Petrie symmetric functions

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Abstract. For any positive integer k and nonnegative integer m, we consider the symmetric function $G(k,m)$ defined as the sum of all monomials of degree m that involve only exponents smaller than k. We call $G(k,m)$ a *Petrie symmetric function* in honor of Flinders Petrie, as the coefficients in its expansion in the Schur basis are determinants of Petrie matrices (and thus belong to $\{0,1,-1\}$ by a classical result of Gordon and Wilkinson). More generally, we prove a Pieri-like rule for expanding a product of the form $G(k,m) \cdot s_\mu$ in the Schur basis whenever μ is a partition; all coefficients in this expansion belong to $\{0,1,-1\}$. We also show that $G(k,1), G(k,2), G(k,3), \ldots$ form an algebraically independent generating set for the symmetric functions when $1-k$ is invertible in the base ring, and we prove a conjecture of Liu and Polo about the expansion of $G(k,2k-1)$ in the Schur basis.

Keywords: symmetric functions, Schur functions, Schur polynomials, combinatorial Hopf algebras, Petrie matrices, Pieri rules, Murnaghan–Nakayama rule.

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Contents

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Considered as a ring, the *symmetric functions* (which is short for "formal power series in countably many indeterminates $x_1, x_2, x_3, \ldots$ that are of bounded degree and fixed under permutations of the indeterminates") are hardly a remarkable object: By a classical result essentially known to Gauss, they form a polynomial ring in countably many indeterminates. The true theory of symmetric functions is rather the study of specific *families* of symmetric functions, often defined by combinatorial formulas (e.g., as multivariate generating functions) but interacting deeply with many other fields of mathematics. Classical families are, for example, the *monomial symmetric functions* m_λ, the *complete homogeneous symmetric functions* h_n, the *power-sum symmetric functions* p_n, and the *Schur functions* s_λ. Some of these families – such as the monomial symmetric functions m_λ and the Schur functions s_λ – form bases of the ring of symmetric functions (as a module over the base ring).

In this paper, we introduce a new family $(G(k,m))_{k\geq 1;\ m\geq 0}$ of symmetric functions, which we call the *Petrie symmetric functions* in honor of Flinders Petrie. For any integers $k \geq 1$ and $m \geq 0$, we define $G(k,m)$ as the sum of all monomials of degree m (in $x_1, x_2, x_3, \ldots$) that involve only exponents smaller than k. When $G(k,m)$ is expanded in the Schur basis (i.e., as a linear combination of Schur functions s_λ), all coefficients belong to $\{0, 1, -1\}$ by a classical result of Gordon and Wilkinson, as they are determinants of so-called *Petrie matrices* (whence our name for $G(k,m)$). We give an explicit combinatorial description for the coefficients as well. More generally, we prove a Pieri-like rule for expanding a product of the form $G(k,m) \cdot s_\mu$ in the Schur basis whenever μ is a partition; all coefficients in this expansion again belong to $\{0, 1, -1\}$ (although we have no explicit combinatorial rule for them). We show some further properties of $G(k,m)$ and prove that if k is a fixed positive integer such that $1-k$ is invertible in the base ring, then $G(k,1), G(k,2), G(k,3), \ldots$ form an algebraically independent generating set for the symmetric functions. We prove a conjecture of Liu and Polo in [LiuPol19, Remark 1.4.5] about the expansion of $G(k, 2k-1)$ in the Schur basis.

This paper begins with Section 1, in which we introduce the notions and notations that the paper will rely on. (Further notations will occasionally be introduced as the need arises.) The rest of the paper consists of two essentially independent parts. The first part comprises Section 2, in which we define the Petrie symmetric functions $G(k,m)$ (and the related power series $G(k)$) and state several of their properties, and Section 3, in which we prove said properties. The second part is Section 4, which is devoted to proving the conjecture of Liu and Polo.[1] A final Section 5 adds a few comments and formulates a conjecture.

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[1] This proof is independent of the first part of the paper, except that it uses the very simple Proposition 2.3 **(c)**.

Remarks

1. A short exposition of the main results of this paper (without proofs), along with an additional question motivated by it, can be found in [Grinbe20a].

2. While finishing this work, I have become aware of three independent discoveries of the Petrie symmetric functions $G(k, m)$:

(a) In [DotWal92, §3.3], Stephen Doty and Grant Walker define a *modular complete symmetric function* h'_d, which is precisely our Petrie symmetric function $G(k, m)$ up to a renaming of variables (namely, their m and d correspond to our k and m). Some of our results appear in their work: Our Theorem 2.22 is (a slight generalization of) [DotWal92, Corollary 3.9]; our Theorem 2.29 is (part of) [DotWal92, Proposition 3.15] restated in the language of Hopf algebras. The h'_d are studied further in Walker's follow-up paper [Walker94], some of whose results mirror ours again (in particular, the maps ψ^p and ψ_p from [Walker94] are our $\mathbf{f}_p$ and $\mathbf{v}_p$).

(b) The preprint [FuMei20] by Houshan Fu and Zhousheng Mei introduces the Petrie symmetric functions $G(k, m)$ and refers to them as *truncated homogeneous symmetric functions* $h_m^{[k-1]}$. Some results below are also independently obtained in [FuMei20]. In particular, Theorem 2.9 is a formula in [FuMei20, §2], and Theorem 2.15 is equivalent to [FuMei20, Proposition 2.9]. The particular case of Theorem 2.22 when $\mathbf{k} = \mathbb{Q}$ is part of [FuMei20, Theorem 2.7].

(c) The paper [BaAhBe18] by Bazeniar, Ahmia and Belbachir introduces the symmetric functions $G(k, m)$ as well, or rather their evaluations $(G(k, m))(x_1, x_2, \ldots, x_n)$ at finitely many variables; it denotes them by $E_m^{(k-1)}(n) = E_m^{(k-1)}(x_1, x_2, \ldots, x_n)$. Ahmia and Merca continue the study of these $E_m^{(k-1)}(x_1, x_2, \ldots, x_n)$ in [AhmMer20]. Our Theorem 2.21 is equivalent to the second formula in [AhmMer20, Theorem 3.3] (although we are using infinitely many variables).

3. The Petrie symmetric functions have been added to Per Alexandersson's collection of symmetric functions at `https://www.math.upenn.edu/~peal/polynomials/petrie.htm` .

Remark on alternative versions

This paper also has a detailed version [Grinbe20b], which includes some proofs that have been omitted from the present version (mostly basic properties of symmetric functions).

