\mathbf{Q}\Sigma'(W_2)$ (see Subsection 3.5). We give in Table VI a complete set of orthogonal primitive idempotents of $\mathbf{Q}\Sigma'(W_2)$. Table VII gives the Cartan matrix of $\Sigma'(W_2)$. As usual, the dots in the tables represent the number 0. Note that

$$w_2 = stst = tsts.$$

We conclude the Section by a description of the algebra $\mathbf{Q}\Sigma'(W_2)$ as a product of classical indecomposable algebras.

Convention. — For avoiding the use of too many parenthesis, we have denoted by $\xi_{\hat{\lambda}}$, $\pi_{\hat{\lambda}}$ or $E_{\hat{\lambda}}$ the objects ξ_{λ} , π_{λ} or E_{λ} respectively. For instance, $\xi_{1, \bar{1}} = \xi_{((1), (1))}$ and $\pi_2 = \pi_{((2), \emptyset)}$ and $E_{\bar{1}, \bar{1}} = E_{(\emptyset, (1, 1))}$.

Table 6.1. Elements.

w	$(w(1), w(2))$	$\mathcal{U}'_2(w)$	$\mathcal{C}(w)$
1	(1, 2)	$\{s, t, sts\}$	(2)
s	(2, 1)	$\{t, sts\}$	(1, 1)
t	$(\bar{1}, 2)$	$\{s, sts\}$	$(\bar{1}, 1)$
st	$(\bar{2}, 1)$	$\{s, sts\}$	$(\bar{1}, 1)$
ts	$(2, \bar{1})$	$\{t\}$	$(1, \bar{1})$
sts	$(1, \bar{2})$	$\{t\}$	$(1, \bar{1})$
tst	$(\bar{2}, \bar{1})$	$\{s\}$	$(\bar{2})$
w_2	$(\bar{1}, \bar{2})$	\emptyset	$(\bar{1}, \bar{1})$

Table 6.2. Conjugacy classes.

$\hat{\lambda}$	c_λ$	|\mathcal{C}_\lambda|$
(2)	st	2
(1, 1)	w_2	1
$(1, \bar{1})$	t	2
$(\bar{2})$	s	2
$(\bar{1}, \bar{1})$	1	1

Table 6.3. Bases of $\Sigma'(W_2)$.

C	W_C	S_C	x_C	y_C	\mathcal{A}_C
(2)	W_2	$\{s, t\}$	1	1	$\{s, t, sts\}$
(1, 1)	$W_1 \times W_1$	$\{t, sts\}$	$1 + s$	s	$\{t, sts\}$
$(\bar{1}, 1)$	$\mathfrak{S}_1 \times W_1$	$\{sts\}$	$1 + s + t + st$	$t + st$	$\{t\}$
$(1, \bar{1})$	$W_1 \times \mathfrak{S}_1$	$\{t\}$	$1 + s + ts + sts$	$ts + sts$	$\{s, sts\}$
$(\bar{2})$	\mathfrak{S}_2	$\{s\}$	$1 + t + st + tst$	tst	$\{s, sts\}$
$(\bar{1}, \bar{1})$	1	\emptyset	$\sum_{w \in W_2} w$	w_2	\emptyset

Table 6.4. Decomposition of induced characters.

	ξ_2	$\xi_{1,1}$	$\xi_{1,\bar{1}}$	$\xi_{\bar{2}}$	$\xi_{\bar{1},\bar{1}}$
$\theta_2(x_2)$	1	.	.	.	.
$\theta_2(x_{1,1})$	1	1	.	.	.
$\theta_2(x_{1,\bar{1}})$	1	1	1	.	.
$\theta_2(x_{\bar{2}})$	1	.	1	1	.
$\theta_2(x_{\bar{1},\bar{1}})$	1	1	2	1	1

Table 6.5. Character table of $\Sigma'(W_2)$.

	x_2	$x_{1,1}$	$x_{1,\bar{1}}$	$x_{\bar{2}}$	$x_{\bar{1},\bar{1}}$
π_2	1	.	.	.	.
$\pi_{1,1}$	1	2	.	.	.
$\pi_{1,\bar{1}}$	1	2	2	.	.
$\pi_{\bar{2}}$	1	.	.	2	.
$\pi_{\bar{1},\bar{1}}$	1	2	4	4	8

Remark. — Using these tables, one can check that $\theta_2(x_{\bar{2}})(x_{1,1}) = 6 \neq 4 = \theta_2(x_{1,1})(x_{\bar{2}})$. In other words, the symmetry property (see [2]) does not hold in our case.

