Subalgebras of Solomon's descent algebra based on alternating runs

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Subalgebras of Solomon’s descent algebra based on alternating runs

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Abstract
The number of alternating runs is a natural permutation statistic. We show it can be used to define some commutative subalgebras of the symmetric group algebra, and more precisely of the descent algebra. The Eulerian peak algebras naturally appear as subalgebras of our run algebras. We also calculate the orthogonal idempotents for run algebras in terms of noncommutative symmetric functions.

1 Introduction

An alternating run of a permutation σ ∈ Sn is a maximal monotone sequence of consecutive elements in σ1, . . . , σn. For example, the alternating runs of σ = 14523687 are 145, 52, 2368, and 87. We denote by run(σ) the number of alternating runs of σ. The enumeration of permutations refined by the number of alternating runs have been the subject of various previous works, beginning with André [3] as early as the late 19th century, then Carlitz in the 70’s [9, 10, 11, 12]. See also [6, 8, 13, 15, 20, 21, 31] for more recent references. It is worth mentioning that the work [15] was motivated by computations in quantum field theory. Also, alternating runs play a role in some algorithms such as pattern matching [7].

However, we take here a different perspective, our goal being to define and study various algebras based on this notion of alternating runs. Such an algebra first arose in Doyle and Rockmore’s study of “ruffle” card-shuffling: [14, Section 5.5] shows that the elements

\[ W_k = \sum_{\sigma \in \mathfrak{S}_n \atop \text{run}(\sigma) = k} \sigma, \]

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for $1 \leq k \leq n - 1$, linearly span a commutative subalgebra of $\mathbb{Z}[\mathfrak{S}_n]$, called the reduced turning algebra. Doyle and Rockmore also considered the number of alternating runs when we add an initial 0 in front of the permutation and obtain in this way another algebra, called the turning algebra [14, Section 5.4]. We will in particular obtain new proofs of these results in the present article.

In fact, it is easily seen that $\text{run}(\sigma)$ only depends on the descent set of $\sigma$, so that the elements $W_k$ lie in the descent algebra $D_n \subseteq \mathbb{Z}[\mathfrak{S}_n]$ (see [27] or the next section for a definition). This widely studied algebra provides other examples of combinatorial statistics such that there is an algebra linearly spanned by sums of permutations having the same value. Consider for example the descent statistic, then the $n$ elements

$$E_k = \sum_{\sigma \in \mathfrak{S}_n, \text{des}(\sigma) = k} \sigma,$$

for $0 \leq k \leq n - 1$ linearly span a subalgebra of $D_n$ called the Eulerian algebra $\mathcal{E}_n$ (see [16, 19]). But those being particularly relevant here are the Eulerian peak algebra and its left peak analogue [2, 23, 24, 25], because peaks and alternating runs are tightly connected.

Our main goal is to introduce a new algebra based on alternating runs, as the linear span of the $2n - 2$ elements:

$$W^+_k := \sum_{\sigma \in \mathfrak{S}_n, \text{run}(\sigma) = k, \text{the first run is ascending}} \sigma, \quad W^-_k := \sum_{\sigma \in \mathfrak{S}_n, \text{run}(\sigma) = k, \text{the first run is descending}} \sigma,$$

for $1 \leq k \leq n - 1$. This algebra is noncommutative, but it contains several commutative subalgebras, in particular the two considered by Doyle and Rockmore and the two Eulerian peak subalgebras.

We give in Section 3 a bijective proof of its existence. Then we show that once we know the existence of this $2n - 2$ dimensional algebra, the existence of the various subalgebras easily follows.

Then in Section 4, we provide a Hopf algebraic proof of the existence of run algebras, using the formalism of noncommutative symmetric functions [16]. Indeed, whereas each homogeneous component has an internal product which is essentially that of the descent algebra, the external Hopf structure permits to build new bases. Also, this algebraic approach easily gives the commutativity of the subalgebras, a property that seems very difficult to get by bijective proofs.

We go on in Section 5 by computing primitive orthogonal idempotents for each of the various run algebras, as generating functions in noncommutative symmetric functions. Part of these calculations appear to be equivalent to Petersen’s computation of peak idempotents via order polynomials of enriched $P$-partitions [24]. We also give some properties of the related characters of the symmetric groups, in the same way as idempotents of the Eulerian subalgebra are related with Foulkes characters [17].

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2 Preliminaries

2.1 Notations

A permutation $\sigma \in \mathfrak{S}_n$ is denoted as the sequence $\sigma_1, \ldots, \sigma_n$ where $\sigma_i = \sigma(i)$. We denote by $\text{Des}(\sigma)$ the set of descents of $\sigma$, i.e. integers $i$ such that $1 \leq i \leq n-1$ and $\sigma(i) > \sigma(i+1)$. Let also $\text{des}(\sigma) = \# \text{Des}(\sigma)$. Let $[n-1]$ denote $\{1, \ldots, n-1\}$. The descent class $D_I$ for $I \subseteq [n-1]$ is the set of $\sigma \in \mathfrak{S}_n$ with $\text{Des}(\sigma) = I$.

A partition $\lambda$ of $n$ is a decreasing sequence of positive integers $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_k$ called parts, such that $\sum_{i=1}^{k} \lambda_i = n$. We also denote by $|\lambda|$ the sum of parts of $\lambda$. The integer $k$ is the length of $\lambda$, and is denoted $\ell(\lambda)$. Also, we denote $\ell_e(\lambda)$ (respectively, $\ell_o(\lambda)$) the even length (respectively, the odd length) of $\lambda$, i.e. the number of even parts (respectively, odd parts). Write $z_\lambda$ for $1^{i_1}2^{i_2}i_3! \cdots$, where $i_r$ is the number of parts of size $r$ in $\lambda$. We denote $\lambda \vdash n$ to say that $\lambda$ is a partition of $n$.

A composition of $n$ is a sequence $I = (i_1, \ldots, i_r)$ of positive integers such that $\sum_{j=1}^{r} i_j = n$. We also denote by $|I|$ the sum of parts of $I$. The integer $r$ is called the length of $I$, and is denoted $\ell(I)$. We write $I \equiv n$ to say that $I$ is a composition of $n$.

In a partition or a composition, we write $1^n$ to mean that $1$ is repeated $n$ times.

The descent set of a composition $I = (i_1, \ldots, i_r)$, denoted $\text{Des}(I)$, is $\left\{i_1, i_1 + i_2, \ldots, \sum_{j=1}^{r-1} i_j \right\}$.

The map $I \mapsto \text{Des}(I)$ is a bijection from compositions of $n$ to subsets of $[n-1]$. When $I, J \vdash n$, we say that $J$ is a refinement of $I$, denoted $I \preceq J$, if $\text{Des}(I) \subseteq \text{Des}(J)$. When we write $I \preceq J$, we always understand that $|I| = |J|$.

2.2 The descent algebra

For $I \equiv n$, consider the following sums in the group algebra $\mathbb{Z}[\mathfrak{S}_n]$: $R_I = \sum_{\sigma \in \mathfrak{S}_n} \sigma, \quad S^I = \sum_{\sigma \in \mathfrak{S}_n} \sigma.$ Note that by an immediate inclusion-exclusion, we have: $S^I = \sum_{J \preceq I} R_J, \quad R_I = \sum_{J \preceq I} (-1)^{\ell(J) - \ell(I)} S^J.$

The linear span of the elements $R_I$ (or equivalently, $S^I$) for $I \equiv n$ is denoted $\mathcal{D}_n$ and called the descent algebra. It was indeed shown by Solomon [27] that $\mathcal{D}_n$ is a subalgebra of the group algebra $\mathbb{Z}[\mathfrak{S}_n]$. However, to facilitate our construction of idempotents of various subalgebras, it will be more convenient to work with rational coefficients, i.e. to consider $\mathcal{D}_n$ as a subalgebra of $\mathbb{Q}[\mathfrak{S}_n]$.

2.3 The Eulerian peak algebras.

Two previously identified subalgebras of the descent algebra will play a key role in the analysis of our new subalgebras. These are based on peaks:

Definition 2.1. A peak of a permutation $\sigma \in \mathfrak{S}_n$ is an integer $i$ with $2 \leq i \leq n-1$ and $\sigma(i-1) < \sigma(i) > \sigma(i+1)$. We denote by $\text{pk}(\sigma)$ the number of peaks of $\sigma$.

Definition 2.2. A left peak of a permutation $\sigma \in \mathfrak{S}_n$ is an integer $i$ with $1 \leq i \leq n-1$ and $\sigma(i-1) < \sigma(i) > \sigma(i+1)$ (with the convention $\sigma(0) = 0$). We denote by $\text{pk}^\circ(\sigma)$ the number of left peaks of $\sigma$. 

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Proposition 2.3. [25, Sec. 9] The elements

\[ P_k = \sum_{\sigma \in S_n, \text{pk}(\sigma) = k} \sigma \]

for \(0 \leq k \leq \left\lfloor \frac{n-1}{2} \right\rfloor\) span the Eulerian peak algebra \(\mathcal{P}_n\), a commutative subalgebra of \(\mathcal{D}_n\). Note that \(\dim(\mathcal{P}_n) = \left\lfloor \frac{n}{2} \right\rfloor\).

The Eulerian peak algebra first appeared in Schocker’s analysis [25] of a larger, noncommutative, peak algebra, spanned by sums of permutations with the same peak positions. This work determined the idempotents of \(\mathcal{P}_n\), which we will recover in the present Theorem 5.3.

Aguiar, Bergeron and Nyman [1] also studied this larger peak algebra, by viewing it as an ideal within the image of projecting the type B descent algebra to \(\mathcal{D}_n\). This viewpoint uncovered a left peak variant of \(\mathcal{P}_n\):

Proposition 2.4. [1, Sec. 6.3] The elements

\[ P_k^\circ = \sum_{\sigma \in S_n, \text{pk}(\sigma) = k} \sigma \]

for \(0 \leq k \leq \left\lfloor \frac{n}{2} \right\rfloor\) span the Eulerian left peak algebra \(\mathcal{P}_n^\circ\), a commutative subalgebra of \(\mathcal{D}_n\). Note that \(\dim(\mathcal{P}_n^\circ) = \left\lfloor \frac{n}{2} \right\rfloor + 1\).

Petersen [24] computed a complete set of primitive orthogonal idempotents of both \(\mathcal{P}_n\) and \(\mathcal{P}_n^\circ\), in terms of enriched \(P\)-partitions. Our re-computation in the present Theorem 5.3 is uncannily similar, despite being in the different language of noncommutative symmetric functions.

Both \(\mathcal{P}_n\) and \(\mathcal{P}_n^\circ\) are subalgebras of our new algebra \(\mathcal{W}_n^\pm\).

This idea of adding an initial 0 is also relevant in the case of runs. As mentioned in the introduction, this definition was used by Doyle and Rockmore [14].

Definition 2.5. With the convention \(\sigma_0 = 0\), a left run of a permutation \(\sigma \in S_n\) is a maximal monotone sequence of consecutive elements in \(\sigma_0, \ldots, \sigma_n\). We denote by \(\text{run}^\circ(\sigma)\) the number of left runs of \(\sigma\).