1. Notations

We will use the following notations (most of which are also used in [GriRei20, §2.1]):

- We let $\mathbb{N} = \{0, 1, 2, \ldots\}$.
- We fix a commutative ring $\mathbf{k}$; we will use this $\mathbf{k}$ as the base ring in what follows.
- A *weak composition* means an infinite sequence of nonnegative integers that contains only finitely many nonzero entries (i.e., a sequence $(\alpha_1, \alpha_2, \alpha_3, \ldots) \in \mathbb{N}^\infty$ such that all but finitely many $i \in \{1, 2, 3, \ldots\}$ satisfy $\alpha_i = 0$).
- We let WC denote the set of all weak compositions.
- For any weak composition α and any positive integer i, we let α_i denote the i-th entry of α (so that $\alpha = (\alpha_1, \alpha_2, \alpha_3, \ldots)$). More generally, we use this notation whenever α is an infinite sequence of any kind of objects.
- The *size* $|\alpha|$ of a weak composition α is defined to be $\alpha_1 + \alpha_2 + \alpha_3 + \cdots \in \mathbb{N}$.
- A *partition* means a weak composition whose entries weakly decrease (i.e., a weak composition α satisfying $\alpha_1 \geq \alpha_2 \geq \alpha_3 \geq \cdots$).
- If $n \in \mathbb{Z}$, then a *partition of* n means a partition α having size n (that is, satisfying $|\alpha| = n$).
- We let Par denote the set of all partitions. For each $n \in \mathbb{Z}$, we let Par_n denote the set of all partitions of n.
- We will sometimes omit trailing zeroes from partitions: i.e., a partition $\lambda = (\lambda_1, \lambda_2, \lambda_3, \ldots)$ will be identified with the k-tuple $(\lambda_1, \lambda_2, \ldots, \lambda_k)$ whenever $k \in \mathbb{N}$ satisfies $\lambda_{k+1} = \lambda_{k+2} = \lambda_{k+3} = \cdots = 0$. For example, $(3, 2, 1, 0, 0, 0, \ldots) = (3, 2, 1) = (3, 2, 1, 0)$.
- The partition $(0, 0, 0, \ldots) = ()$ is called the *empty partition* and denoted by $\varnothing$.
- A *part* of a partition λ means a nonzero entry of λ. For example, the parts of the partition $(3, 1, 1) = (3, 1, 1, 0, 0, 0, \ldots)$ are $3, 1, 1$.
- We will use the notation 1^k for "$\underbrace{1, 1, \ldots, 1}_{k \text{ times}}$" in partitions. (For example, $\left(2, 1^4\right) = (2, 1, 1, 1, 1)$. This notation is a particular case of the more general notation m^k for "$\underbrace{m, m, \ldots, m}_{k \text{ times}}$" in partitions, used, e.g., in [GriRei20, Definition 2.2.1].)
- We let Λ denote the ring of symmetric functions in infinitely many variables $x_1, x_2, x_3, \ldots$ over $\mathbf{k}$. This is a subring of the ring $\mathbf{k}[[x_1, x_2, x_3, \ldots]]$ of formal power series. To be more specific, Λ consists of all power series in $\mathbf{k}[[x_1, x_2, x_3, \ldots]]$ that are symmetric (i.e., invariant under permutations of the variables) and of bounded degree (see [GriRei20, §2.1] for the precise meaning of this).

- A *monomial* shall mean a formal expression of the form $x_1^{\alpha_1} x_2^{\alpha_2} x_3^{\alpha_3} \cdots$ with $\alpha \in \mathrm{WC}$. Formal power series are formal infinite $\mathbf{k}$-linear combinations of such monomials.

- For any weak composition α, we let $\mathbf{x}^\alpha$ denote the monomial $x_1^{\alpha_1} x_2^{\alpha_2} x_3^{\alpha_3} \cdots$.

- The *degree* of a monomial $\mathbf{x}^\alpha$ is defined to be $|\alpha|$.

- A formal power series is said to be *homogeneous of degree n* (for some $n \in \mathbb{N}$) if all monomials appearing in it (with nonzero coefficient) have degree n. In particular, the power series 0 is homogeneous of any degree.

- If $f \in \mathbf{k}[[x_1, x_2, x_3, \ldots]]$ is a power series, then there is a unique family $(f_i)_{i \in \mathbb{N}} = (f_0, f_1, f_2, \ldots)$ of formal power series $f_i \in \mathbf{k}[[x_1, x_2, x_3, \ldots]]$ such that each f_i is homogeneous of degree i and such that $f = \sum\limits_{i \in \mathbb{N}} f_i$. This family $(f_i)_{i \in \mathbb{N}}$ is called the *homogeneous decomposition* of f, and its entry f_i (for any given $i \in \mathbb{N}$) is called the *i-th degree homogeneous component* of f.

- The $\mathbf{k}$-algebra Λ is graded: i.e., any symmetric function f can be uniquely written as a sum $\sum\limits_{i \in \mathbb{N}} f_i$, where each f_i is a homogeneous symmetric function of degree i, and where all but finitely many $i \in \mathbb{N}$ satisfy $f_i = 0$.

We shall use the symmetric functions $m_\lambda, h_n, e_n, p_n, s_\lambda$ in Λ as defined in [GriRei20, Sections 2.1 and 2.2]. Let us briefly recall how they are defined:

- For any partition λ, we define the *monomial symmetric function $m_\lambda \in \Lambda$* by[2]

$$m_\lambda = \sum \mathbf{x}^\alpha,$$

  where the sum ranges over all weak compositions $\alpha \in \mathrm{WC}$ that can be obtained from λ by permuting entries[3]. For example,

$$m_{(2,2,1)} = \sum_{i<j<k} x_i^2 x_j^2 x_k + \sum_{i<j<k} x_i^2 x_j x_k^2 + \sum_{i<j<k} x_i x_j^2 x_k^2.$$

  The family $(m_\lambda)_{\lambda \in \mathrm{Par}}$ (that is, the family of the symmetric functions m_λ as λ ranges over all partitions) is a basis of the $\mathbf{k}$-module Λ.

- For each $n \in \mathbb{Z}$, we define the *complete homogeneous symmetric function $h_n \in \Lambda$* by

$$h_n = \sum_{i_1 \leq i_2 \leq \cdots \leq i_n} x_{i_1} x_{i_2} \cdots x_{i_n} = \sum_{\substack{\alpha \in \mathrm{WC}; \\ |\alpha| = n}} \mathbf{x}^\alpha = \sum_{\lambda \in \mathrm{Par}_n} m_\lambda.$$

[2] This definition of m_λ is not the same as the one given in [GriRei20, Definition 2.1.3]; but it is easily seen to be equivalent to the latter (i.e., it defines the same m_λ). See [Grinbe20b] for the details of the proof.

[3] Here, we understand λ to be an infinite sequence, not a finite tuple, so the entries being permuted include infinitely many 0's.

Thus, $h_0 = 1$ and $h_n = 0$ for all $n < 0$.

We know (e.g., from [GriRei20, Proposition 2.4.1]) that the family $(h_n)_{n\geq 1} = (h_1, h_2, h_3, \ldots)$ is algebraically independent and generates Λ as a $\mathbf{k}$-algebra. In other words, Λ is freely generated by $h_1, h_2, h_3, \ldots$ as a commutative $\mathbf{k}$-algebra.