Table 6.6. A complete set of orthogonal primitive idempotents.

$$\begin{aligned}
 E_2 &= x_2 - \frac{1}{2}x_{\bar{2}} - \frac{1}{4}x_{1,\bar{1}} + \frac{1}{4}x_{\bar{1},1} - \frac{1}{2}x_{1,1} + \frac{1}{4}x_{\bar{1},\bar{1}} \\
 E_{1,1} &= \frac{1}{2} \left(x_{1,1} - \frac{1}{2}x_{1,\bar{1}} - \frac{1}{2}x_{\bar{1},1} + \frac{1}{4}x_{\bar{1},\bar{1}} \right) \\
 E_{1,\bar{1}} &= \frac{1}{2} \left(x_{1,\bar{1}} - \frac{1}{2}x_{\bar{1},\bar{1}} \right) \\
 E_{\bar{2}} &= \frac{1}{2} \left(x_{\bar{2}} - \frac{1}{2}x_{\bar{1},\bar{1}} \right) \\
 E_{\bar{1},\bar{1}} &= \frac{1}{8}x_{\bar{1},\bar{1}}
 \end{aligned}$$

We will now give the Cartan matrix of $\Sigma'(W_2)$. If $\mu \in \text{Bip}(2)$, we denote by Π_μ the character of the projective cover $\mathbf{Q}\Sigma'(W_2)E_\mu$ of \mathbf{Q}_μ . Write

$$\Pi_\mu = \sum_{\lambda \in \text{Bip}(2)} \gamma_{\lambda\mu} \pi_\lambda.$$

Then $(\gamma_{\lambda\mu})_{\lambda,\mu \in \text{BiP}(2)}$ is the Cartan matrix of $\Sigma'(W_2)$. It is given in the following table:

Table 6.7. Cartan matrix of $\Sigma'(W_2)$.

$\hat{\lambda} \setminus \hat{\mu}$	(2)	(1, 1)	(1, $\bar{1}$)	($\bar{2}$)	($\bar{1}, \bar{1}$)
(2)	1	.	.	.	.
(1, 1)	.	1	.	.	.
(1, $\bar{1}$)	.	.	1	1	.
($\bar{2}$)	.	.	.	1	.
($\bar{1}, \bar{1}$)	1

Let $E_0 = E_{1,\bar{1}} + E_{\bar{2}}$. Then $(E_2, E_{1,1}, E_0, E_{\bar{2}})$ is a complete set of central primitive idempotents (they are of course orthogonal). Therefore, write $A_\omega = \mathbf{Q}\Sigma'(W_2)E_\omega$, for $\omega \in \{2, (1, 1), 0, \bar{2}\}$. Then

$$\mathbf{Q}\Sigma'(W_2) = A_2 \oplus A_{1,1} \oplus A_{\bar{2}} \oplus A_0,$$

as a sum of algebras. Moreover, $A_2 \simeq \mathbf{Q}$, $A_{1,1} \simeq \mathbf{Q}$, $A_{\bar{2}} \simeq \mathbf{Q}$. On the other hand,

$$A_0 = \mathbf{Q}E_{1,\bar{1}} \oplus \mathbf{Q}E_{\bar{2}} \oplus \mathbf{Q}(x_{1,\bar{1}} - x_{\bar{1},1}),$$

as a vector space. Now, let B be the algebra

$$B = \left\{ \begin{pmatrix} a & b \\ 0 & c \end{pmatrix} \mid a, b, c \in \mathbf{Q} \right\}.$$

Then the \mathbf{Q} -linear map $\sigma : A_0 \rightarrow B$ such that

$$\sigma(E_{1,\bar{1}}) = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \quad \sigma(E_{\bar{2}}) = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

and

$$\sigma(x_{1,\bar{1}} - x_{\bar{1},1}) = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$$

is an isomorphism of algebras. Therefore, we have an isomorphism of algebras

$$\mathbf{Q}\Sigma'(W_2) \simeq \mathbf{Q} \oplus \mathbf{Q} \oplus \mathbf{Q} \oplus B.$$

A. Appendix: Comparison with Specht's construction by Pierre BAUMANN & Christophe HOHLWEG

The present text is an appendix to the article *Generalized descent algebra and construction of irreducible characters of hyperoctahedral groups*, by Cédric Bonnafé and the second present author. Our aim here is to relate two constructions of the irreducible characters of the hyperoctahedral groups: the one given in that article, and Specht's one [19]. Meant as a sequel to Bonnafé and Hohlweg's article, this text uses the same notations and references.