Note that if the first run of \(\sigma\) is ascending, then \(\text{run}^\circ(\sigma) = \text{run}(\sigma)\), and the first left run is obtained from the first run by adding the initial zero. If the first run is descending, then \(\text{run}^\circ(\sigma) = \text{run}(\sigma) + 1\), and the first left run is 0, \(\sigma_1\).

2.4 Noncommutative symmetric functions

To find and express the idempotents of the run algebras, it is useful to view the descent algebra from another perspective, that contains extra algebraic structure.

Let \(\text{Sym}\) denote the Hopf algebra of noncommutative symmetric functions, which is the direct sum of \(\text{Sym}_n\), its degree \(n\) homogeneous components (see [16] as a general reference on this subject). Its product \(\ast\) and coproduct \(\Delta\) are defined below. It will be convenient to also work in \(\hat{\text{Sym}}\), the completion, which allows infinite sums of the elements of \(\text{Sym}\), of unbounded degree.

As a vector space, we have the identification \(\text{Sym}_n = \mathcal{D}_n\). Under this identification, the image of \(S^i\) are the complete noncommutative symmetric functions, and the image of \(R_I\) are the ribbon noncommutative symmetric functions. We write \(S^i, R_I\) for these images also.

The product on \(\mathcal{D}_n\) is extended to \(\text{Sym}\) by the rule \(xy = 0\) if \(x \in \text{Sym}_m\), \(y \in \text{Sym}_n\), and \(m \neq n\). We call it the internal product of \(\text{Sym}\), to distinguish from the external product. However, it is to be noted that the usual internal product of noncommutative symmetric functions is taken in the opposite order (see [16]).

\(\text{Sym}\) also admits an external product \(\ast\), for which degree is additive: \(\text{Sym}_n \ast \text{Sym}_{n'} \subseteq \text{Sym}_{n+n'}\). In the complete basis, this is given by concatenation of compositions:

\[ S^{(i_1,\ldots,i_{\ell(I)})} \ast S^{(j_1,\ldots,j_{\ell(J)})} = S^{(i_1,\ldots,i_{\ell(I)},j_1,\ldots,j_{\ell(J)})}. \]
Hence, for any composition $I = (i_1, \ldots, i_r)$, we have $S^I = S_{i_1} \star \cdots \star S_{i_r}$, so **Sym** is a free algebra for the external product, generated by the $S_i$, the complete noncommutative symmetric functions indexed by compositions with a single part.

In the ribbon basis, the external product results in “near-concatenation”:

$$R_{(i_1, \ldots, i_{\ell(I)})} \star R_{(j_1, \ldots, j_{\ell(J)})} = R_{(i_1, \ldots, i_{\ell(I)}, j_1, \ldots, j_{\ell(J)})} + R_{(i_1, \ldots, i_{\ell(I)-1}, i_{\ell(I)}+j_1, j_2, \ldots, j_{\ell(J)})}.$$  

For example, $S^{(2,3)} \star S^{(5,1,1)} = S^{(2,3,5,1,1)}$ and $R^{(2,3)} \star R^{(5,1,1)} = R^{(2,3,5,1,1)} + R^{(2,8,1,1)}$. We write $F^{\star k}$ for powers under the external product, to distinguish from the internal product power $F^k$.

The two products are related by the splitting formula of [16, Prop. 5.2]; this involves a third algebraic operation, the coproduct. This is the (external) algebra homomorphism $\Delta : **Sym** \to **Sym** \otimes **Sym**$ with $\Delta(S_n) = \sum_{t=0}^n S_t \otimes S_{n-t}$. (The convention is that $S_0 = 1.$) It follows that $\sum_{n \geq 0} R_n$ and $\sum_{n \geq 0} R_{(1^n)}$ are grouplike — that is, they satisfy $\Delta(G) = G \otimes G$. It is a standard fact of Hopf algebras that (external) products of grouplike elements are also grouplike. For grouplike $G$, the splitting formula simplifies to:

$$G(F_1 \star \cdots \star F_k) = (GF_1) \star \cdots \star (GF_k).$$

This simplified version is the only case of the splitting formula that we will need.

**Remark 2.6.** Since we are interested in subalgebras of the descent algebra, it is natural to use a special symbol for the external product of (noncommutative) symmetric functions, the product without a special symbol meaning the internal product. However this differs from the usual notation.

### 2.5 Symmetric functions

Let **Sym** denote the algebra of symmetric functions and **Sym**$_n$ its degree $n$ homogeneous component. We follow the notation of [22] so that $h_\lambda$, $e_\lambda$, $p_\lambda$, $s_\lambda$ are respectively the homogeneous, elementary, power sum, and Schur symmetric functions associated with a partition $\lambda$. If $I = (i_1, \ldots, i_{\ell(I)})$ is a composition, there is a unique ribbon (i.e. a skew shape which is connected and contains no 2 $\times$ 2 square) whose row lengths from top to bottom in French notation are $i_1, \ldots, i_{\ell(I)}$, and the skew Schur function associated with it is denoted $r_I$. It is given by $r_I = \sum_{J \triangleright I} (-1)^{\ell(I)-\ell(J)} h_J$ where $h_J = \prod_{j} h_{j\downarrow}$ where $\downarrow$ runs through the parts of $J$. To be coherent with our notation on noncommutative symmetric functions, the usual product of **Sym** is denoted $\star$, whereas the internal product on **Sym**$_n$ has no particular symbol.

There is a well-known map $\Gamma : **Sym** \to **Sym**$, defined by the two equivalent formulas:

$$\Gamma(R_I) = r_I, \quad \Gamma(S_I) = h_I.$$  

In particular, we have:

$$\Gamma(S_n) = h_n, \quad \Gamma(R_{(1^n)}) = e_n.$$  

This map is an algebra morphism for both the internal and external product of symmetric functions:

$$\Gamma(xy) = \Gamma(x)\Gamma(y), \quad \Gamma(x \star y) = \Gamma(x) \star \Gamma(y).$$  

One fact about **Sym**$_n$ that will be particularly useful for us is that the rescaled power sums $\frac{1}{z_j^\lambda} p_\lambda$ form a basis of orthogonal idempotents (under the internal product). It follows that, if $\Lambda_1, \Lambda_2, \ldots, \Lambda_K$ are disjoint subsets of partitions of $n$, then $\sum_{\lambda \in \Lambda_k} \frac{1}{z_{\lambda, j}} p_{\lambda}$ form a coarser set of orthogonal idempotents. In fact, every subalgebra of **Sym**$_n$ has a basis of orthogonal idempotents of this form, and identifying the $\Lambda_k$ is particularly interesting if we view **Sym**$_n$ as the character ring of $\mathfrak{S}_n$ [28, Sec. 7.18]. (In this light, $\Gamma$ is the homomorphism of Solomon from the descent algebra of a finite Coxeter group to its character ring [27].) For example, the idempotents of $\Gamma(\mathfrak{S}_n)$, the symmetric function image of the Eulerian algebra, are $\sum_{\ell(\lambda) = k} \frac{1}{z_{\lambda, j}} p_{\lambda}$ [16, Sec. 5.3], corresponding to the indicator functions on permutations with $k$ cycles. By definition, $\sum_{\ell(I) = k} r_I$
is also a basis of $\Gamma(\mathcal{E}_n)$. So, writing $\chi_I$ for the character corresponding to $r_I$, this slickly recovers a result of Foulkes [17, Th. 3.1], [18]:

$$\left\{ \sum_{\ell(I)=k} \chi_I : 1 \leq k \leq n \right\}$$

gives a basis for the subspace of functions $\mathcal{S}_n \rightarrow \mathbb{R}$ depending only on the number of cycles. Applying this idea to our new commutative run algebras yields similar characters that depend only on the numbers of odd cycles and of even cycles, see Corollary 5.4.

### 3 Bijective proof for the existence of run algebras

Recall that $\text{run}(\sigma)$ is defined at the beginning of the introduction, and $\text{run}^o(\sigma)$ in Definition 2.5.

**Definition 3.1.** Let

$$\mathcal{W}_k^+: = \{ \sigma \in \mathcal{S}_n : \text{run}(\sigma) = k \text{ and the first run is ascending} \},$$

$$\mathcal{W}_k^- : = \{ \sigma \in \mathcal{S}_n : \text{run}(\sigma) = k \text{ and the first run is descending} \},$$

$$\mathcal{W}_k : = \{ \sigma \in \mathcal{S}_n : \text{run}(\sigma) = k \} = \mathcal{W}_k^+ \cup \mathcal{W}_k^-,$$

for $1 \leq k \leq n - 1$, and

$$\mathcal{W}_k^o : = \{ \sigma \in \mathcal{S}_n : \text{run}^o(\sigma) = k \} = \mathcal{W}_k^+ \cup \mathcal{W}_{k-1}^-$$

for $1 \leq k \leq n$. The given range for $k$ indicates when these sets are nonempty. Note that in the definition of $\mathcal{W}_k^o$ we need to specify that $\mathcal{W}_n^+ = \mathcal{W}_0^- = \emptyset$. And let

$$W_k^- : = \sum_{\sigma \in \mathcal{W}_k^-} \sigma, \quad W_k^+ : = \sum_{\sigma \in \mathcal{W}_k^+} \sigma, \quad W_k : = \sum_{\sigma \in \mathcal{W}_k} \sigma, \quad W_k^o : = \sum_{\sigma \in \mathcal{W}_k^o} \sigma.$$

Note that $W_k = W_k^- + W_k^+$ and $W_k^o = W_{k-1}^- + W_k^+$. Then we define subspaces of the descent algebra $\mathcal{D}_n$ as follows:

$$\mathcal{W}^\pm : = \text{Vect}(W_k^+, W_k^- : 1 \leq k \leq n - 1),$$

$$\mathcal{W} : = \text{Vect}(W_k : 1 \leq k \leq n - 1),$$

$$\mathcal{W}^o : = \text{Vect}(W_k^o : 1 \leq k \leq n),$$

$$\mathcal{C} : = \text{Vect}(W_{2k} : 1 \leq k \leq \lfloor \frac{n}{2} \rfloor) \oplus \text{Vect}(W_{2k-1}^+ \cup W_{2k-1}^- : 1 \leq k \leq \lfloor \frac{n}{2} \rfloor).$$

Note that in each definition, the given generators are linearly independent, since they are sums of permutations over disjoint nonempty subsets. It follows that:

$$\dim(\mathcal{W}^\pm) = 2n - 2, \quad \dim(\mathcal{W}) = n - 1, \quad \dim(\mathcal{W}^o) = n, \quad \dim(\mathcal{C}) = \lfloor \frac{3n-2}{2} \rfloor.$$

**Theorem 3.2.** The space $\mathcal{W}^\pm$ is a subalgebra of $\mathcal{D}_n$, and the spaces $\mathcal{W}$, $\mathcal{W}^o$, $\mathcal{C}$, $\mathcal{P}$ and $\mathcal{P}^o$ are subalgebras of $\mathcal{W}^\pm$.