- For each $n \in \mathbb{Z}$, we define the *elementary symmetric function* $e_n \in \Lambda$ by

$$e_n = \sum_{i_1 < i_2 < \cdots < i_n} x_{i_1} x_{i_2} \cdots x_{i_n} = \sum_{\substack{\alpha \in \mathrm{WC} \cap \{0,1\}^\infty; \\ |\alpha| = n}} \mathbf{x}^\alpha.$$

Thus, $e_0 = 1$ and $e_n = 0$ for all $n < 0$. If $n \geq 0$, then $e_n = m_{(1^n)}$, where, as we have agreed above, the notation (1^n) stands for the n-tuple $(1, 1, \ldots, 1)$.

- For each positive integer n, we define the *power-sum symmetric function* $p_n \in \Lambda$ by

$$p_n = x_1^n + x_2^n + x_3^n + \cdots = m_{(n)}.$$

- For each partition λ, we define the *Schur function* $s_\lambda \in \Lambda$ by

$$s_\lambda = \sum \mathbf{x}_T,$$

where the sum ranges over all semistandard tableaux T of shape λ, and where $\mathbf{x}_T$ denotes the monomial obtained by multiplying the x_i for all entries i of T. We refer the reader to [GriRei20, Definition 2.2.1] or to [Stanle01, §7.10] for the details of this definition and further descriptions of the Schur functions. One of the most important properties of Schur functions (see, e.g., [GriRei20, (2.4.12) for $\mu = \varnothing$] or [MenRem15, Theorem 2.32] or [Stanle01, Theorem 7.16.1 for $\mu = \varnothing$] or [Sagan20, Theorem 7.2.3 (a)]) is the fact that

$$s_\lambda = \det\left(\left(h_{\lambda_i - i + j}\right)_{1 \leq i \leq \ell,\ 1 \leq j \leq \ell}\right) \tag{1}$$

for any partition $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_\ell)$. This is known as the *(first, straight-shape) Jacobi–Trudi formula*.

The family $(s_\lambda)_{\lambda \in \mathrm{Par}}$ is a basis of the $\mathbf{k}$-module Λ, and is known as the *Schur basis*. It is easy to see that each $n \in \mathbb{N}$ satisfies $s_{(n)} = h_n$ and $s_{(1^n)} = e_n$. Moreover, for each partition λ, the Schur function $s_\lambda \in \Lambda$ is homogeneous of degree $|\lambda|$.

Among the many relations between these symmetric functions is an expression for the power-sum symmetric function p_n in terms of the Schur basis:

Proposition 1.1. Let n be a positive integer. Then,

$$p_n = \sum_{i=0}^{n-1} (-1)^i s_{(n-i,1^i)}.$$

Proof. This is a classical formula, and appears (e.g.) in [Egge19, Problem 4.21], [GriRei20, Exercise 5.4.12(g)] and [MenRem15, Exercise 2.2]. Alternatively, this is an easy consequence of the Murnaghan–Nakayama rule (see [MenRem15, Theorem 6.3] or [Sam17, Theorem 4.4.2] or [Stanle01, Theorem 7.17.3] or [Wildon15, (1)]), applied to the product $p_n s_\varnothing$ (since $s_\varnothing = 1$). $\square$

Finally, we will sometimes use the *Hall inner product* $(\cdot, \cdot) : \Lambda \times \Lambda \to \mathbf{k}$ as defined in [GriRei20, Definition 2.5.12].[4] This is the $\mathbf{k}$-bilinear form on Λ that is defined by the requirement that

$$(s_\lambda, s_\mu) = \delta_{\lambda,\mu} \qquad \text{for any } \lambda, \mu \in \operatorname{Par}$$

(where $\delta_{\lambda,\mu}$ denotes the Kronecker delta). Thus, the Schur basis $(s_\lambda)_{\lambda \in \operatorname{Par}}$ of Λ is an orthonormal basis with respect to the Hall inner product. It is easy to see[5] that the Hall inner product $(\cdot, \cdot)$ is graded: i.e., we have

$$(f, g) = 0 \tag{2}$$

if f and g are two homogeneous symmetric functions of different degrees. We shall also use the following two known evaluations of the Hall inner product:

Proposition 1.2. Let n be a positive integer. Then, $(h_n, p_n) = 1$.

Proposition 1.3. Let n be a positive integer. Then, $(e_n, p_n) = (-1)^{n-1}$.

See Subsection 3.2 for the proofs of these two propositions.

2. Theorems

2.1. Definitions

The main role in this paper is played by two power series that we will now define:

Definition 2.1. **(a)** For any positive integer k, we let[6]

$$G(k) = \sum_{\substack{\alpha \in \mathrm{WC}; \\ \alpha_i < k \text{ for all } i}} \mathbf{x}^\alpha. \tag{3}$$

This is a symmetric formal power series in $\mathbf{k}[[x_1, x_2, x_3, \ldots]]$ (but does not belong to Λ in general).

[4] The Hall inner product also appears (for $\mathbf{k} = \mathbb{Z}$ and $\mathbf{k} = \mathbb{Q}$) in [Egge19, Definition 7.5], in [Stanle01, §7.9] and in [Macdon95, Section I.4]. Note that it is denoted by $\langle \cdot, \cdot \rangle$ in all these sources. Note also that the definitions of the Hall inner product in [Stanle01, §7.9] and in [Macdon95, Section I.4] are different from ours, but they are equivalent to ours (because of [Stanle01, Corollary 7.12.2] and [Macdon95, Chapter I, (4.8)]).

[5] See, e.g., [GriRei20, Exercise 2.5.13(a)] for a proof.

(b) For any positive integer k and any $m \in \mathbb{N}$, we let

$$G(k,m) = \sum_{\substack{\alpha \in \mathrm{WC}; \\ |\alpha| = m; \\ \alpha_i < k \text{ for all } i}} \mathbf{x}^{\alpha} \in \Lambda. \tag{4}$$

Example 2.2. **(a)** We have

$$\begin{aligned} G(2) &= \sum_{\substack{\alpha \in \mathrm{WC}; \\ \alpha_i < 2 \text{ for all } i}} \mathbf{x}^{\alpha} \\ &= 1 + x_1 + x_2 + x_3 + \cdots + x_1x_2 + x_1x_3 + x_2x_3 + \cdots \\ &\qquad + x_1x_2x_3 + x_1x_2x_4 + x_2x_3x_4 + \cdots \\ &\qquad + \cdots \\ &= \sum_{m \in \mathbb{N}} \underbrace{\sum_{1 \le i_1 < i_2 < \cdots < i_m} x_{i_1} x_{i_2} \cdots x_{i_m}}_{= e_m} = \sum_{m \in \mathbb{N}} e_m. \end{aligned}$$

(b) For each $m \in \mathbb{N}$, we have

$$G(2,m) = \sum_{\substack{\alpha \in \mathrm{WC}; \\ |\alpha| = m; \\ \alpha_i < 2 \text{ for all } i}} \mathbf{x}^{\alpha} = \sum_{1 \le i_1 < i_2 < \cdots < i_m} x_{i_1} x_{i_2} \cdots x_{i_m} = e_m.$$

We suggest the name *k-Petrie symmetric series* for $G(k)$ and the name (k,m)*-Petrie symmetric function* for $G(k,m)$. The reason for this naming is that the coefficients of these functions in the Schur basis of Λ are determinants of Petrie matrices, as we will see in Subsection 3.7.