We first recall briefly Specht's construction, using Macdonald's book as a reference [14, I, Appendix B].

Specht's construction

Let G be a finite group, let G_* be the set of conjugacy classes in G and let G^* be the set of irreducible characters of G . Given a conjugacy class $c \in G_*$, we denote by ζ_c the order of the centralizer of an element of c . We denote the value of a character γ of G at any element of a conjugacy class $c \in G_*$ by $\gamma(c)$.

We denote the wreath product $G \wr \mathfrak{S}_n$ by G_n . This wreath product is the semidirect product $G^n \rtimes \mathfrak{S}_n$ for the action of \mathfrak{S}_n on G^n given by

$$\sigma \cdot (g_1, \dots, g_n) = (g_{\sigma^{-1}(1)}, \dots, g_{\sigma^{-1}(n)}),$$

where $\sigma \in \mathfrak{S}_n$ and $(g_1, \dots, g_n) \in G^n$, so that we can always represent an element in G_n as a product $(g_1, \dots, g_n) \sigma$.

Given a complex representation V of G , we construct a complex representation $\eta_n(V)$ of G_n on the space $V^{\otimes n}$ by letting a product $(g_1, \dots, g_n) \sigma$ act on a pure tensor $v_1 \otimes \dots \otimes v_n \in V^{\otimes n}$ in the following way:

$$((g_1, \dots, g_n) \sigma) \cdot (v_1 \otimes \dots \otimes v_n) = (g_1 \cdot v_{\sigma^{-1}(1)}) \otimes \dots \otimes (g_n \cdot v_{\sigma^{-1}(n)}).$$

The character of $\eta_n(V)$ does not depend on V but only of its character; if ρ denotes the latter, then we will denote the former by $\eta_n(\rho)$.

We let \mathcal{P} be the set of all partitions, and we set $\mathcal{P}_G = \mathcal{P}^{G^*}$. Given an element $\lambda = (\lambda_\gamma)_{\gamma \in G^*}$ in \mathcal{P}_G , we denote by $|\lambda|$ the sum $\sum_\gamma |\lambda_\gamma|$.

Now let $\Lambda_{\mathbf{C}}$ be the (free) ring of symmetric polynomials with complex coefficients. As is well-known, $\Lambda_{\mathbf{C}}$ is generated over \mathbf{C} by a countable family of algebraically independent elements: one can choose for generators the family $(h_n)_{n \geq 1}$ of complete symmetric functions or the family $(p_n)_{n \geq 1}$ of

power sums. On the other hand, the family of Schur functions $(s_\lambda)_{\lambda \in \mathcal{P}}$ is a basis of the vector space $\Lambda_{\mathbf{C}}$. Following Macdonald, we denote by $\Lambda_{\mathbf{C}}(G)$ the ring of polynomials over \mathbf{C} in the family of variables $(p_n(c))_{n \geq 1, c \in G^*}$. Setting

$$p_n(\gamma) = \sum_{c \in G^*} \zeta_c^{-1} \gamma(c) p_r(c)$$

for any $\gamma \in G^*$, one deduces from the invertibility of the character table of G that $\Lambda_{\mathbf{C}}(G)$ is also the ring of polynomials in the variables $(p_n(\gamma))_{n \geq 1, \gamma \in G^*}$. Each symmetric polynomial $P \in \Lambda_{\mathbf{C}}$ can be uniquely expressed as a polynomial with complex coefficients in the power sums p_n ; given $\gamma \in G^*$, we denote by $P(\gamma)$ the element of $\Lambda_{\mathbf{C}}(G)$ obtained by replacing the variables p_n by the variables $p_n(\gamma)$ in the expression of P . Given an element $\lambda = (\lambda_\gamma)_{\gamma \in G^*}$ in \mathcal{P}_G , we set

$$s_\lambda = \prod_{\gamma \in G^*} s_{\lambda_\gamma}(\gamma).$$

The set of complex irreducible characters of G_n is a basis of the algebra of complex-valued class functions of G_n , so that we can denote this latter by $\mathbf{C} \text{Irr}(G_n)$. The direct sum