Note that $\mathcal{W}$ and $\mathcal{W}^o$ are respectively the reduced turning algebra and the turning algebra of Doyle and Rockmore [14]. And $\mathcal{P}$ and $\mathcal{P}^o$ are the Eulerian peak and Eulerian left peak algebra, as described in Subsection 2.3.

The rest of this section contains the bijective proof. In Subsections 3.1 to 3.3, we prove the result for $\mathcal{W}^\pm$. Then, in Subsection 3.4, we show how the other parts of the theorem follow.

The beginning of the proof, in particular using the connectedness in the left weak order, essentially follows Atkinson’s proof of the existence of the descent algebra [4] (which is also in Tits [30, §6] although in a somewhat different language and very concise style).
3.1 Alternating runs and the left weak order

This subsection contains a preliminary result about the sets $M_j^+$ and $M_j^-$. Let $s_i$ denote the simple transposition $(i, i + 1) \in S_n$. Let us recall that the left weak order on $S_n$ is defined by the covering relations $\sigma \lessdot s_i \sigma$ if $i$ is to the left of $i + 1$ in $\sigma$, for all $\sigma \in S_n$ and $1 \leq i \leq n - 1$. It is known that descent classes are intervals for this order [5]. In particular, each descent class is a connected subset in $S_n$ (seen as an undirected graph whose edges are given by the cover relation of the left weak order).

Lemma 3.3. Let $I, J \subseteq [n - 1]$ with $I \neq J$. The descent classes $D_I$ and $D_J$ are connected to each other (in the sense that there are $u \in D_I, v \in D_J$ such that $u < v$ or $v > u$) if and only if one of the following conditions is true:

- $I \subseteq J$ and $\#I = \#J - 1$, or
- $J \subseteq I$ and $\#J = \#I - 1$.

Proof. We compare the descents sets of $\sigma$ and $s_i \sigma$. If $i$ and $i + 1$ are not adjacent in $\sigma$, Des($\sigma$) = Des($s_i \sigma$). Otherwise, either Des($\sigma$) = Des($s_i \sigma$) $\cup \{i\}$ or Des($s_i \sigma$) = Des($\sigma$) $\cup \{i\}$. It follows that if $D_I$ and $D_J$ are connected, $I$ and $J$ satisfy the given conditions.

As for the other implication, suppose $I$ and $J$ satisfy the given conditions, for example $I = J \cup \{i\}$. It is easy to find $\sigma \in D_I$ such that $\sigma_i = \sigma_{i + 1} + 1$. Then the two permutations $\sigma$ and $s_i \sigma$ in $D_I$ and $D_J$ show that $D_I$ and $D_J$ are connected.

Lemma 3.4. Each set $M_j^+$ or $M_j^-$ is connected in the left weak order.

Proof. By symmetry, we only need to consider the case of $M_j^+$. This set is a union of descent classes. Since each descent class is connected, it remains to show that these descent classes are connected to each other, using the previous lemma.

The descent classes included in $M_j^+$ are those indexed by subsets $X \subseteq \{1, \ldots, n - 1\}$ such that:

- $X$ is a union of $\lfloor j/2 \rfloor$ intervals and no less (i.e. the number of descending runs),
- $1 \notin X$ (since the elements in $M_j^+$ begin with an ascending run),
- $n - 1 \in X$ if and only if $j$ is even (since the first run is ascending, the last run is descending if and only if $j$ is even).

By adding or removing elements in these subsets as in the previous lemma, (and staying in the same class of subsets) we can reach a particular chosen subset, for example $\{2, 4, 6, \ldots, 2\lfloor j/2 \rfloor\}$ if $j$ is odd and $\{2, 4, 6, \ldots, 2\lfloor j/2 \rfloor - 1, n - 1\}$ if $j$ is even. This fact is rather straightforward so we omit the full formal proof. Connectedness easily follows.

3.2 The scheme of proof

To prove that $W^\pm$ is an algebra, we show $W_j^+ W_k^- \in W^\pm$. The other products, i.e. $W_j^+ W_k^+$, $W_j^- W_k^+$, and $W_j^- W_k^-$, can be done similarly (or more formally, one can use symmetry properties described in Subsection 3.4).

For each permutation $\sigma \in S_n$, let

$$C_{j,k}^\sigma = \{(\alpha, \beta) \in M_j^+ \times M_k^- : \alpha \beta = \sigma\}.$$

Then $C_{j,k}^\sigma$ is the coefficient of $\sigma$ in the product $W_j^+ W_k^-$. Our goal is to prove that $C_{j,k}^\sigma = c_{j,k}^\sigma$ if $\sigma, \tau$ are both in $M_j^+$ or both in $M_k^-$. We only consider the case where $\sigma$ and $\tau$ are neighbours in the left weak order, i.e., either $\sigma \lessdot \tau$ or $\tau \lessdot \sigma$. Indeed, using the connectedness shown in Lemma 3.4, this implies the general case. So we assume $s_i \sigma = \tau$ for some $i$. 

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Let us first consider the case where $i$ and $i + 1$ are not adjacent in $\sigma = \sigma_1 \ldots \sigma_n$ (and hence in $\tau = s_i \sigma$). It implies that $\sigma$ and $\tau$ are in the same descent class. But since $W^+_j W^+_k$ is in the descent algebra (as $W^+_j$ and $W^+_k$ both are), the coefficients of $\sigma$ and $\tau$ are equal, i.e. $c^\sigma_{j,k} = c^\tau_{j,k}$ as we wanted.

It remains to consider the case where $i$ and $i + 1$ are adjacent in $\sigma$ (and hence in $\tau$). We will give a bijection $\Phi : \mathcal{C}^\tau_{j,k} \rightarrow \mathcal{C}^\sigma_{j,k}$. This bijection is rather long to define as we need to consider many cases, and it is described in the next subsection. Note that $\sigma$ and $\tau$ have symmetric roles here, since we did not specify which of $\sigma < \tau$ or $\tau < \sigma$ is true. So by exchanging the role of $\sigma$ and $\tau$, the definition in the next subsection also describes another map $\Psi : \mathcal{C}^\tau_{j,k} \rightarrow \mathcal{C}^\sigma_{j,k}$. At each step of the definition, we can check that $\Psi$ is in the inverse map of $\Phi$, so that these maps are indeed bijections.

### 3.3 The bijection $\Phi$

We are now in the case where $i$ and $i + 1$ are adjacent in $\sigma$. So there is an integer $h$ such that $\tau = s_i \sigma = \sigma s_h$, and also $\sigma(\{h, h+1\}) = \tau(\{h, h+1\}) = \{i, i+1\}$.

Note that for any $u \in \mathfrak{S}_n$, $u$ and $u s_1$ cannot be both in $\mathcal{W}_m^+$ or both in $\mathcal{W}_m^-$. The same is true for $u$ and $u s_{n-1}$. So we have $2 \leq h \leq n - 2$.

#### 3.3.1 First case

In the first case, we assume that $s_i \alpha \in \mathcal{W}_j^+$. Thus we can define $\Phi((\alpha, \beta)) = (s_i \alpha, \beta)$, this pair being clearly in $\mathcal{C}^\tau_{j,k}$.

Note that the pair $(s_i \alpha, \beta) \in \mathcal{C}^\tau_{j,k}$ also leads to the first case when we apply the map $\Psi$, so that $\Psi \circ \Phi$ is the identity when applied on $(\alpha, \beta)$ falling in the first case.

From now on, assume $s_i \alpha \notin \mathcal{W}_j^+$. It follows that $s_i \alpha$ is not in the same descent class as $\alpha$, so $i$ and $i + 1$ are adjacent in $\alpha$. So there is an integer $g$ such that $s_i \alpha = \alpha s_g$. We also have $s_g \beta = \beta s_h$ since $\alpha s_g \beta = s_i \alpha \beta = \alpha \beta s_{h}$.

Also, $\alpha(\{g, g+1\}) = \{i, i+1\}$ and $\beta(\{h, h+1\}) = \{g, g+1\}$.

#### 3.3.2 Second case

In the second case, we assume that $s_g \beta \in \mathcal{W}_k^+$. We define $\Phi((\alpha, \beta)) = (\alpha, s_g \beta)$, which is in $\mathcal{C}^\tau_{j,k}$ (since $\alpha s_g \beta = s_i \alpha \beta = \alpha \beta s_{h}$).

Note that the pair $(\alpha, s_g \beta) \in \mathcal{C}^\tau_{j,k}$ also leads to this second case when we apply the map $\Psi$, so that $\Psi \circ \Phi$ is the identity when applied on $(\alpha, \beta)$ falling in the second case.

So from now on, assume that $s_g \beta \notin \mathcal{W}_k^+$. This is our last case.

#### 3.3.3 Third case

We will extensively use the following fact. The proof is clear upon inspection of a few cases.

**Lemma 3.5.** Let $u \in \mathfrak{S}_n$ and $a, b$ such that $s_a u = u s_b$ (so that $u(\{h, h+1\}) = \{a, a+1\}$). Then $u$ and $s_a u$ are both in $\mathcal{W}_m^+$ or both in $\mathcal{W}_m^-$ for some $m$, if and only if:

- $2 \leq b \leq n - 2$, and
- $u(b-1)$ and $u(b+1)$ are both $< a$ or both $> a + 1$.

To begin, let us apply this lemma to $\beta \in \mathcal{W}_k^+$ and $s_g \beta = \beta s_h \notin \mathcal{W}_k^+$. Since we already know $2 \leq h \leq n - 2$, we obtain:

- either $\beta(h-1) < g$ and $\beta(h+2) > g + 1$, \hspace{1cm} (A)
- or $\beta(h-1) > g + 1$ and $\beta(h+2) < g$. \hspace{1cm} (B)
Note that this implies \( 2 \leq g \leq n - 2 \).

Next, we apply the lemma to \( \alpha \in \mathcal{W}^+_j \) and \( s_i \alpha = \alpha s_g \notin \mathcal{W}^+_j \). Since we just got \( 2 \leq g \leq n - 2 \), it follows:

- either \( \alpha(g - 1) < i \) and \( \alpha(g + 2) > i + 1 \), (C)
- or \( \alpha(g - 1) > i + 1 \) and \( \alpha(g + 2) < i \). (D)

Next, we apply the lemma to \( \sigma \) and \( s_i \sigma = \sigma s_h \), which are both in \( \mathcal{W}^+_m \). Since \( 2 \leq h \leq n - 1 \), we get (writing \( \alpha \beta \) instead of \( \sigma \)):

- either \( \alpha(\beta(h - 1)) < i \) and \( \alpha(\beta(h + 2)) < i \), (E)
- or \( \alpha(\beta(h - 1)) > i + 1 \) and \( \alpha(\beta(h + 2)) > i + 1 \). (F)

To define \( \Phi \), we only need to distinguish between cases C or D, and E or F. Suppose first that we are in case C-E.