2.2. Basic identities

We begin our study of the $G(k)$ and $G(k,m)$ with some simple properties:

Proposition 2.3. Let k be a positive integer.

(a) The symmetric function $G(k,m)$ is the m-th degree homogeneous component of $G(k)$ for each $m \in \mathbb{N}$.

(b) We have

$$G(k) = \sum_{\substack{\alpha \in \mathrm{WC}; \\ \alpha_i < k \text{ for all } i}} \mathbf{x}^{\alpha} = \sum_{\substack{\lambda \in \mathrm{Par}; \\ \lambda_i < k \text{ for all } i}} m_\lambda = \prod_{i=1}^{\infty} \left(x_i^0 + x_i^1 + \cdots + x_i^{k-1} \right).$$

[6] Here and in all similar situations, "for all i" means "for all positive integers i".

(c) We have

$$G(k,m) = \sum_{\substack{\alpha \in \mathrm{WC};\\ |\alpha|=m;\\ \alpha_i<k \text{ for all } i}} \mathbf{x}^{\alpha} = \sum_{\substack{\lambda \in \mathrm{Par};\\ |\lambda|=m;\\ \lambda_i<k \text{ for all } i}} m_\lambda$$

for each $m \in \mathbb{N}$.

(d) If $m \in \mathbb{N}$ satisfies $k > m$, then $G(k,m) = h_m$.

(e) If $m \in \mathbb{N}$ and $k = 2$, then $G(k,m) = e_m$.

(f) If $m = k$, then $G(k,m) = h_m - p_m$.

Proving Proposition 2.3 makes good practice in understanding the definitions of m_λ, h_n, e_n, p_n, $G(k)$ and $G(k,n)$. We omit the proof here; it can be found in full (hardly necessary) detail in [Grinbe20b].

Parts **(d)** and **(e)** of Proposition 2.3 show that the Petrie symmetric functions $G(k,m)$ can be seen as interpolating between the h_m and the e_m.

2.3. The Schur expansion

The solution to [Stanle01, Exercise 7.3] gives an expansion of $G(3)$ in terms of the elementary symmetric functions (due to I. M. Gessel); this expansion can be rewritten as

$$G(3) = \sum_{n\in\mathbb{N}} e_n^2 + \sum_{m<n} c_{m,n} e_m e_n, \qquad \text{where } c_{m,n} = (-1)^{m-n} \begin{cases} 2, & \text{if } 3 \mid m-n; \\ -1, & \text{if } 3 \nmid m-n \end{cases}.$$

We shall instead expand $G(k)$ in terms of Schur functions. For this, we need to define some notations.

Convention 2.4. We shall use the *Iverson bracket notation*: i.e., if $\mathcal{A}$ is a logical statement, then $[\mathcal{A}]$ shall denote the truth value of $\mathcal{A}$ (that is, the integer $\begin{cases} 1, & \text{if } \mathcal{A} \text{ is true;} \\ 0, & \text{if } \mathcal{A} \text{ is false} \end{cases}$).

We shall furthermore use the notation $(a_{i,j})_{1\le i\le \ell,\ 1\le j\le \ell}$ for the $\ell \times \ell$-matrix whose (i,j)-th entry is $a_{i,j}$ for each $i,j \in \{1,2,\ldots,\ell\}$.

Definition 2.5. Let $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_\ell) \in \mathrm{Par}$ and $\mu = (\mu_1, \mu_2, \ldots, \mu_\ell) \in \mathrm{Par}$, and let k be a positive integer. Then, the *k-Petrie number* $\mathrm{pet}_k(\lambda,\mu)$ of λ and μ is the integer defined by

$$\mathrm{pet}_k(\lambda,\mu) = \det\left(\left([0 \le \lambda_i - \mu_j - i + j < k] \right)_{1\le i\le \ell,\ 1\le j\le \ell} \right).$$

Note that this integer does not depend on the choice of ℓ (in the sense that it does not change if we enlarge ℓ by adding trailing zeroes to the representations of λ and μ); this follows from Lemma 2.7 below.

Example 2.6. Let λ be the partition $(3,2,1) \in \operatorname{Par}$, let μ be the partition $(1,1) \in \operatorname{Par}$, let $\ell = 3$, and let k be a positive integer. Then, the definition of $\operatorname{pet}_k(\lambda,\mu)$ yields

$$\begin{aligned}
&\operatorname{pet}_k(\lambda,\mu) \\
&= \det\left(\left([0 \leq \lambda_i - \mu_j - i + j < k]\right)_{1\leq i\leq \ell,\ 1\leq j\leq \ell}\right) \\
&= \det\begin{pmatrix} [0 \leq \lambda_1 - \mu_1 < k] & [0 \leq \lambda_1 - \mu_2 + 1 < k] & [0 \leq \lambda_1 - \mu_3 + 2 < k] \\ [0 \leq \lambda_2 - \mu_1 - 1 < k] & [0 \leq \lambda_2 - \mu_2 < k] & [0 \leq \lambda_2 - \mu_3 + 1 < k] \\ [0 \leq \lambda_3 - \mu_1 - 2 < k] & [0 \leq \lambda_3 - \mu_2 - 1 < k] & [0 \leq \lambda_3 - \mu_3 < k] \end{pmatrix} \\
&= \det\begin{pmatrix} [0 \leq 3 - 1 < k] & [0 \leq 3 - 1 + 1 < k] & [0 \leq 3 - 0 + 2 < k] \\ [0 \leq 2 - 1 - 1 < k] & [0 \leq 2 - 1 < k] & [0 \leq 2 - 0 + 1 < k] \\ [0 \leq 1 - 1 - 2 < k] & [0 \leq 1 - 1 - 1 < k] & [0 \leq 1 - 0 < k] \end{pmatrix} \\
&\qquad \left(\begin{array}{c} \text{since } \lambda_1 = 3 \text{ and } \lambda_2 = 2 \text{ and } \lambda_3 = 1 \\ \text{and } \mu_1 = 1 \text{ and } \mu_2 = 1 \text{ and } \mu_3 = 0 \end{array}\right) \\
&= \det\begin{pmatrix} [0 \leq 2 < k] & [0 \leq 3 < k] & [0 \leq 5 < k] \\ [0 \leq 0 < k] & [0 \leq 1 < k] & [0 \leq 3 < k] \\ [0 \leq -2 < k] & [0 \leq -1 < k] & [0 \leq 1 < k] \end{pmatrix}.
\end{aligned}$$