$$R(G) = \bigoplus_{n \geq 0} \mathbf{C} \text{Irr}(G_n)$$

can be endowed with the structure of a commutative and cocommutative \mathbf{N} -graded Hopf algebra, where the product is given by the induction functors $\text{Ind}_{G_m \times G_n}^{G_{m+n}}$ and the coproduct is afforded by the restriction functors $\text{Res}_{G_m \times G_n}^{G_{m+n}}$ [14, I, Appendix B, 4 and I, 7, Example 26]. Since $\Lambda_{\mathbf{C}}(G)$ is a free commutative algebra, there is a unique homomorphism of \mathbf{C} -algebras

$$\text{ch}^{-1} : \Lambda_{\mathbf{C}}(G) \rightarrow R(G)$$

with the following property: for each $n \geq 1$ and each $c \in G^*$, ch^{-1} maps the variable $p_n(c)$ to the characteristic function of the conjugacy class of G_n consisting of the products $(g_1, g_2, \dots, g_n) \sigma$, where the permutation $\sigma \in \mathfrak{S}_n$ is a n -cycle and the product $g_1 g_2 \cdots g_n$ belongs to the conjugacy class c . It turns out that ch^{-1} is an isomorphism of Hopf algebra, whose inverse will be denoted by ch . Then, using arguments of orthogonality and integrality, it can be shown [14, I, Appendix B, 9] that the image under ch of the irreducible characters of G_n are the elements s_λ , where $\lambda \in \mathcal{P}_G$ is such that $|\lambda| = n$.

Later on, we will need to know the image under ch of characters $\eta_n(\rho)$. We do the computation now.

LEMMA A.1. — Let $\gamma_1, \dots, \gamma_s$ be the irreducible characters of G , let c_1, \dots, c_s be non-negative integers, and set $\rho = c_1\gamma_1 + \dots + c_s\gamma_s$. Then

$$\sum_{n \geq 0} \text{ch}(\eta_n(\rho)) = \prod_{i=1}^s \left(\sum_{n \geq 0} h_n(\gamma_i) \right)^{c_i}.$$

Proof. — The proof given in [14, I, Appendix B, 8] for the case where ρ is irreducible can be easily adapted. Indeed in the computation that follows Equation (8.2) in that reference, the steps that lead to the equality

$$\sum_{n \geq 0} \text{ch}(\eta_n(\gamma)) = \exp \left(\sum_{r \geq 1} \frac{1}{r} \sum_{c \in G_*} \zeta_c^{-1} \gamma(c) p_r(c) \right)$$

are valid even if the character γ is reducible. Applying this formula to the character ρ , we get

$$\begin{aligned} \sum_{n \geq 0} \text{ch}(\eta_n(\rho)) &= \exp \left(\sum_{r \geq 1} \frac{1}{r} \sum_{c \in G_*} \zeta_c^{-1} \rho(c) p_r(c) \right) \\ &= \prod_{i=1}^s \left[\exp \left(\sum_{r \geq 1} \frac{1}{r} \sum_{c \in G_*} \zeta_c^{-1} \gamma_i(c) p_r(c) \right) \right]^{c_i} \\ &= \prod_{i=1}^s \left[\exp \left(\sum_{r \geq 1} \frac{1}{r} p_r(\gamma_i) \right) \right]^{c_i} \\ &= \prod_{i=1}^s \left[\sum_{n \geq 0} h_n(\gamma_i) \right]^{c_i}, \end{aligned}$$

the last step in the computation coming from Newton’s formulas. □

The comparison result

Having now recalled Specht’s construction of the irreducible characters for the wreath product $G \wr \mathfrak{S}_n$ of an arbitrary finite group G by the symmetric group \mathfrak{S}_n , we specialize to the case where G is the group $W = \mathbf{Z}/2\mathbf{Z}$ with two elements. The notation W_n for the wreath product $W \wr \mathfrak{S}_n$ then agrees with its use by Bonnafé and Hohlweg. The Hopf algebra $R(W)$ is identical to the complexified Hopf algebra $\mathcal{CHAR} \otimes_{\mathbf{Z}} \mathbf{C}$ with its product \bullet . The set W^* of irreducible characters of W has two elements, namely the trivial character τ and the signature ε . One can view an element $\lambda = (\lambda_\tau, \lambda_\varepsilon)$ of \mathcal{P}_W as a bipartition (λ^+, λ^-) by setting $\lambda^+ = \lambda_\tau$ and $\lambda^- = \lambda_\varepsilon$. As a final piece of notation, we set $\lambda^* = (\lambda^+, (\lambda^-)')$ for any bipartition $\lambda = (\lambda^+, \lambda^-)$, where $(\lambda^-)'$ is the conjugate of the partition λ^- .