**Lemma 3.6.** In case C-E as above, there is a unique (word) factorization \( \alpha_1 \ldots \alpha_n = X_1X_2X_3X_4 \) where the four factors are nonempty and such that: \( X_2 = i, i + 1 \) or \( X_2 = i + 1, i \), \( X_3 \) contains only letters \( > i + 1 \), the first letter of \( X_4 \) is \( < i \).

**Proof.** To begin, \( X_2 \) is defined as the factor containing \( i \) and \( i + 1 \) (we have \( \alpha(\{g, g + 1\}) = \{i, i + 1\} \)). Since \( g \geq 2 \), we deduce that \( X_1 \) is nonempty. Since \( \alpha(g + 2) > i + 1 \), i.e. the first letter to the right of \( X_2 \) is \( > i + 1 \), we can define \( X_3 \) as the largest factor following \( X_2 \) and containing letters \( > i + 1 \).

Then, we have \( \alpha(\beta(h - 1)) < i \) and \( \alpha(\beta(h + 2)) < i \). Since at least one of \( \beta(h - 1) \) and \( \beta(h + 2) \) is \( > g + 1 \), it follows that there is at least one letter \( < i \) to the right of \( X_2 \). So \( X_4 \) is nonempty. \( \square \)

Then we define \( \Phi((\alpha, \beta)) = (\alpha', \beta') \) as follows:

- \( \alpha' = X_1X_3X_2X_4 \) where \( X_2 \) is \( X_2 \) in reversed order.
- \( \beta' \) is such that \( \beta'(h) = \beta(h) + |X_3| \), \( \beta'(h + 1) = \beta(h + 1) + |X_3| \). if \( \alpha(\beta(u)) \) appears in \( X_3 \), then \( \beta'(u) = \beta(u) - 2 \), otherwise (i.e. \( \alpha(\beta(v)) \) appears in \( X_1 \) or \( X_4 \)) then \( \beta'(u) = \beta(u) \). Here \( |X_3| \) is the length of \( X_3 \).

**Lemma 3.7.** We have \((\alpha', \beta') \in C^*_{j,k} \).

**Proof.** Since the last letter of \( X_1 \) (i.e. \( \alpha(g - 1) \)) and the first of \( X_4 \) are both \( < i \), and \( X_3 \) contains only letters \( > i + 1 \), we easily get that \( \alpha' \in \mathcal{W}^+_{j} \) (knowing \( \alpha \in \mathcal{W}^+_{j} \)).

Among the two letters \( \alpha(\beta(h - 1)) \) and \( \alpha(\beta(h + 2)) \), one appears in \( X_1 \) and the other in \( X_4 \). One can deduce that four letters \( \beta'(h - 1), \ldots, \beta'(h + 2) \) are in the same relative order as \( \beta(h - 1), \ldots, \beta(h + 2) \). Then, suppose we are in the case \( \beta'(u) = \beta(u) - 2 \), i.e. \( \alpha(\beta(u)) \) appears in \( X_3 \). Let \( v = u \pm 1 \), then \( \alpha(\beta(v)) \) can appear in \( X_1, X_3, \) or \( X_4 \). In each case, we check that \( \beta'(u) \) and \( \beta'(v) \) are in the same relative order as \( \beta(u) \) and \( \beta(v) \). So \( \beta' \) is in the same descent class as \( \beta \) and in particular \( \beta' \in \mathcal{W}^+_{j} \).

By distinguishing which of the factors \( X_1, \ldots, X_4 \) contains \( \alpha(\beta(u)) \), from the definition of \( \beta' \) we can check that \( \alpha'(\beta'(u)) = s_i(\alpha(\beta(u))) \). So \( \alpha' \beta' = s_i \alpha \beta \). \( \square \)

Let \( g' = g + |X_3| \). We have \( s_i \alpha' = \alpha s_{g'} \) and \( s_g \beta' = \beta s_h \) by definition of \( \alpha' \) and \( \beta' \). So \( (\alpha', \beta') \) falls in the third case when we apply \( \Psi \). Moreover:

- \( \alpha'(g' - 1) > i + 1 \) (since this number is the last letter of \( X_3 \) ), so \( (\alpha', \beta') \) falls in case D.
- \( \alpha'(\beta'(h - 1)) = \alpha(\beta(h - 1)) < i \) (since \( \alpha' \beta' = s_i \alpha \beta \) ), so \( (\alpha', \beta') \) falls in case E.

So \( (\alpha', \beta') \) falls in case D-E. Consequently, there is only one way to define \( \Phi \) in case D-E in order to get that \( \Psi \Phi \) is the identity. Namely, if \( (\alpha, \beta) \) falls in case D-E, we factor \( \alpha = X_1X_2X_3X_4 \) where \( X_3 \) is \( i, i + 1 \) or \( i + 1, i \), \( X_2 \) contains only letters \( > i + 1 \), the last letter of \( X_1 \) is \( < i \). Once again the factorization exists and is unique. Then we define \( \Phi((\alpha, \beta)) = (\alpha', \beta') \) as follows:
3.4 The case of the other subalgebras

Knowing that \( W^\pm \) is an algebra, we can finish the proof of Theorem 3.2.

**Proposition 3.8.** \( W^\circ \) is a subalgebra of \( W^\pm \).

**Proof.** For each permutation \( \sigma \), we define:

\[
\mathcal{D}_j^\sigma = \{ (\alpha, \beta) \in \mathcal{M}_j^\sigma \times \mathcal{M}_k^\sigma : \alpha \beta = \sigma \},
\]

and \( d_{j,k}^\sigma = \#\mathcal{D}_j^\sigma \). If \( \sigma \in \mathcal{M}_m^+ \) or \( \sigma \in \mathcal{M}_m^- \), then \( d_{j,k}^\sigma \) is the coefficient of \( W_m^+ \) or \( W_m^- \), respectively, in \( W_j^+ W_k^- \). We will show that for each \( m \) such that \( 2 \leq m \leq n-1 \), we have \( d_{j,k}^\sigma = d_{j,k}^\tau \) for some well-chosen \( \sigma \in \mathcal{M}_m^+ \) and \( \tau \in \mathcal{M}_m^- \). Indeed this implies \( W_j^+ W_k^- \in W^\circ \).

It is easy to find an element \( \sigma \in \mathcal{M}_m^+ \) such that \( s_1 = n-1 \) and \( s_2 = n \). We deduce that \( \tau = s_{n-1,1} = s_{n,1} \). Thus, it remains only to find a bijection between \( \mathcal{D}_j^\sigma \) and \( \mathcal{D}_j^\tau \).

This bijection \( \Delta \) is defined as follows. Let \( (\alpha, \beta) \in \mathcal{D}_{j,k}^\sigma \). In the first case, if \( s_{n-1,1} \in \mathcal{M}_j^+ \), we set \( \Delta(\alpha, \beta) = (s_{n-1,1}, \alpha) \).

Otherwise, it easily follows \( s_{n-1,1} = \alpha s_{n-1} \). In the second case, if \( s_{n-1,1} \in \mathcal{M}_j^- \), we set \( \Delta(\alpha, \beta) = (\alpha, s_{n-1,1}) \).

There is in fact no other case to consider: if we are not in the first case, we have necessarily \( s_{n-1,1} \in \mathcal{M}_j^- \). Otherwise, we would have \( s_{n-1,1} = \beta s_{n-1} \), and it would follow that \( s_{n-1,1} \sigma = \sigma s_{n-1} \) (this is a contradiction to \( s_{n-1,1} \sigma = s_{s_{n-1}} \)).

As for the other subalgebras, we don’t need to do a similar bijection, as it is more convenient to use some symmetry properties. Let \( \omega := W_j^- = n \ldots 21 \). We clearly have \( \text{run}(\omega \sigma) = \text{run}(\sigma \omega) = \text{run}(\sigma) \) for any \( \sigma \in \mathcal{S}_n \). Moreover, \( 1 \in \text{Des}(\sigma) \) iff \( 1 \notin \text{Des}(\omega \sigma) \), so that:

\[
\omega W_k^+ = W_k^-, \quad \omega W_k^- = W_k^+.
\]

Note that if \( \sigma \in \mathcal{S}_n \) has an odd number of alternating runs, the first and last runs are of similar nature (both ascending or both descending), but if \( \sigma \) has an even number of runs, they are of different nature (one is ascending, the other descending). It is then easy to read the alternating runs of \( \sigma \omega = \sigma_n \ldots \sigma_1 \) from those of \( \sigma = \sigma_1 \ldots \sigma_n \). It follows:

\[
W_k^+ \omega = \begin{cases} W_k^- & \text{if } k \text{ is odd,} \\
W_k^+ & \text{if } k \text{ is even,} \end{cases} \quad W_k^- \omega = \begin{cases} W_k^+ & \text{if } k \text{ is odd,} \\
W_k^- & \text{if } k \text{ is even,} \end{cases}
\]

(1)

Note that this implies

\[
W_j^- W_k^+ = \omega W_j^+ W_k^- \]

\[
W_j^+ W_k^- = \begin{cases} W_j^+ W_k^- & \text{if } j \text{ is even,} \\
\omega W_j^+ W_k^- & \text{if } j \text{ is odd,} \end{cases}
\]

\[
W_j^- W_k^- = \begin{cases} W_j^+ W_k^+ & \text{if } j \text{ is odd,} \\
\omega W_j^+ W_k^+ & \text{if } j \text{ is even.} \end{cases}
\]

As a consequence, to show that \( W^\pm \) is an algebra it suffices to show that \( W_j^+ W_k^+ \in W^\pm \), as was mentioned earlier.
Proposition 3.9. \( \mathcal{W} \) is a subalgebra of \( \mathcal{W}^\pm \).

Proof. From the elementary properties of \( \omega = W_1^- \) (and \( W_1^+ \), the unit element), we have \( W_1 W_k^+ = W_1^+ W_k^- = W_k \). It follows that \( \mathcal{W} \) is the right ideal \( W_1 \mathcal{W}^\pm \) and \emph{a fortiori} a subalgebra. \( \square \)

Remark 3.10. The previous proposition should be understood in the sense of nonunital algebras, since \( \mathcal{W} \) does not contain contain the unit of \( \mathcal{W}^\pm \). Still, \( \mathcal{W} \) has a unit element as an abstract algebra, namely \( \frac{1}{2}W_1 \) (at the condition of allowing rational coefficients).

Proposition 3.11. \( \mathcal{C} \) is a subalgebra of \( \mathcal{W}^\pm \).

Proof. From the elementary properties of \( \omega = W_1^- \), we have:

\[
\omega W_k^+ \omega = \begin{cases} W_k^+ & \text{if } k \text{ is odd}, \\ W_k^- & \text{if } k \text{ is even}, \end{cases} \quad \omega W_k^- \omega = \begin{cases} W_k^- & \text{if } k \text{ is odd}, \\ W_k^+ & \text{if } k \text{ is even}. \end{cases}
\]

Using that \( x \mapsto \omega x \omega \) is a linear symmetry, it follows that

\[
\{ x \in \mathcal{W}^\pm : \omega x \omega = x \} = \text{Vect}(W_{2k+1}^+, W_{2k+1}^-, W_{2k}) = \mathcal{C}.
\]

If \( x, y \in \mathcal{C} \), we have \( \omega xy \omega = \omega x^2y \omega = xy \), so \( \mathcal{C} \) is closed under product. \( \square \)

We turn to the case of peak algebras.