Thus, taking $k = 4$, we obtain

$$\begin{aligned}
\operatorname{pet}_4(\lambda,\mu) &= \det\begin{pmatrix} [0 \leq 2 < 4] & [0 \leq 3 < 4] & [0 \leq 5 < 4] \\ [0 \leq 0 < 4] & [0 \leq 1 < 4] & [0 \leq 3 < 4] \\ [0 \leq -2 < 4] & [0 \leq -1 < 4] & [0 \leq 1 < 4] \end{pmatrix} \\
&= \det\begin{pmatrix} 1 & 1 & 0 \\ 1 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix} = 0.
\end{aligned}$$

On the other hand, taking $k = 3$, we obtain

$$\begin{aligned}
\operatorname{pet}_3(\lambda,\mu) &= \det\begin{pmatrix} [0 \leq 2 < 3] & [0 \leq 3 < 3] & [0 \leq 5 < 3] \\ [0 \leq 0 < 3] & [0 \leq 1 < 3] & [0 \leq 3 < 3] \\ [0 \leq -2 < 3] & [0 \leq -1 < 3] & [0 \leq 1 < 3] \end{pmatrix} \\
&= \det\begin{pmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} = 1.
\end{aligned}$$

Lemma 2.7. Let $\lambda \in \operatorname{Par}$ and $\mu \in \operatorname{Par}$, and let k be a positive integer. Let $\ell \in \mathbb{N}$ be such that $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_\ell)$ and $\mu = (\mu_1, \mu_2, \ldots, \mu_\ell)$. Then, the determinant $\det\left(\left([0 \leq \lambda_i - \mu_j - i + j < k]\right)_{1\leq i\leq \ell,\ 1\leq j\leq \ell}\right)$ does not depend on the choice of ℓ.

See Subsection 3.6 for the simple proof of Lemma 2.7.

Surprisingly, the k-Petrie numbers $\operatorname{pet}_k(\lambda,\mu)$ can take only three possible values:

Proposition 2.8. Let $\lambda \in \operatorname{Par}$ and $\mu \in \operatorname{Par}$, and let k be a positive integer. Then, $\operatorname{pet}_k(\lambda,\mu) \in \{-1,0,1\}$.

Proposition 2.8 will be proved in Subsection 3.7.

We can now expand the Petrie symmetric functions $G(k,m)$ and the power series $G(k)$ in the basis $(s_\lambda)_{\lambda\in\operatorname{Par}}$ of Λ:

Theorem 2.9. Let k be a positive integer. Then,

$$G(k) = \sum_{\lambda\in\operatorname{Par}} \operatorname{pet}_k(\lambda,\varnothing)\, s_\lambda.$$

(Recall that $\varnothing$ denotes the empty partition $() = (0,0,0,\ldots)$.)

We will not prove Theorem 2.9 directly; instead, we will first show a stronger result (Theorem 2.17), and then derive Theorem 2.9 from it in Subsection 3.10.

Corollary 2.10. Let k be a positive integer. Let $m \in \mathbb{N}$. Then,

$$G(k,m) = \sum_{\lambda\in\operatorname{Par}_m} \operatorname{pet}_k(\lambda,\varnothing)\, s_\lambda.$$

Corollary 2.10 easily follows from Theorem 2.9 using Proposition 2.3 **(a)**; but again, we shall instead derive it from a stronger result (Corollary 2.18) in Subsection 3.10.

We will see a more explicit description of the k-Petrie numbers $\operatorname{pet}_k(\lambda,\varnothing)$ in Subsection 2.4.

Remark 2.11. Corollary 2.10, in combination with Proposition 2.8, shows that each k-Petrie function $G(k,m)$ (for any $k>0$ and $m\in\mathbb{N}$) is a linear combination of Schur functions, with all coefficients belonging to $\{-1,0,1\}$. It is natural to expect the more general symmetric functions

$$\widetilde{G}(k,k',m) = \sum_{\substack{\alpha\in\operatorname{WC};\\ |\alpha|=m;\\ k'\le\alpha_i<k \text{ for all } i}} \mathbf{x}^\alpha, \qquad \text{where } 0<k'\le k,$$

to have the same property. However, this is not the case. For example,

$$\widetilde{G}(4,2,5) = m_{(3,2)} = -2s_{(1,1,1,1,1)} + 2s_{(2,1,1,1)} - s_{(2,2,1)} - s_{(3,1,1)} + s_{(3,2)}.$$

2.4. An explicit description of the k-Petrie numbers $\operatorname{pet}_k(\lambda, \varnothing)$

Can the k-Petrie numbers $\operatorname{pet}_k(\lambda, \varnothing)$ from Definition 2.5 be described more explicitly than as determinants? To be somewhat pedantic, the answer to this question depends on one's notion of "explicit", as determinants are not hard to compute, and another algorithm for calculating $\operatorname{pet}_k(\lambda, \varnothing)$ can be extracted from our proof of Proposition 2.8 (when combined with [GorWil74, proof of Theorem 1]). Nevertheless, there is a more explicit description. This description will be stated in Theorem 2.15 further below.

First, let us get a simple case out of the way:

Proposition 2.12. Let $\lambda \in \operatorname{Par}$, and let k be a positive integer such that $\lambda_1 \geq k$. Then, $\operatorname{pet}_k(\lambda, \varnothing) = 0$.

Proof of Proposition 2.12. Write λ as $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_\ell)$. Thus, $\ell \geq 1$ (since $\lambda_1 \geq k > 0$). Moreover, $\varnothing = (\varnothing_1, \varnothing_2, \ldots, \varnothing_\ell)$ (since $\ell(\varnothing) = 0 \leq \ell$).