Generalizing Poirier and Reutenauer’s work [17] for symmetric groups to the case of W_n , we define a linear map

$$f : \mathcal{Q} \otimes_{\mathbf{Z}} \mathbf{C} \longrightarrow \Lambda_{\mathbf{C}}(W)$$

by setting $f(z_Q^{(n)}) = s_{(\text{sh } Q)^*}$ for any bitableau $Q \in \mathcal{SBT}(n)$. With all these notations, our result can be stated as follows:

THEOREM A.2. — *The following diagram of \mathbf{N} -graded Hopf algebras*

$$\begin{array}{ccc}
 \mathcal{Q} \otimes_{\mathbf{Z}} \mathbf{C} & \xrightarrow{f} & \Lambda_{\mathbf{C}}(W) \\
 \uparrow i & \searrow \tilde{\theta} & \uparrow \sim \text{ch} \\
 \Sigma' \otimes_{\mathbf{Z}} \mathbf{C} & \xrightarrow{\theta} & \mathcal{CHAR} \otimes_{\mathbf{Z}} \mathbf{C}
 \end{array}$$

is commutative. In particular $\text{ch}(\xi_\lambda) = s_{\lambda^*}$, for any bipartition λ , so that Bonnafé and Hohlweg’s construction is equivalent to Specht’s one, up to a relabelling.

Some further notation and a bijection will be needed for the proof. We present them now.

Some notation and a bijection

We call quasicomposition a sequence $E = (e_1, e_2, e_3, \dots)$ of non-negative integers, all of whose terms but a finite number vanish. The size $|E|$ of E is the sum $e_1 + e_2 + e_3 + \dots$ of the terms. Given a partition μ and a quasicomposition E , we denote by $\text{Tab}(\mu, E)$ the set of all semistandard tableau of shape μ and weight E , that is the set of all fillings of the Ferrers diagram of shape μ with positive integers, in such a way that the numbers are weakly increasing from left to right in the rows, strictly increasing from top to bottom in the columns, and that there is e_1 times the number 1, e_2 times the number 2, and so on [14, p. 5]. The set $\text{Tab}(\mu, E)$ is of course empty unless $|\mu| = |E|$. Given any quasicomposition $E = (e_1, e_2, e_3, \dots)$, the formula

$$h_{e_1} h_{e_2} h_{e_3} \dots = \sum_{\mu \in \mathcal{P}} |\text{Tab}(\mu, E)| s_\mu$$

holds in $\Lambda_{\mathbf{C}}$ (see [14, I, (6.4)] for a proof).

Now we fix a positive integer n and a signed composition $C = (c_1, \dots, c_\ell)$ of it. Let ℓ be the length of C . We define $\text{Comp}(C)$ as the set of all quasicompositions $D = (d_1, \dots, d_\ell)$ such that $d_i = 0$ if $c_i > 0$ and

$0 \leq d_i \leq -c_i$ if $c_i < 0$. Given such a D , we further define two quasicompositions $T_{C,D} = (t_1, \dots, t_\ell)$ and $E_{C,D} = (e_1, \dots, e_\ell)$ by

$$t_i = \begin{cases} c_i & \text{if } c_i > 0, \\ d_i & \text{if } c_i < 0; \end{cases} \quad \text{and} \quad e_i = \begin{cases} 0 & \text{if } c_i > 0, \\ -c_i - d_i & \text{if } c_i < 0. \end{cases}$$

The signed composition obtained by omitting the zeros in the list

$$(-e_1, t_1, -e_2, t_2, \dots, -e_\ell, t_\ell)$$

will be denoted by $B_{C,D}$. For instance, for $C = (2, \bar{2}, \bar{3}, 1, \bar{1}, 2, 2, \bar{2}) \models 15$, we can choose $D = (0, 0, 2, 0, 1, 0, 0, 0)$, and then $T_{C,D} = (2, 0, 2, 1, 1, 2, 2, 0)$, $E_{C,D} = (0, 2, 1, 0, 0, 0, 0, 2)$ and $B_{C,D} = (2, \bar{2}, \bar{1}, 2, 1, 1, 2, 2, \bar{2})$.

Finally, given a bipartition $\lambda = (\lambda^+, \lambda^-)$ and a signed composition C with $|\lambda| = |C|$, we define $\text{Bitab}(\lambda, C)$ as the set of all standard bitableaux Q such that $\text{sh}(Q) = \lambda^*$ and $C \leftarrow \mathbf{C}(Q)$ (see Remark 4.7).