Lemma 3.12. We have:

\[
P_k = W_{2k}^+ + W_{2k+1}^- + W_{2k+1}^+ + W_{2k+2}^- \\
P_k^c = W_{2k-1}^- + W_{2k}^- + W_{2k}^+ + W_{2k+1}^+.
\]

Proof. For the first equality, consider a permutation \( \sigma \) with \( \text{pk}(\sigma) = k \). It has at least 2\( k \) runs, since each peak follows an ascending run, and precedes a descending run. Besides these 2\( k \) runs, whose first is ascending, there is possibly an additional descending run at the beginning, and possibly an additional ascending run at the end. The four possibilities give the four terms in the sum.

As for the second equality, consider a permutation \( \text{pk}^c(\sigma) = k \). It has at least 2\( k - 1 \) runs, since now the first peak might not follow an ascending run (if it is equal to 1). Besides these 2\( k - 1 \) runs, whose first is descending, there is possibly an additional ascending run at the beginning, and possibly an additional ascending run at the end. Once again, the four possibilities give the four terms in the sum. \( \square \)

Proposition 3.13. \( \mathcal{P} \) and \( \mathcal{P}^c \) are subalgebras of \( \mathcal{W}^\pm \).

Proof. The previous lemma shows that \( \mathcal{P} \) and \( \mathcal{P}^c \) are subspaces of \( \mathcal{W}^\pm \), so it remains to show that they are closed under product.

We begin with the case of \( \mathcal{P}^c \). From the previous lemma, we have \( P_k^c = \omega P_k^c \omega = W_{2k}^- + W_{2k+1}^+ + W_{2k+1}^- + W_{2k+2}^+ \). Now let \( x \in \mathcal{P}^c \), then it is in \( \mathcal{P}^c \) iff the coefficients of \( W_{2k}^- \) and \( W_{2k+1}^+ \) are the same for all \( k \). This is also equivalent to the equality of the coefficients of \( W_{2k}^+ \) and \( W_{2k}^- \) in \( x \), i.e. to the condition \( x \in \mathcal{C} \). So we have \( \mathcal{P}^c = \mathcal{W}^\circ \cap \mathcal{C} \), and this is a subalgebra as an intersection of subalgebras.

In the case of \( \mathcal{P} \), we first note that it is closed under product iff \( \omega \mathcal{P} \omega \) is also closed under product. We have:

\[
\omega P_k \omega = W_{2k}^- + W_{2k+1}^- + W_{2k+1}^+ + W_{2k+2}^+ = W_{2k+1}^+ + W_{2k+2}^+.
\]

so \( \omega \mathcal{P} \omega \subseteq \mathcal{W}^\circ \). Now let \( x \in \mathcal{W}^\circ \), then it is in \( \omega \mathcal{P} \omega \) iff the coefficients of \( W_{2k+1}^+ \) and \( W_{2k+2}^+ \) are the same for all \( k \). This is also equivalent to the equality of the coefficients of \( W_{2k+1}^+ \) and \( W_{2k+1}^- \) in \( x \), and also to the condition \( x \omega = x \). So we have \( \omega \mathcal{P} \omega = \{ x \in \mathcal{W}^\circ : x \omega = x \} \), which is clearly closed under product. \( \square \)
4 Algebraic proof for the existence of run algebras

This section gives a second proof, using noncommutative symmetric functions, that grouping permutations by the number of runs gives an algebra. This will require working in all degrees $n$ at the same time, so from now on add a second index to all previous quantities indicating the degree, if these quantities involve one degree only. For example, we now write $W_n$ for the commutative run algebra in degree $n$, and $W_{k,n}$ for its basis.

First define the following elements in $\text{Sym}$:

$$V_1^+ := \sum_{i \geq 0} R_i = \sum_{n \geq 0} W_{1,n}^+, \quad V_1^- := \sum_{i \geq 0} R_{(1^i)} = \sum_{n \geq 0} W_{1,n}^-.$$  

The intuition is that $V_1^+$ is an ascending run and $V_1^-$ is a descending run. To obtain multiple runs, one concatenates ascending runs and descending runs alternately. Since external product roughly expresses concatenation, it is no surprise that we define

$$V_{2k}^+ := (V_1^+ \ast V_1^-)^* k, \quad V_{2k}^- := (V_1^- \ast V_1^+)^* k,$$

and

$$V_k := V_k^+ + V_k^-.$$

Write $V_{k,n}^+$ for the degree $n$ part of $V_k^+$, and similarly for $V_{k,n}^-$, $V_{k,n}$, so

$$V_k^+ = \sum_{n \geq 0} V_{k,n}^+, \quad V_k^- = \sum_{n \geq 0} V_{k,n}^-, \quad V_k = \sum_{n \geq 0} V_{k,n}.$$

Note that $V_{k,n}^+, V_{k,n}^-$ are non-zero even when $k > n$.

Recall from Section 2.4 that $V_1^+, V_1^-$ are grouplike. Being a product of grouplike elements, $V_k^+, V_k^-$ are also grouplike. Thus the simplified splitting formula in Section 2.4 holds, and this allows a straightforward proof that the $V$s are “multiplicative” (under the internal product) in the following way:

**Proposition 4.1.** We have:

$$V_k^+ V_l^+ = V_{kl}^+, \quad V_k^- V_l^+ = V_k^-.$$

If $k$ is even, then

$$V_k^+ V_l^- = V_{kl}^+, \quad V_k^- V_l^- = V_{kl}^-.$$

If $k$ is odd, then

$$V_k^+ V_l^- = V_{kl}^-, \quad V_k^- V_l^- = V_{kl}^+.$$  

**Proof.** The splitting formula asserts that, for any $F_1, \ldots, F_l$ in $\hat{\text{Sym}}$, it holds that

$$V_k^+(F_1 \ast \cdots \ast F_l) = (V_k^+ F_1) \ast \cdots \ast (V_k^+ F_l),$$

and similarly for $V_k^-$. So in particular:

$$V_k^+ V_l^+ = (V_k^+ V_l^+) \ast (V_k^- V_l^-) \ast \cdots \ast (V_k^+ V_l^+).$$

where the $\pm$ is $+ \text{ or } -$ depending on the parity of $l$. For even $k$, once we know that $V_k^+ V_l^+ = V_{k}^+ V_1^- = V_k^+$ (the case $l = 1$), this simplifies to

$$V_k^+ V_l^+ = V_k^+ V_k^+ \ast \cdots \ast V_k^+ = V_k^+.$$
For odd $k$, once we know that $V_{k_1}^+ V_{k_1}^+ = V_{k_1}^+$ and $V_{k_1}^+ V_{k_1}^- = V_{k_1}^-$ (the case $l = 1$), this simplifies to
\[
V_{k_1}^+ V_{k_1}^+ = V_{k_1}^+ \star V_{k_1}^- \star \cdots \star V_{k_1}^+ = V_{k_1^+}^+.
\]

The other products are treated similarly, and we are left with the case $l = 1$.

Recall $V_{1}^+ = \sum_i R_i$ and $R_i$ is the identity for the internal product, so $V_{k_1}^+ V_{1}^+ = V_{k_1}^+$, and $V_{k_1}^- V_{1}^+ = V_{k_1}^-$. Now $V_{1}^- = \sum_{i \geq 0} R_i$, and $R_i$ is the maximal permutation $\omega_i = i, i+1, \ldots, 3, 2, 1$. Internal product to the right by $\omega_i$ sends a permutation $\sigma$ to its reversal $\sigma_1, \ldots, \sigma_1$, which exchanges the ascents and descents and reverses their order. Given a composition $I$, let $I$ denote the result after this exchanging and reversing, e.g. $(1,3,2) \mapsto (2,1,2,1) \mapsto (1,2,1,2)$. Then $R_i V_{1}^- = R_i$, and
\[
(R_I \star R_J) V_{1}^- = (R_{i_1, \ldots, i_{l(I)}, j_1, \ldots, j_{l(J)}}) + R_{i_1, \ldots, i_{l(I)}, -1, i_{l(I)} + j_1, 2, \ldots, j_{l(J)}} + R_{i_1, \ldots, i_{l(I)}, -1, i_{l(I)} + j_1, 2, \ldots, j_{l(J)}} + \cdots
\]
\[
= R_{j_1, \ldots, j_{l(J)}} \star R_I = (R_J V_{1}^-) \star \cdots \star (R_{j_1, \ldots, j_{l(J)}}).
\]

By linearity, it follows that, for any $G_1, G_2 \in \text{Sym}$, we have $(G_1 \star G_2)V_{1}^- = (G_2 V_{1}^-) \star (G_1 V_{1}^-)$, and similarly $(G_1 \star \cdots \star G_l)V_{1}^- = (G_1 V_{1}^-) \star \cdots \star (G_1 V_{1}^-)$ Also we have $V_{1}^- V_{1}^- = V_{1}^+$, since reversing a permutation twice does not change it. As a result, if $k$ is even, then
\[
V_{k}^+ V_{1}^- = (V_{k}^+ V_{1}^-) \star (V_{1}^+ V_{1}^-) \star \cdots \star (V_{1}^+ V_{1}^-) = V_{k}^+ \star V_{1}^- \star \cdots \star V_{1}^- = V_{k}^+
\]
\[
V_{k}^- V_{1}^- = (V_{k}^+ V_{1}^-) \star (V_{1}^- V_{1}^-) \star \cdots \star (V_{1}^- V_{1}^-) = V_{1}^- \star V_{1}^- \star \cdots \star V_{1}^- = V_{k}^-
\]

And if $k$ is odd, then
\[
V_{k}^+ V_{1}^- = (V_{k}^+ V_{1}^-) \star (V_{1}^- V_{1}^-) \star \cdots \star (V_{1}^+ V_{1}^-) = V_{1}^- \star V_{1}^- \star \cdots \star V_{1}^- = V_{k}^-
\]
\[
V_{k}^- V_{1}^- = (V_{k}^- V_{1}^-) \star (V_{1}^- V_{1}^-) \star \cdots \star (V_{1}^- V_{1}^-) = V_{1}^+ \star V_{1}^- \star \cdots \star V_{1}^- = V_{k}^+
\]

(Note that the sign rule here is the same as in Equation (1). This will be explained by the relation between $V$s and $W$s given below.)

Now it is clear that $\text{Vect}(V_{k,n}^+, V_{k,n}^-, k \in \mathbb{N})$ is closed under the internal product, and it is easy to identify subspaces, such as $\text{Vect}(V_{k,n}^+, V_{k,n}^- : k \in \mathbb{N})$, which form subalgebras. It remains to equate these to the run algebras $W_n^k$ and $W_n$, and see how the $V$s give them new bases. We will do this by relating $V_{2k}$ and $V_{2k+1}$ to the Eulerian peak and left peak algebras respectively, via a triangular change of basis.