Thus, we have $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_\ell)$ and $\varnothing = (\varnothing_1, \varnothing_2, \ldots, \varnothing_\ell)$. Hence, the definition of $\operatorname{pet}_k(\lambda, \varnothing)$ yields

$$\begin{aligned} \operatorname{pet}_k(\lambda, \varnothing) &= \det\left(\left(\left[0 \leq \lambda_i - \underbrace{\varnothing_j}_{=0} - i + j < k\right]\right)_{1 \leq i \leq \ell,\ 1 \leq j \leq \ell}\right) \\ &= \det\left(\left([0 \leq \lambda_i - i + j < k]\right)_{1 \leq i \leq \ell,\ 1 \leq j \leq \ell}\right). \end{aligned} \tag{5}$$

But each $j \in \{1, 2, \ldots, \ell\}$ satisfies $[0 \leq \lambda_1 - 1 + j < k] = 0$ (since $\lambda_1 - 1 + \underbrace{j}_{\geq 1} \geq \lambda_1 - 1 + 1 = \lambda_1 \geq k$). In other words, the $\ell \times \ell$-matrix $\left([0 \leq \lambda_i - i + j < k]\right)_{1 \leq i \leq \ell,\ 1 \leq j \leq \ell}$ has first row $(0, 0, \ldots, 0)$. Therefore, its determinant is 0. In other words, $\operatorname{pet}_k(\lambda, \varnothing) = 0$ (since $\operatorname{pet}_k(\lambda, \varnothing)$ is its determinant[7]). This proves Proposition 2.12. □

Stating Theorem 2.15 will require some notation:

Definition 2.13. For any $\lambda \in \operatorname{Par}$, we define the *transpose* of λ to be the partition $\lambda^t \in \operatorname{Par}$ determined by

$$\left(\lambda^t\right)_i = \left|\left\{j \in \{1, 2, 3, \ldots\} \mid \lambda_j \geq i\right\}\right| \qquad \text{for each } i \geq 1.$$

This partition λ^t is also known as the *conjugate* of λ, and is perhaps easiest to understand in terms of Young diagrams: To wit, the Young diagram of λ^t is obtained from that of λ by a flip across the main diagonal.

[7] by (5)

One important use of transpose partitions is the following fact (see, e.g., [GriRei20, (2.4.13) for $\mu = \varnothing$] or [MenRem15, Theorem 2.32] or [Stanle01, Theorem 7.16.2 applied to λ^t and $\varnothing$ instead of λ and μ] for proofs): We have

$$s_{\lambda^t} = \det \left(\left(e_{\lambda_i - i + j} \right)_{1 \leq i \leq \ell,\ 1 \leq j \leq \ell} \right) \tag{6}$$

for any partition $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_\ell)$. This is known as the *(second, straight-shape) Jacobi–Trudi formula*.

We will use the following notation for quotients and remainders:

Convention 2.14. Let k be a positive integer. Let $n \in \mathbb{Z}$. Then, $n\%k$ shall denote the remainder of n divided by k, whereas $n//k$ shall denote the quotient of this division (an integer). Thus, $n//k$ and $n\%k$ are uniquely determined by the three requirements that $n//k \in \mathbb{Z}$ and $n\%k \in \{0, 1, \ldots, k-1\}$ and $n = (n//k) \cdot k + (n\%k)$.

The "$//$" and "$\%$" signs bind more strongly than the "$+$" and "$-$" signs. That is, for example, the expression "$a + b\%k$" shall be understood to mean "$a + (b\%k)$" rather than "$(a+b)\%k$".

Now, we can state our "formula" for k-Petrie numbers of the form $\operatorname{pet}_k(\lambda, \varnothing)$.

Theorem 2.15. Let $\lambda \in \operatorname{Par}$, and let k be a positive integer. Let $\mu = \lambda^t$.

(a) If $\mu_k \neq 0$, then $\operatorname{pet}_k(\lambda, \varnothing) = 0$.

From now on, let us assume that $\mu_k = 0$.

Define a $(k-1)$-tuple $(\beta_1, \beta_2, \ldots, \beta_{k-1}) \in \mathbb{Z}^{k-1}$ by setting

$$\beta_i = \mu_i - i \qquad \text{for each } i \in \{1, 2, \ldots, k-1\}. \tag{7}$$

Define a $(k-1)$-tuple $(\gamma_1, \gamma_2, \ldots, \gamma_{k-1}) \in \{1, 2, \ldots, k\}^{k-1}$ by setting

$$\gamma_i = 1 + (\beta_i - 1)\%k \qquad \text{for each } i \in \{1, 2, \ldots, k-1\}. \tag{8}$$

(b) If the $k-1$ numbers $\gamma_1, \gamma_2, \ldots, \gamma_{k-1}$ are not distinct, then $\operatorname{pet}_k(\lambda, \varnothing) = 0$.

(c) Assume that the $k-1$ numbers $\gamma_1, \gamma_2, \ldots, \gamma_{k-1}$ are distinct. Let

$$g = \left| \left\{ (i, j) \in \{1, 2, \ldots, k-1\}^2 \ \mid \ i < j \text{ and } \gamma_i < \gamma_j \right\} \right|.$$

Then, $\operatorname{pet}_k(\lambda, \varnothing) = (-1)^{(\beta_1 + \beta_2 + \cdots + \beta_{k-1}) + g + (\gamma_1 + \gamma_2 + \cdots + \gamma_{k-1})}$.

The proof of this theorem is technical and will be given in Subsection 3.11.

It is possible to restate part of Theorem 2.15 without using λ^t:

Proposition 2.16. Let $\lambda \in \operatorname{Par}$, and let k be a positive integer. Assume that $\lambda_1 < k$. Define a subset B of $\mathbb{Z}$ by

$$B = \{\lambda_i - i \ \mid \ i \in \{1, 2, 3, \ldots\}\}.$$

Let $\overline{0}, \overline{1}, \ldots, \overline{k-1}$ be the residue classes of the integers $0, 1, \ldots, k-1$ modulo k (considered as subsets of $\mathbb{Z}$). Let W be the set of all integers smaller than $k-1$.

Then, $\operatorname{pet}_k(\lambda, \varnothing) \neq 0$ if and only if each $i \in \{0, 1, \ldots, k-1\}$ satisfies $\left|\left(\overline{i} \cap W\right) \setminus B\right| \leq 1$.

In Subsection 3.11, we will outline how this proposition can be derived from Theorem 2.15.

The sets B and $\left(\overline{i} \cap W\right) \setminus B$ in Proposition 2.16 are related to the *k-modular structure* of the partition λ, such as the *β-set*, the *k-abacus*, the *k-core* and the *k-quotient* (see [Olsson93, §§1–3] for some of these concepts). Essentially equivalent concepts include the *Maya diagram* of λ (see, e.g., [Crane18, §3.3])[8] and the *first column hook lengths* of λ (see [Olsson93, Proposition (1.3)]).

2.5. A "Pieri" rule

Now, the following generalization of Theorem 2.9 holds:

Theorem 2.17. Let k be a positive integer. Let $\mu \in \operatorname{Par}$. Then,

$$G(k) \cdot s_\mu = \sum_{\lambda \in \operatorname{Par}} \operatorname{pet}_k(\lambda, \mu) s_\lambda.$$

Theorem 2.9 is the particular case of Theorem 2.17 for $\mu = \varnothing$.

We shall give two proofs of Theorem 2.17 in Subsections 3.8 and 3.9.