One of the keys to the proof of Theorem A.2 is the following combinatorial result.

PROPOSITION A.3. — *Given a bipartition λ and a signed composition C with $|\lambda| = |C|$, the sets $\text{Bitab}(\lambda, C)$ and*

$$\coprod_{D \in \text{Comp}(C)} \text{Tab}(\lambda^+, T_{C,D}) \times \text{Tab}(\lambda^-, E_{C,D})$$

have the same cardinality.

Proof. — Let n be a positive integer, C be a signed composition of n , and $\lambda = (\lambda^+, \lambda^-)$ be a bipartition with $|\lambda| = n$. We construct mutually inverse bijections between $\text{Bitab}(\lambda, C)$ and

$$\coprod_{D \in \text{Comp}(C)} \text{Tab}(\lambda^+, T_{C,D}) \times \text{Tab}(\lambda^-, E_{C,D})$$

as follows.

First let (R, S) be in the second set, so that $R \in \text{Tab}(\lambda^+, T_{C,D})$ and $S \in \text{Tab}(\lambda^-, E_{C,D})$ for some $D \in \text{Comp}(C)$. We put a total order on the boxes in R and S by requiring that:

- A box is smaller than another one if the label written in it is smaller than the one in the other.
- Given two boxes with the same label in it, a box in S is smaller than a box in R .
- For boxes containing the same label and located in the same tableau (R or S), boxes located south-west are smaller than boxes located north-east.

Then we enumerate in increasing order the boxes in R and S . Filling now each box of R and S by its rank of appearance in the enumeration, we construct a standard bitableau \tilde{Q} of shape λ . We then define Q as the bitableau obtained from \tilde{Q} by transposing \tilde{Q}^- , so that Q has shape λ^* . Comparing this construction with the combinatorial rule in Remark 4.7 that computes $\mathbf{C}(Q)$, we easily check that the signed composition $B_{C,D}$ can be obtained from $\mathbf{C}(Q)$ by refinement of the parts, so that $C \xleftarrow{B} B_{C,D} \xleftarrow{R} \mathbf{C}(Q)$, which implies $Q \in \text{Bitab}(\lambda, C)$.

In the other direction, let Q be a given element in $\text{Bitab}(\lambda, C)$. From Theorem 3.15, there exists a unique signed composition B such that $C \xleftarrow{B} B \xleftarrow{R} \mathbf{C}(Q)$, and we can find a (unique) element $D \in \text{Comp}(C)$ so that $B = B_{C,D}$. Now we transpose Q^- and get a bitableau \tilde{Q} . We construct a list $L = (l_1, l_2, \dots, l_n)$ of positive integers by placing first $|c_1|$ times the number 1, then $|c_2|$ times the number 2, and so on. Then we substitute l_1 to 1, l_2 to 2, and so on, in the boxes of \tilde{Q} , and obtain in this way a pair (R, S) of tableaux of shapes λ^+ and λ^- respectively. The fact that $B_{C,D} \xleftarrow{R} \mathbf{C}(Q)$ implies that this construction yields two semistandard tableaux R and S with weights $T_{C,D}$ and $E_{C,D}$ respectively, that is to say

$$(R, S) \in \text{Tab}(\lambda^+, T_{C,D}) \times \text{Tab}(\lambda^-, E_{C,D}).$$

It is a routine task to check that the two above constructions yield mutually inverse bijections between

$$\coprod_{D \in \text{Comp}(C)} \text{Tab}(\lambda^+, T_{C,D}) \times \text{Tab}(\lambda^-, E_{C,D})$$

and $\text{Bitab}(\lambda, C)$. □

We end this paragraph by an example that illustrates the constructions needed in the proof above. We take $n = 15$ and choose the same signed composition C as in the previous example, namely

$$C = (2, \bar{2}, \bar{3}, 1, \bar{1}, 2, 2, \bar{2}).$$

We choose $\lambda^+ = 631$ and $\lambda^- = 41$, so that $\lambda^* = (631, 2111)$. Starting from the pair (R, S) with

$$R = \begin{array}{|c|c|c|c|c|c|} \hline 1 & 1 & 3 & 3 & 4 & 7 \\ \hline 5 & 6 & 7 & & & \\ \hline 6 & & & & & \\ \hline \end{array} \quad \text{and} \quad S = \begin{array}{|c|c|c|c|} \hline 2 & 2 & 3 & 8 \\ \hline 8 & & & \\ \hline \end{array},$$