**Proposition 4.2.** For all $k$, we have $V_{2k,n}^- \in \mathcal{P}_n$, the Eulerian peak algebra. Moreover, if $k \leq \frac{n+1}{2}$, then
\[
V_{2k,n}^- = 2^{2k-1} P_{2k-1,n} + \sum_{l < k} a_{k,l,n} P_{l,n}
\]
for some constants $a_{k,l,n}$. Hence $\{V_{2k,n}^- : 1 \leq k \leq \lfloor \frac{n+1}{2} \rfloor \}$ is a basis for $\mathcal{P}_n$.

**Proof.** For the first assertion, it suffices to show that, for each composition $I$, the coefficient of $R_I$ in $V_{2k,n}$ depends only on the number of peaks in any permutation with descent composition $I$ - let $\sigma_I$ denote such a permutation.

First observe that $V_{2k}^+ = (V_2^+)^k$ by definition, and that $V_{2k}^- = 1 + 2 \sum R_I$ over all compositions $I$ where $\sigma_I$ has no peaks.

Recall that
\[
R_{(i_1, \ldots, i_{l(I)})} \star R_{(j_1, \ldots, j_{l(J)})} = R_{(i_1, \ldots, i_{l(I)}, j_1, \ldots, j_{l(J)})} + R_{(i_1, \ldots, i_{l(I)}, -1, i_{l(I)} + j_1, 2, \ldots, j_{l(J)})} + R_{(i_1, \ldots, i_{l(I)}, -1, i_{l(I)} + j_1, 2, \ldots, j_{l(J)})} + \cdots
\]

So the coefficient of $R_I$ in any external product $F \star G$ of noncommutative symmetric functions is the sum, over all $J := (j_1, \ldots, j_{l(J)})$, $J' := (j'_1, \ldots, j'_{l(J')})$ with $I = (j_1, \ldots, j_{l(J)}, j'_1, \ldots, j'_{l(J')})$
or \( I = (j_1, \ldots, j_{\ell(I)-1}, j_{\ell(I)} + j_1', j_2', \ldots, j_{\ell(I')}'), \) of the products of the coefficient of \( R_I \) in \( F \) with the coefficient of \( R_{I'} \) in \( G \). Hence the coefficient of \( R_I \) in \( V_{2k,n}^- \) is the weighted number of ways to “cut” \( \sigma_I \) into \( k \) pieces, possibly trivial, so that each piece contains no peak. The weight is \( 2^{k'} \), where \( k' \) is the number of non-trivial pieces (because of the coefficient 2 in \( V_{2}^{-} = 1 + 2 \sum R_I \)).

Since each piece must be peakless, there must be a cut immediately to the left or immediately to the right of any peak; other than this the positions of cuts are unconstrained. These pair of positions, for any set of peaks, are disjoint, so the number of ways to cut \( \sigma_I \) into \( k' \) non-trivial peakless pieces depends only on the number of peaks in \( \sigma_I \).

If \( \sigma_I \) has more than \( k - 1 \) peaks, then \( \sigma_I \) cannot be cut into \( k \) peakless pieces, so \( R_I \) does not appear in \( V_{2k}^- \). If \( \sigma_I \) has exactly \( k - 1 \) peaks, then the ways to cut \( \sigma_I \) into \( k \) peakless pieces are precisely when there is one cut either immediately to the left or immediately to the right of each peak. There are \( 2^{k-1} \) such ways, and the weight of this cut is \( 2^k \), since no piece is trivial. Hence the coefficient of \( P_{k-1,n} \) in \( V_{2k,n}^- \) is \( 2^{2k-1} \).

Next, we apply a similar argument to \( V_{2k+1,n}^+ \).

**Proposition 4.3.** For all \( k \), we have \( V_{2k+1,n}^+ \in \mathcal{P}_n^\circ \), the Eulerian left peak algebra. Moreover, if \( k \leq \frac{n}{2} \), then

\[
V_{2k+1,n}^+ = 2^{2k} P_{k,n}^\circ + \sum_{l<k} a_{k,l,n}^\circ P_{l,n}^\circ
\]

for some constants \( a_{k,l,n}^\circ \). Hence \( \{ V_{2k+1,n}^+ : 0 \leq k \leq \lfloor \frac{n}{2} \rfloor \} \) is a basis for \( \mathcal{P}_n^\circ \).

**Proof.** By the same logic as above, the coefficient of \( R_I \) in \( V_{2k+1,n}^+ \) is the weighted number of ways to “cut” \( \sigma_I \) into \( k+1 \) pieces, possibly trivial, so that the leftmost piece has no descents, and the \( k \) other pieces each contain no peak. The weight is \( 2^{k'} \), where \( k' \) is the number of non-trivial pieces among the \( k \) peakless pieces.

Since each piece must be peakless, there must be a cut immediately to the left or immediately to the right of all peaks. Additionally, if \( \sigma_I \) has a descent in position 1, then the first cut must be immediately before or after position 1, because the first piece must not contain descents. Hence the two conditions may be summarised as requiring a cut immediately to the left or immediately to the right of all left peaks.

As before, these positions, for any set of left peaks, are disjoint, so the number of ways to cut into \( \sigma_I \) a descentless first piece and \( k' \) further non-trivial peakless pieces depends only on the number of left peaks in \( \sigma_I \).

If \( \sigma_I \) has more than \( k \) left peaks, then \( \sigma_I \) cannot be cut into a descentless first piece and \( k \) further peakless pieces, so \( R_I \) does not appear in \( V_{2k+1}^+ \). If \( \sigma_I \) has exactly \( k \) left peaks, then the ways to cut \( \sigma_I \) into a descentless first piece and \( k \) further peakless pieces are precisely when there is one cut either immediately to the left or immediately to the right of each left peak. There are \( 2^k \) such ways, and the weight of this cut is \( 2^k \), since none of the peakless pieces are trivial. Hence the coefficient of \( P_{k,n}^\circ \) in \( V_{2k+1,n}^+ \) is \( 2^{2k} \).

From the above two propositions, and Equations (2) and (3) relating \( P_{k,n} \) and \( P_{k,n}^\circ \) to \( W_{k,n}^- \), \( W_{k,n}^+ \), we see that:

\[
V_{2k,n}^- = 2^{2k-1} W_{2k,n}^- + \sum_{l<k} a_{k,l,n} W_{2l+1,n}^+ + a_{k,l,n} W_{2l,n}^+ + a_{k,l-1,n} W_{2l-1,n}^+;
\]

\[
V_{2k+1,n}^+ = 2^{2k} W_{2k+1,n}^+ + \sum_{l<k} a_{k,l,n}^\circ W_{2l,n}^+ + a_{k,l-1,n}^\circ W_{2l-1,n}^+ + a_{k,l-1,n}^\circ W_{2l-1,n}^-.
\]
By exchanging ascending and descending runs, it is also true that
\[ V^+_{2k,n} = 2^{2k-1}W^+_{2k,n} + \sum_{l<k} a_{k,l,n}W_{2l+1,n} + a_{k,l,n}W_{2l,n} + a_{k,l-1,n}W^+_{2l-1,n}; \]
\[ V^-_{2k+1,n} = 2^{2k}W^-_{2k+1,n} + \sum_{l<k} a_{k,l,n}W_{2l,n} + a_{k,l-1,n}W^-_{2l-1,n} + a_{k,l,n}W^+_{2l-1,n}. \]

Also, because \( P_k^o = W_{2k}^o + W_{2k+1}^o \), and
\[ P_k = W_{2k}^+ + W_{2k+1}^+ + W_{2k+2}^o; \]
\[ W_{2k+1}^o + W_{2k+2}^o = W_{2k}^+ + W_{2k+1}^+ + W_{2k+2}^o, \]
we have
\[ V^+_{2k+1,n} = 2^{2k}W_{2k+1}^o + 2^{2k}W_{2k}^o + \sum_{l<k} a_{k,l,n}(W_{2l+1,n}^o + W_{2l,n}^o); \]
\[ V^+_{2k,n} = 2^{2k-1}W_{2k}^o + 2^{2k-1}W_{2k-1}^o + \sum_{l<k} a_{k,l-1,n}(W_{2l,n}^o + W_{2l-1,n}^o). \]

Combining all this with the multiplicativity of the \( V_k \)’s in Proposition 4.1, we can conclude:

**Theorem 4.4.** For each \( n \),
\[ \text{Vect}(V^+_{k,n}, V^-_{k,n} : k \in \mathbb{N}) = \text{Vect}(V^+_{k,n}, V^-_{k,n} : 1 \leq k < n) = W_n^\pm \]
is an algebra under the internal product. Five commutative subalgebras of \( W_n^\pm \) are:
\[
\begin{align*}
\text{Vect}(V_{k,n}^- : k \in \mathbb{N}) &= \text{Vect}(V_{k,n}^- : 1 \leq k < n) = W_n^o, \\
\text{Vect}(V_{k,n}^+ : k \in \mathbb{N}) &= \text{Vect}(V_{k,n}^+ : 1 \leq k \leq n) = W_n^o, \\
\text{Vect}(V^-_{2k,n} : k \in \mathbb{N}) &= \text{Vect}(V^-_{2k,n} : 1 \leq 2k \leq n + 1) = \mathcal{P}_n, \\
\text{Vect}(V^+_{2k+1,n} : k \in \mathbb{N}) &= \text{Vect}(V^+_{2k+1,n} : 1 \leq 2k + 1 \leq n + 1) = \mathcal{P}_n^o,
\end{align*}
\]
and
\[ \text{Vect}(V^+_{2k+1,n}, V^-_{2k+1,n}, V_{2k,n} : k \in \mathbb{N}) = \\
\text{Vect}(V^+_{2k+1,n}, V^-_{2k+1,n}, V_{2l,n} : 1 \leq 2k + 1, 2l < n) = \mathcal{C}_n. \]

Furthermore, \( \mathcal{P}_n^o \) is central in \( W_n^\pm \).

**Remark 4.5.** The quantities \( V^+_{k,n}, V^-_{k,n} \) previously appeared in [24], as order polynomials of enriched \( P \)-partitions. The translation between his notation and ours is
\[
\begin{align*}
\rho(x) &= V^-_{2x,n}; \\
\bar{\rho}(x) &= V^+_{2x,n}; \\
\rho^{(l)}(x) &= V^+_{2x+1,n}; \\
\rho^{(c)}(x) &= V^-_{2x+1,n}.
\end{align*}
\]

Our Proposition 4.1, the multiplication rule, is his Theorems 3.1, 3.3 and 3.5.