We can also generalize Corollary 2.10 to obtain a Pieri-like rule for multiplication by $G(k, m)$:

Corollary 2.18. Let k be a positive integer. Let $m \in \mathbb{N}$. Let $\mu \in \operatorname{Par}$. Then,

$$G(k, m) \cdot s_\mu = \sum_{\lambda \in \operatorname{Par}_{m+|\mu|}} \operatorname{pet}_k(\lambda, \mu) s_\lambda.$$

Corollary 2.18 follows from Theorem 2.17 by projecting onto the $(m + |\mu|)$-th graded component of Λ. (We shall explain this argument in more detail in Subsection 3.10.)

[8] The *Maya diagram* of λ is a coloring of the set $\left\{z + \frac{1}{2} \mid z \in \mathbb{Z}\right\}$ with the colors black and white, in which the elements $\lambda_i - i + \frac{1}{2}$ (for all $i \in \{1, 2, 3, \ldots\}$) are colored black while all remaining elements are colored white. Borcherds's proof of the Jacobi triple product identity ([Camero94, §13.3]) also essentially constructs this Maya diagram (wording it in terms of the "*Dirac sea*" model for electrons).

2.6. Coproducts of Petrie functions

In the following, the "$\otimes$" sign will always stand for $\otimes_{\mathbf{k}}$ (that is, tensor product of $\mathbf{k}$-modules or of $\mathbf{k}$-algebras).

The $\mathbf{k}$-algebra Λ is a Hopf algebra due to the presence of a comultiplication $\Delta : \Lambda \to \Lambda \otimes \Lambda$. We recall (from [GriRei20, §2.1]) one way to define this comultiplication:

Consider the rings

$$\mathbf{k}[[\mathbf{x}]] := \mathbf{k}[[x_1, x_2, x_3, \ldots]] \qquad \text{and} \qquad \mathbf{k}[[\mathbf{x}, \mathbf{y}]] := \mathbf{k}[[x_1, x_2, x_3, \ldots, y_1, y_2, y_3, \ldots]]$$

of formal power series. We shall use the notations $\mathbf{x}$ and $\mathbf{y}$ for the sequences $(x_1, x_2, x_3, \ldots)$ and $(y_1, y_2, y_3, \ldots)$ of indeterminates. If $f \in \mathbf{k}[[\mathbf{x}]]$ is any formal power series, then $f(\mathbf{y})$ shall mean the result of substituting $y_1, y_2, y_3, \ldots$ for the variables $x_1, x_2, x_3, \ldots$ in f. (This will be a formal power series in $\mathbf{k}[[y_1, y_2, y_3, \ldots]]$.) For the sake of symmetry, we also use the analogous notation $f(\mathbf{x})$ for the result of substituting $x_1, x_2, x_3, \ldots$ for $x_1, x_2, x_3, \ldots$ in f; of course, this $f(\mathbf{x})$ is just f. Finally, if the power series $f \in \mathbf{k}[[\mathbf{x}]]$ is symmetric, then we use the notation $f(\mathbf{x}, \mathbf{y})$ for the result of substituting the variables $x_1, x_2, x_3, \ldots, y_1, y_2, y_3, \ldots$ for the variables $x_1, x_2, x_3, \ldots$ in f (that is, choosing some bijection $\phi : \{x_1, x_2, x_3, \ldots\} \to \{x_1, x_2, x_3, \ldots, y_1, y_2, y_3, \ldots\}$ [9] and substituting $\phi(x_i)$ for each x_i in f). This result does not depend on the order in which the former variables are substituted for the latter (i.e., on the choice of the bijection ϕ) because f is symmetric.

Now, the comultiplication of Λ is the map $\Delta : \Lambda \to \Lambda \otimes \Lambda$ determined as follows: For a symmetric function $f \in \Lambda$, we have

$$\Delta(f) = \sum_{i \in I} f_{1,i} \otimes f_{2,i}, \tag{9}$$

where $f_{1,i}, f_{2,i} \in \Lambda$ are such that

$$f(\mathbf{x}, \mathbf{y}) = \sum_{i \in I} f_{1,i}(\mathbf{x}) f_{2,i}(\mathbf{y}). \tag{10}$$

More precisely, if $f \in \Lambda$, if I is a finite set, and if $(f_{1,i})_{i \in I} \in \Lambda^I$ and $(f_{2,i})_{i \in I} \in \Lambda^I$ are two families satisfying (10), then $\Delta(f)$ is given by (9). [10]

For example, for any $n \in \mathbb{N}$, it is easy to see that

$$e_n(\mathbf{x}, \mathbf{y}) = \sum_{i=0}^{n} e_i(\mathbf{x}) e_{n-i}(\mathbf{y}),$$

[9] Such bijections clearly exist, since the sets $\{x_1, x_2, x_3, \ldots\}$ and $\{x_1, x_2, x_3, \ldots, y_1, y_2, y_3, \ldots\}$ have the same cardinality (namely, $\aleph_0$). This is one of several observations commonly illustrated by the metaphor of "Hilbert's hotel".

[10] In the language of [GriRei20, §2.1], this can be restated as $\Delta(f) = f(\mathbf{x}, \mathbf{y})$, because $\Lambda \otimes \Lambda$ is identified with a certain subring of $\mathbf{k}[[\mathbf{x}, \mathbf{y}]]$ in [GriRei20, §2.1] (via the injection $\Lambda \otimes \Lambda \to \mathbf{k}[[\mathbf{x}, \mathbf{y}]]$ that sends any $u \otimes v \in \Lambda \otimes \Lambda$ to $u(\mathbf{x}) v(\mathbf{y}) \in \mathbf{k}[[\mathbf{x}, \mathbf{y}]]$).

and thus the above definition of Δ yields

$$\Delta(e_n) = \sum_{i=0}^{n} e_i \otimes e_{n-i}.$$

A similar formula exists for the image of a Petrie symmetric function under Δ:

Theorem 2.19. Let k be a positive integer. Let $m \in \mathbb{N}$. Then,

$$\Delta(G(k,m)) = \sum_{i=0}^{m} G(k,i) \otimes G(k,m-i).$$

The proof of Theorem 2.19 is given in Subsection 3.12; it is a simple consequence (albeit somewhat painful to explain) of (9).

It is well-known that $\Delta : \Lambda \to \Lambda \otimes \Lambda$ is a $\mathbf{k}$-algebra homomorphism. Equipping the $\mathbf{k}$-algebra Λ with the comultiplication Δ (as well as a counit $\varepsilon : \Lambda \to \mathbf{k}$, which we won't need here) yields a connected graded Hopf algebra. (See, e.g., [GriRei20, §2.1] for proofs.)

2.7. The Frobenius endomorphisms and Petrie functions

We shall next derive another formula for the Petrie symmetric functions $G(k,m)$. For this formula, we need the following definition ([GriRei20, Exercise 2.9.9]):

Definition 2.20. Let $n \in \{1,2,3,\ldots\}$. We define a map $\mathbf{f}_n : \Lambda \to \Lambda$ by

$$(\mathbf{f}_n(a) = a(x_1^n, x_2^n, x_3^n, \ldots) \qquad \text{for each } a \in \Lambda).$$

This map $\mathbf{f}_n$ is called the *n-th Frobenius endomorphism* of Λ.