we construct $\tilde{Q} = (\tilde{Q}^+, \tilde{Q}^-)$ where

$$\tilde{Q}^+ = \begin{array}{|c|c|c|c|c|c|} \hline 1 & 2 & 6 & 7 & 8 & 13 \\ \hline 9 & 11 & 12 & & & \\ \hline 10 & & & & & \\ \hline \end{array} \quad \text{and} \quad \tilde{Q}^- = \begin{array}{|c|c|c|c|} \hline 3 & 4 & 5 & 15 \\ \hline 14 & & & \\ \hline \end{array},$$

whence $Q = (Q^+, Q^-)$ with

$$Q^+ = \tilde{Q}^+ = \begin{array}{|c|c|c|c|c|c|} \hline 1 & 2 & 6 & 7 & 8 & 13 \\ \hline 9 & 11 & 12 & & & \\ \hline 10 & & & & & \\ \hline \end{array} \quad \text{and} \quad Q^- = {}^t\tilde{Q}^- = \begin{array}{|c|c|} \hline 3 & 14 \\ \hline 4 & \\ \hline 5 & \\ \hline 15 & \\ \hline \end{array}.$$

Since $\mathbf{C}(Q) = (2, \bar{3}, 3, 1, 4, \bar{2})$, it holds that $C \xleftarrow{B} B \xleftarrow{R} \mathbf{C}(Q)$ with

$$B = (2, \bar{2}, \bar{1}, 2, 1, 1, 2, 2, \bar{2}),$$

which implies $C \leftarrow \mathbf{C}(Q)$.

In the other direction, we start from the bitableau Q . We observe that the signed composition B such that $C \xleftarrow{B} B \xleftarrow{R} \mathbf{C}(Q)$ is $B_{C,D}$, where D is given by $D = (0, 0, 2, 0, 1, 0, 0, 0)$. Now we write down the list

$$L = (1, 1, 2, 2, 3, 3, 3, 4, 5, 6, 6, 7, 7, 8, 8)$$

from C . Transposing the negative tableau Q^- , we write down \tilde{Q} and substitute the elements of L to the numbers in the boxes of \tilde{Q} . We recover our original pair (R, S) . We easily verify that R has weight

$$T_{C,D} = (2, 0, 2, 1, 1, 2, 2, 0)$$

and that S has weight

$$E_{C,D} = (0, 2, 1, 0, 0, 0, 0, 2).$$

Proof of Theorem A.2

1. — We first compute the image by ch of the induced character $\text{Ind}_{\mathfrak{S}_n}^{W_n} 1$ of W_n , where n is a positive integer. To do that, we construct the complex representation $\eta_n(V)$ of W_n , where V is the left regular representation of $W = \mathbf{Z}/2\mathbf{Z}$. Denoting by \mathbf{C}_1 the trivial representation of \mathfrak{S}_n , we then observe that the isomorphism of vector spaces $\text{Ind}_{\mathfrak{S}_n}^{W_n} \mathbf{C}_1 \cong \eta_n(V)$ given by the sequence of natural identifications

$$\text{Ind}_{\mathfrak{S}_n}^{W_n} \mathbf{C}_1 \cong \mathbf{C}W_n \otimes_{\mathbf{C}\mathfrak{S}_n} \mathbf{C}_1 \cong \mathbf{C}[W^n] \cong (\mathbf{C}W)^{\otimes n} = V^{\otimes n} = \eta_n(V)$$

is compatible with the action of W_n . Since V has $\tau + \varepsilon$ for character, it follows that $\text{Ind}_{\mathfrak{S}_n}^{W_n} 1 = \eta_n(\tau + \varepsilon)$. Lemma A.1 now implies that

$$\sum_{n \geq 0} \text{ch}(\text{Ind}_{\mathfrak{S}_n}^{W_n} 1) = \left(\sum_{n \geq 0} h_n(\tau) \right) \left(\sum_{n \geq 0} h_n(\varepsilon) \right).$$

On the other side, it is easy to check that $\eta_n(\tau)$ is the trivial character of W_n . Therefore ch maps the trivial character $\text{Ind}_{W_n}^{W_n} 1$ of W_n to $h_n(\tau)$. To

comply with the philosophy used by Bonnafé and Hohlweg, we write for any positive integer n

$$\varphi_{\pm n} = \text{ch}(\text{Ind}_{W_{\pm n}}^{W_n} 1) = \begin{cases} \text{ch}(\text{Ind}_{W_n}^{W_n} 1) = h_n(\tau) & \text{for '+' sign,} \\ \text{ch}(\text{Ind}_{\mathfrak{S}_n}^{W_n} 1) = \sum_{k=0}^n h_k(\tau)h_{n-k}(\varepsilon) & \text{for '-' sign.} \end{cases}$$