## 5 Computation of the orthogonal idempotents

In this section, we compute a complete set of primitive idempotents for \( W_n^\pm \) and for its five commutative subalgebras in Theorem 4.4.
5.1 Orthogonal idempotents of the commutative subalgebras

The starting point is the orthogonal idempotents of the Eulerian peak and left peak algebras. These were computed in [24, 25], but we rederive them here so this paper is self-contained. The argument here mirrors the approach of Loday (see [16, Sec. 5.3]) for the idempotents of the Eulerian (descent) algebra. The key is the following observation:

**Lemma 5.1.** For some multiplicatively-closed subset \( I \subseteq \mathbb{N} \), suppose \( \{ X_i : i \in I \} \) generate a subalgebra \( \mathcal{A} \) of \( \widehat{\text{Sym}} \) with \( X_i X_j = X_{ij} \) (under the internal product). Assume also that there are elements \( J_{ik} \) in this subalgebra such that, for each \( i \), we have \( X_i = \sum_{k \geq 0} i^k J_{ik} \) (as an identity of formal power series within \( \widehat{\text{Sym}} \)). Then the non-zero \( J_{ik} \) form a basis of orthogonal idempotents for \( \mathcal{A} \).

**Proof.** For all \( i, j \in I \), we have

\[
\sum_{k} (ij)^k J_{ik} = X_{ij} = \sum_{r, s} i^r J_r J_s.
\]

Equating coefficients of \((ij)^k\) then shows that \( J_r J_s = 0 \) if \( r \neq s \), and \( J_{ik}^2 = J_{ik} \). \( \square \)

Recall from Theorem 4.4 that the Eulerian peak algebra is generated by \( \{ V_{i,n}^- : i \) even \} and the Eulerian left peak algebra by \( \{ V_{i,n}^+ : i \) odd \}. By Proposition 4.1, these generating sets satisfy the multiplicative condition of Lemma 5.1. Thus, to calculate the orthogonal idempotents, it suffices to find \( I_{k,n}, J_{k,n}^\ddagger \) such that \( V_{2i,n}^- = \sum_{k \geq 0} (2i)^k I_{k,n}^- \) and \( V_{2i+1,n}^+ = \sum_{k \geq 0} (2i + 1)^k J_{k,n}^\ddagger \). Such expressions come from the formal exponential and logarithm operations in \( \widehat{\text{Sym}} \), defined via their familiar power series expansions:

\[
\log_*(1 + F) = F - \frac{1}{2} F^2 + \frac{1}{3} F^3 - \ldots,
\]

\[
\exp_* F = 1 + F + \frac{1}{2!} F^2 + \frac{1}{3!} F^3 + \ldots,
\]

for \( F \in \widehat{\text{Sym}} \) with no term in degree 0. It can be checked that \( \exp_* (F + G) = (\exp_* F) \ast (\exp_* G) \) whenever \( F \) and \( G \) commute. Also, \( (1 + F)^k = \exp_* (k \log_*(1 + F)) \) for all positive integers \( k \) (and all \( F \in \widehat{\text{Sym}} \) with no term in degree 0), and this can be used to define \((1 + F)^\ddagger \) when \( k \) is not a positive integer.

Now we have

\[
V_{2i}^- = (V_2^-)^i = \exp_* (i \log_* V_2^-) = \sum_{k \geq 0} \frac{1}{k!} (i \log_* V_2^-)^\ddagger \]

\[
= \sum_{k \geq 0} (2i)^k \left( \frac{1}{2k!} (\log_* V_2^-)^\ddagger \right),
\]

and

\[
V_{2i+1}^+ = V_1^\ddagger \ast (V_2^-)^\ddagger (-\frac{i}{2}) (V_2^-)^\ddagger (i + \frac{1}{2})
\]

\[
= V_1^\ddagger \ast (V_2^-)^\ddagger (-\frac{i}{2}) \ast \exp_* \left( \left( i + \frac{1}{2} \right) \log_* V_2^- \right)
\]

\[
= \sum_{k \geq 0} (2i + 1)^k \left( \frac{1}{2k!} V_1^\ddagger \ast (V_2^-)^\ddagger (-\frac{i}{2}) \ast (\log_* V_2^-)^\ddagger \right).
\]
This motivates the definitions:

\[ I_i^- := \frac{1}{2} \log_2 V_i^-, \quad I_i^+ := \frac{1}{2} \log_2 V_i^+, \]
\[ I_k^- := \frac{1}{k} I_k^{-*k}, \quad I_k^+ := \frac{1}{k} I_k^{+*k}, \]
\[ J_0^+ := V_1^+ \ast (V_2^-)^{(-\frac{1}{2})}, \quad J_0^- := V_1^- \ast (V_2^+)^{(-\frac{1}{2})}, \]
\[ J_k^+ := J_0^+ \ast I_k^-, \quad J_k^- := J_0^- \ast I_k^+. \]

Also, make the convention \( I_0^- = I_0^+ = 1 \). As with the \( V_i \), write \( I_{k,n}^+, I_{k,n}^-, J_{k,n}^+, \) and \( J_{k,n}^- \) for the degree \( n \) part of \( I_k^+, I_k^-, J_k^+, \) and \( J_k^- \). The above calculations show that \( I_{k,n}^-, J_{k,n}^+ \) are orthogonal idempotents for the Eulerian peak and left peak algebras respectively. However, we will see that \( I_{k,n}^- \) is not orthogonal to \( J_{k,n}^+ \). A first attempt to rectify this might be to calculate products such as \( I_{k,n}^- J_{k,n}^+ \), and guess simple linear combinations of these idempotents that are orthogonal. These product calculations are considerably easier in the symmetric functions - that is, we calculate the images of \( I_{k,n}^-, I_{k,n}^+, J_{k,n}^+, J_{k,n}^- \) under the homomorphism \( \Gamma : \text{Sym} \to \text{Sym} \), then find simple linear combinations whose images have the form \( \sum_{\lambda \in \Lambda_i} \frac{1}{z_{\lambda}} p_{\lambda} \) over disjoint subsets \( \Lambda_i \) of partitions of \( n \) (see the last paragraph of Subsection 2.5).

**Remark 5.2.** Note that \( I_{k,n}^- \) is not a system of orthogonal idempotents. Indeed, the proof below will show that the symmetric function images \( \Gamma(I_{k,n}^-) \) are not of the form \( \sum_{\lambda \in \Lambda_i} \frac{1}{z_{\lambda}} p_{\lambda} \). The problem is that \( \{V_{2i+1}^-\} \) is not closed under the internal product, so the analogue of Equation (4) cannot be applied in Proposition 5.1.

**Theorem 5.3.** With notation as above:

i) A basis of orthogonal idempotents of \( W_n \) is given by

\[ \frac{1}{2} (I_{k,n}^+ + I_{k,n}^-), \quad 1 \leq k \leq n \quad \text{and} \quad k \equiv n \mod 2 \]

and

\[ \frac{1}{2} (J_{l,n}^+ + J_{l,n}^- - I_{l,n}^+ - I_{l,n}^-), \quad 0 \leq l \leq n - 4 \quad \text{and} \quad l \equiv n \mod 2. \]

Their images under \( \Gamma : \text{Sym} \to \text{Sym} \) are

\[ \sum_{\lambda \vdash n, \ell_\omega(\lambda) = k, \ell_\omega(\lambda) = 0} \frac{1}{z_{\lambda}} p_{\lambda}, \quad 1 \leq k \leq n \quad \text{and} \quad k \equiv n \mod 2 \]

and

\[ \sum_{\lambda \vdash n, \ell_\omega(\lambda) = l, \ell_\omega(\lambda) > 0 \text{ even}} \frac{1}{z_{\lambda}} p_{\lambda}, \quad 0 \leq l \leq n - 4 \quad \text{and} \quad l \equiv n \mod 2. \]

ii) A basis of orthogonal idempotents of \( W_n^o \) is given by

\[ I_{k,n}^+, \quad 1 \leq k \leq n \quad \text{and} \quad k \equiv n \mod 2 \]

and

\[ \frac{1}{2} (J_{l,n}^+ - I_{l,n}^+), \quad 0 \leq l \leq n - 2 \quad \text{and} \quad l \equiv n \mod 2. \]

Their images under \( \Gamma : \text{Sym} \to \text{Sym} \) are

\[ \sum_{\lambda \vdash n, \ell_\omega(\lambda) = k, \ell_\omega(\lambda) = 0} \frac{1}{z_{\lambda}} p_{\lambda}, \quad 1 \leq k \leq n \quad \text{and} \quad k \equiv n \mod 2 \]
and
\[ \sum_{\lambda \vdash n} \frac{1}{z_\lambda^l} p_\lambda, \quad 0 \leq l \leq n - 2 \text{ and } l \equiv n \mod 2. \]

iii) A basis of orthogonal idempotents of \( C_n \) is given by
\[ \frac{1}{2} (I_{k,n}^+ + I_{k,n}^-), \quad 1 \leq k \leq n \text{ and } k \equiv n \mod 2 \]
and
\[ \frac{1}{2} (J_{l,n}^+ + J_{l,n}^- - I_{l,n}^+ - I_{l,n}^-), \quad 0 \leq l \leq n - 4 \text{ and } l \equiv n \mod 2 \]
and
\[ \frac{1}{2} (J_{m,n}^+ - J_{m,n}^-), \quad 0 \leq m \leq n - 2 \text{ and } m \equiv n \mod 2. \]

Their images under \( \Gamma : \text{Sym} \to \text{Sym} \) are
\[ \sum_{\lambda \vdash n} \frac{1}{z_\lambda^k} p_\lambda, \quad 1 \leq k \leq n \text{ and } k \equiv n \mod 2 \]
and
\[ \sum_{\lambda \vdash n} \frac{1}{z_\lambda^l} p_\lambda, \quad 0 \leq l \leq n - 4 \text{ and } l \equiv n \mod 2 \]
and
\[ \sum_{\lambda \vdash n} \frac{1}{z_\lambda^m} p_\lambda, \quad 0 \leq m \leq n - 2 \text{ and } m \equiv n \mod 2. \]

iv) A basis of orthogonal idempotents of \( \mathcal{P}_n \) is given by
\[ I_{k,n}^-, \quad 1 \leq k \leq n \text{ and } k \equiv n \mod 2. \]

Their images under \( \Gamma : \text{Sym} \to \text{Sym} \) are
\[ \sum_{\lambda \vdash n} \frac{1}{z_\lambda^k} p_\lambda, \quad 1 \leq k \leq n \text{ and } k \equiv n \mod 2. \]

v) A basis of orthogonal idempotents of \( \mathcal{P}_n^\circ \) is given by
\[ J_{k,n}^+, \quad 0 \leq k \leq n \text{ and } k \equiv n \mod 2. \]

Their images under \( \Gamma : \text{Sym} \to \text{Sym} \) are
\[ \sum_{\lambda \vdash n} \frac{1}{z_\lambda^k} p_\lambda, \quad 0 \leq k \leq n \text{ and } k \equiv n \mod 2. \]

**Proof.** Observe that each set of claimed images under \( \Gamma \) have cardinality equal to the dimension of the corresponding subalgebra. Thus, if these images are correct, \( \Gamma : \text{Sym} \to \text{Sym} \) must restrict to an algebra isomorphism on each of these subalgebras. Hence the claimed sets are orthogonal and idempotent if and only if their images under \( \Gamma \) are orthogonal and idempotent.