2. — We now prove the equality $f \circ i = \text{ch} \circ \theta$. Given any signed composition $C = (c_1, \dots, c_\ell)$, there holds $x_C = x_{c_1} \cdots x_{c_\ell}$. Since θ is a morphism of Hopf algebras, we can write

$$\text{Ind}_{W_C}^{W_{|C|}} 1_C = \theta(x_C) = \theta(x_{c_1}) \cdots \theta(x_{c_\ell}) = \text{Ind}_{W_{c_1}}^{W_{|c_1|}} \mathbf{1} \bullet \cdots \bullet \text{Ind}_{W_{c_\ell}}^{W_{|c_\ell|}} \mathbf{1},$$

and taking its image under ch ,

$$\text{ch Ind}_{W_C}^{W_{|C|}} = \text{ch} \circ \theta(x_C) = \varphi_{c_1} \cdots \varphi_{c_\ell}.$$

The formula

$$\varphi_{-n} = \sum_{k=0}^n h_k(\tau)h_{n-k}(\varepsilon),$$

valid for any positive integer n , makes possible to continue the computation:

$$\text{ch} \circ \theta(x_C) = \sum_{D \in \text{Comp}(C)} h_{t_1}(\tau) \cdots h_{t_\ell}(\tau) h_{e_1}(\varepsilon) \cdots h_{e_\ell}(\varepsilon),$$

where the quasicompositions (t_1, \dots, t_ℓ) and (e_1, \dots, e_ℓ) appearing in the sum are $T_{C,D}$ and $E_{C,D}$ respectively. We thus get, using Proposition A.3 and the decomposition of X_C given at the end of Remark 4.7:

$$\begin{aligned} \text{ch} \circ \theta(x_C) &= \sum_{D \in \text{Comp}(C)} \left(\sum_{\lambda^+ \in \mathcal{P}} |\text{Tab}(\lambda^+, T_{C,D})|_{s_{\lambda^+}(\tau)} \right) \\ &\quad \times \left(\sum_{\lambda^- \in \mathcal{P}} |\text{Tab}(\lambda^-, E_{C,D})|_{s_{\lambda^-}(\varepsilon)} \right) \\ &= \sum_{(\lambda^+, \lambda^-) \in \mathcal{P}_W} \left(\sum_{D \in \text{Comp}(C)} |\text{Tab}(\lambda^+, T_{C,D}) \times \text{Tab}(\lambda^-, E_{C,D})| \right) \\ &\quad \times s_{\lambda^+}(\tau) s_{\lambda^-}(\varepsilon) \\ &= \sum_{\lambda \in \mathcal{P}_W} |\text{Bitab}(\lambda, C)|_{s_\lambda} \\ &= \sum_{\substack{Q \text{ std. bitableau} \\ C \leftarrow C(Q)}} S_{(\text{sh } Q)^*} \end{aligned}$$

$$\begin{aligned}
&= \sum_{\substack{Q \text{ std. bitableau} \\ C \leftarrow C(Q)}} f(z_Q^{(|C|)}) \\
&= f \circ i(x_C).
\end{aligned}$$

Since the elements x_C generate $\Sigma' \otimes_{\mathbf{Z}} \mathbf{C}$ as a vector space, it follows that $\text{ch} \circ \theta = f \circ i$.

3. — Step 2 implies that the maps f and $\text{ch} \circ \tilde{\theta}$ coincide on the image of i in $\mathcal{Q} \otimes_{\mathbf{Z}} \mathbf{C}$, because $\theta = \tilde{\theta} \circ i$. On the other hand, f and $\text{ch} \circ \tilde{\theta}$ have the same kernel, namely the graded subspace of \mathcal{Q} whose degree n component is the span \mathcal{Q}_n^{\perp} of the elements $z_Q^{(n)} - z_{Q'}^{(n)}$, where Q and Q' are standard bitableaux with the same shape (see Theorem 4.14). Moreover this kernel and the image of i together span $\mathcal{Q} \otimes_{\mathbf{Z}} \mathbf{C}$, because θ is surjective (see Proposition 4.12). It follows that $f = \text{ch} \circ \tilde{\theta}$, which completes the proof of Theorem A.2.

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