Each claimed symmetric function image is a sum of \( \frac{p_\lambda}{z_\lambda^l} \), the orthogonal idempotents of \( \text{Sym} \), hence their sums are also idempotent. Furthermore, for each subalgebra, no partition \( \lambda \) appears in more than one sum, so the sums are orthogonal.
So it suffices to check that the claimed idempotents are indeed in the correct subalgebras, and have the claimed images under $\Gamma$. Note that $I_{-1}^-$ is a series in $V_{-2}^-$, and $I_{1}^+$ is a series in $V_{2}^+$, so
\[
I_{k,n}^- \in \text{Vect}(V_{2k,n}) = \mathcal{P}_n,
I_{k,n}^+ \in \text{Vect}(V_{2k,n}),
J_{k,n}^+ \in \text{Vect}(V_{2k+1,n}) = \mathcal{P}_n^o,
J_{k,n}^- \in \text{Vect}(V_{2k+1,n}).
\]
By symmetry in the definitions of $I_{k}^-, J_{k}^-, I_{k}^+, J_{k}^+$, it is clear that
\[
I_{k,n}^+ + J_{k,n}^- \in \text{Vect}(V_{2k,n}),
J_{k,n}^+ + J_{k,n}^- \in \text{Vect}(V_{2k+1,n}).
\]
Thus all claimed idempotents are in the correct subalgebras.

To calculate the symmetric function images, first recall that
\[
\Gamma(V_{-1}^+) = \sum_{n \geq 0} h_n = \exp \left( \sum_{i \geq 1} \frac{p_i}{i} \right),
\]
\[
\Gamma(V_{1}^-) = \sum_{n \geq 0} e_n = \exp \left( \sum_{i \geq 1} \frac{(-1)^{i-1} p_i}{i} \right).
\]
Hence
\[
\Gamma(I_{-1}^-) = \frac{1}{2} \Gamma(\log_*(V_{1}^- * V_{1}^+))
= \frac{1}{2} \left( \log_*(\Gamma(V_{1}^-)) + \log_*(\Gamma(V_{1}^+)) \right)
= \frac{1}{2} \left( \sum_{i \geq 1} \frac{p_i}{i} + \frac{(-1)^{i-1} p_i}{i} \right)
= \sum_{i \text{ odd}} \frac{p_i}{i},
\]
and similarly
\[
\Gamma(I_{1}^+) = \frac{1}{2} \Gamma(\log_*(V_{1}^+ * V_{1}^-))
= \frac{1}{2} \left( \log_*(\Gamma(V_{1}^+)) + \log_*(\Gamma(V_{1}^-)) \right)
= \sum_{i \text{ odd}} \frac{p_i}{i}.
\]
Consequently,
\[
\Gamma(I_{-1}^-) = \Gamma(I_{1}^+) = \frac{1}{k!} \left( \sum_{i \text{ odd}} \frac{p_i}{i} \right)^* k
= \sum_{\ell, \chi(\lambda) = k, \ell_0(\lambda) = 0} \frac{1}{z_{\lambda}} p_{\lambda}.
\]
Also,

\[
\Gamma(J_0^+) = \Gamma(V_1^+) * \Gamma(V_1^-)^{(-\frac{1}{2})} * \Gamma(V_1^+)^{(-\frac{1}{2})} \\
= \exp\left( \frac{1}{2} \left( \sum_{i \geq 1} \frac{p_i}{i} - \frac{(-1)^{i-1}p_i}{i} \right) \right) \\
= \sum_{\ell_e(\lambda) = 0 \atop \ell_o(\lambda) = 0} \frac{1}{z^\lambda} p_\lambda,
\]

and

\[
\Gamma(J_0^-) = \Gamma(V_1^-) * \Gamma(V_1^+)^{(-\frac{1}{2})} * \Gamma(V_1^-)^{(-\frac{1}{2})} \\
= \exp\left( \frac{1}{2} \left( \sum_{i \geq 1} \frac{p_i}{i} + \frac{(-1)^{i-1}p_i}{i} \right) \right) \\
= \sum_{i > 0 \text{ even}} \frac{1}{z^\lambda} p_\lambda.
\]

So

\[
\Gamma(J_k^+) = \Gamma(J_0^+) * \Gamma(J_k^+) \\
= \left( \sum_{\ell_e(\lambda) = 0} \frac{1}{z^\lambda} p_\lambda \right) * \left( \sum_{\ell_o(\lambda) = k, \ell_o(\lambda) = 0} \frac{1}{z^\lambda} p_\lambda \right) \\
= \sum_{\ell_o(\lambda) = k} \frac{1}{z^\lambda} p_\lambda,
\]

and

\[
\frac{1}{2} \Gamma(J_k^+ + J_k^-) = \frac{1}{2} \Gamma(J_0^+ + J_0^-) * \Gamma(J_k^-) \\
= \left( \sum_{\ell_o(\lambda) = 0, \ell_e(\lambda) \text{ even}} \frac{1}{z^\lambda} p_\lambda \right) * \left( \sum_{\ell_o(\lambda) = k, \ell_o(\lambda) = 0} \frac{1}{z^\lambda} p_\lambda \right) \\
= \sum_{\ell_o(\lambda) = k, \ell_e(\lambda) \text{ even}} \frac{1}{z^\lambda} p_\lambda,
\]

and

\[
\frac{1}{2} \Gamma(J_k^+ - J_k^-) = \frac{1}{2} \Gamma(J_0^+ - J_0^-) * \Gamma(J_k^-) \\
= \left( \sum_{\ell_o(\lambda) = 0, \ell_o(\lambda) \text{ odd}} \frac{1}{z^\lambda} p_\lambda \right) * \left( \sum_{\ell_o(\lambda) = k, \ell_o(\lambda) = 0} \frac{1}{z^\lambda} p_\lambda \right) \\
= \sum_{\ell_o(\lambda) = k, \ell_e(\lambda) \text{ odd}} \frac{1}{z^\lambda} p_\lambda.
\]
As remarked at the end of Section 2.5, the identification of the commutative images of the idempotents leads to analogues of the characters of Foulkes \([17]\), that only depend on certain features of the cycle type:

**Corollary 5.4.** Write \(\chi_I\) for the symmetric group character corresponding to the ribbon skew shape for \(I\). Let \(\text{run}(I), \text{pk}(I)\) etc. denote \(\text{run}(\sigma), \text{pk}(\sigma)\) for any permutation \(\sigma\) with \(\text{Des}(\sigma) = \text{Des}(I)\). Then

i) The set of characters

\[
\left\{ \sum_{\text{run}(I) = k} \chi_I : 1 \leq k < n \right\}
\]

is a basis for functions \(S_n \rightarrow \mathbb{R}\) depending only on the number of odd cycles and whether there are even cycles, and are zero on permutations with an odd number of even cycles.

ii) The set of characters

\[
\left\{ \sum_{\text{run}^\circ(I) = k} \chi_I : 1 \leq k \leq n \right\}
\]

is a basis for functions \(S_n \rightarrow \mathbb{R}\) depending only on the number of odd cycles and whether there are even cycles.

iii) The set of characters

\[
\left\{ \sum_{\text{run}(I) = 2l} \chi_I : 1 \leq 2l < n \right\} \cup \left\{ \sum_{\text{run}(I) = 2k+1} \chi_I : 1 \leq 2k + 1 < n \right\} \cup \left\{ \sum_{\text{run}(I) = 2k+1} \chi_I : 1 \leq 2k + 1 < n \right\}
\]

is a basis for functions \(S_n \rightarrow \mathbb{R}\) depending only on the number of odd cycles and whether the number of even cycles is zero, even positive, or odd.

iv) The set of characters

\[
\left\{ \sum_{\text{pk}(I) = k} \chi_I : 1 \leq 2k \leq n + 1 \right\}
\]

is a basis for functions \(S_n \rightarrow \mathbb{R}\) depending only on the number of odd cycles and are zero on permutations with an odd number of even cycles.

v) The set of characters

\[
\left\{ \sum_{\text{pk}^\circ(I) = k} \chi_I : 1 \leq 2k + 1 \leq n + 1 \right\}
\]

is a basis for functions \(S_n \rightarrow \mathbb{R}\) depending only on the number of odd cycles.

**Proof.** If \(\{\sum_{I \in \mathcal{J}_k} R_I\}\) span a commutative subalgebra of the descent algebra (for some disjoint sets \(\mathcal{J}_k\) of compositions), and the symmetric function image of this subalgebra has a basis of orthogonal idempotents of the form \(\{\sum_{\lambda \in \Lambda_k} z_{\lambda I}\}\), then \(\sum_{I \in \mathcal{J}_k} \chi_I\) is a basis for functions \(S_n \rightarrow \mathbb{R}\) that are constant on permutations with cycle type within each \(\Lambda_k\), and are zero on permutations with cycle type not in any \(\Lambda_k\). \(\square\)
5.2 Orthogonal idempotents for the noncommutative run algebra \( W_n^\pm \)

We now show that the idempotents of \( C_n \) constructed in Theorem 5.3 are in fact a complete set of primitive orthogonal idempotents for \( W_n^\pm \).

**Theorem 5.5.** A complete set of primitive orthogonal idempotents for \( W_n^\pm \) is given by

\[
\frac{1}{2}(I_{k,n}^+ + I_{k,n}^-) \quad 1 \leq k \leq n \text{ and } k \equiv n \mod 2
\]

and

\[
\frac{1}{2}(I_{l,n}^+ + J_{l,n}^- - I_{l,n}^- - J_{l,n}^+) \quad 0 \leq l \leq n - 4 \text{ and } l \equiv n \mod 2
\]

and

\[
\frac{1}{2}(J_{m,n}^+ - J_{m,n}^-) \quad 0 \leq m \leq n - 2 \text{ and } m \equiv n \mod 2.
\]

**Proof.** The key is to show that \( C_n \) is a complement to \( K_n := \ker \Gamma \cap W_n^\pm \). As noted in the previous section, \( \Gamma \) restricted to \( C_n \) is an isomorphism, so \( C_n \) and \( K_n \) have trivial intersection. Since \( \dim C_n = n - 1 + \left\lfloor \frac{n}{2} \right\rfloor \), it must be that \( \dim K_n \leq \left\lceil \frac{n}{2} \right\rceil - 1 \). Now \( W_{2k,n} = \omega W_{2k,n} \omega \) for \( 1 \leq k \leq \left\lfloor \frac{n}{2} \right\rfloor - 1 \), so \( W_{2k,n} - W_{2k,n}^- \in K_n \), and these elements are linearly independent, so \( \dim K_n = \left\lceil \frac{n}{2} \right\rceil - 1 \), and \( W_n^\pm = C_n \oplus K_n \).

By [26, Cor. 2.2], the Jacobson radical of any subalgebra \( A \) of \( \text{Sym}_n \) (under the internal product) is equal to \( \ker \Gamma \cap A \). Hence \( K_n \) is the Jacobson radical of \( W_n^\pm \), so any complete set of primitive orthogonal idempotents for the complement \( C_n \) is a complete set of primitive orthogonal idempotents for \( W_n^\pm \). \[\square\]

**References**


L. Carlitz: The number of permutations with a given number of sequences. Fibonacci Quart. 18(4) (1980), 347–352.