Clearly, this map $\mathbf{f}_n$ is a $\mathbf{k}$-algebra endomorphism of Λ (since it amounts to a substitution of indeterminates). It is known (from [GriRei20, Exercise 2.9.9(d)]) that this map $\mathbf{f}_n : \Lambda \to \Lambda$ is a Hopf algebra endomorphism of Λ.

Theorem 2.21. Let k be a positive integer. Let $m \in \mathbb{N}$. Then,

$$G(k,m) = \sum_{i\in\mathbb{N}} (-1)^i h_{m-ki} \cdot \mathbf{f}_k(e_i).$$

(The sum on the right hand side of this equality is well-defined, since all sufficiently high $i \in \mathbb{N}$ satisfy $m - ki < 0$ and thus $h_{m-ki} = 0$.)

Theorem 2.21 will be proved in Subsection 3.13 below.

2.8. The Petrie functions as polynomial generators of Λ

We now claim the following:

Theorem 2.22. Fix a positive integer k. Assume that $1-k$ is invertible in $\mathbf{k}$.

Then, the family $(G(k,m))_{m\geq 1} = (G(k,1), G(k,2), G(k,3), \ldots)$ is an algebraically independent generating set of the commutative $\mathbf{k}$-algebra Λ. (In other words, the canonical $\mathbf{k}$-algebra homomorphism

$$\mathbf{k}[u_1,u_2,u_3,\ldots] \to \Lambda, \qquad u_m \mapsto G(k,m)$$

is an isomorphism.)

We shall prove Theorem 2.22 in Subsection 3.14. The proof uses the following two formulas:[11]

Lemma 2.23. Let k and m be positive integers. Let $j \in \mathbb{N}$. Then, $(p_m, \mathbf{f}_k(e_j)) = (-1)^{j-1}[m=kj]\,k$.

Proposition 2.24. Let k and m be positive integers. Then, $(p_m, G(k,m)) = 1 - [k \mid m]\,k$.

Both of these formulas will be proved in Subsection 3.14 as well.

2.9. The Verschiebung endomorphisms

Now we recall another definition ([GriRei20, Exercise 2.9.10]):

Definition 2.25. Let $n \in \{1,2,3,\ldots\}$. We define a $\mathbf{k}$-algebra homomorphism $\mathbf{v}_n : \Lambda \to \Lambda$ by

$$\left(\mathbf{v}_n(h_m) = \begin{cases} h_{m/n}, & \text{if } n \mid m; \\ 0, & \text{if } n \nmid m \end{cases} \qquad \text{for each } m > 0\right).$$

(This is well-defined, since the sequence $(h_1,h_2,h_3,\ldots)$ is an algebraically independent generating set of the commutative $\mathbf{k}$-algebra Λ.)

This map $\mathbf{v}_n$ is called the *n-th Verschiebung endomorphism* of Λ.

Again, it is known ([GriRei20, Exercise 2.9.10(e)]) that this map $\mathbf{v}_n : \Lambda \to \Lambda$ is a Hopf algebra endomorphism of Λ. Moreover, the following holds ([GriRei20, Exercise 2.9.10(f)]):

[11] Here, we are again using the Iverson bracket notation.

Proposition 2.26. Let $n \in \{1, 2, 3, \ldots\}$. Then, the maps $\mathbf{f}_n : \Lambda \to \Lambda$ and $\mathbf{v}_n : \Lambda \to \Lambda$ are adjoint with respect to the Hall inner product on Λ. That is, any $a \in \Lambda$ and $b \in \Lambda$ satisfy

$$(a, \mathbf{f}_n (b)) = (\mathbf{v}_n (a), b).$$

Furthermore, any positive integers n and m satisfy

$$\mathbf{v}_n (p_m) = \begin{cases} n p_{m/n}, & \text{if } n \mid m; \\ 0, & \text{if } n \nmid m \end{cases} . \tag{11}$$

(This is [GriRei20, Exercise 2.9.10(a)].)

2.10. The Hopf endomorphisms U_k and V_k

In this final subsection, we shall show another way to obtain the Petrie symmetric functions $G(k, m)$ using the machinery of Hopf algebras. We refer, e.g., to [GriRei20, Chapters 1 and 2] for everything we will use about Hopf algebras.

Convention 2.27. As already mentioned, Λ is a connected graded Hopf algebra. We let S denote its antipode.

Definition 2.28. If C is a $\mathbf{k}$-coalgebra and A is a $\mathbf{k}$-algebra, and if $f, g : C \to A$ are two $\mathbf{k}$-linear maps, then the *convolution* $f \star g$ of f and g is defined to be the $\mathbf{k}$-linear map $m_A \circ (f \otimes g) \circ \Delta_C : C \to A$, where $\Delta_C : C \to C \otimes C$ is the comultiplication of the $\mathbf{k}$-coalgebra C, and where $m_A : A \otimes A \to A$ is the $\mathbf{k}$-linear map sending each pure tensor $a \otimes b \in A \otimes A$ to $ab \in A$.

We also recall Definition 2.25 and Definition 2.20. We now claim the following.

Theorem 2.29. Fix a positive integer k. Let U_k be the map $\mathbf{f}_k \circ S \circ \mathbf{v}_k : \Lambda \to \Lambda$. Let V_k be the map $\mathrm{id}_\Lambda \star U_k : \Lambda \to \Lambda$. (This is well-defined by Definition 2.28, since Λ is both a $\mathbf{k}$-coalgebra and a $\mathbf{k}$-algebra.) Then:

(a) The map U_k is a $\mathbf{k}$-Hopf algebra homomorphism.

(b) The map V_k is a $\mathbf{k}$-Hopf algebra homomorphism.

(c) We have $V_k (h_m) = G(k, m)$ for each $m \in \mathbb{N}$.

(d) We have $V_k (p_n) = (1 - [k \mid n] k) p_n$ for each positive integer n.

See Subsection 3.15 for a proof of this theorem.

Note that Theorem 2.29 can be used to give a second proof of Theorem 2.19; see [Grinbe20b] for this.

We also obtain the following corollary from Theorem 2.19:

Corollary 2.30. Let k and n be two positive integers. Then, there exists a polynomial $f \in \mathbf{k}[x_1, x_2, x_3, \ldots]$ such that

$$(1 - [k \mid n] k) p_n = f(G(k,1), G(k,2), G(k,3), \ldots). \tag{12}$$

This corollary will be proved in Subsection 3.16.

3. Proofs

3.1. The symmetric functions h_λ

We shall now approach the proofs of the claims made above. First, let us introduce a family of symmetric functions, obtained by multiplying several h_n's:

Definition 3.1. Let λ be a partition. Write λ in the form $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_\ell)$, where $\lambda_1, \lambda_2, \ldots, \lambda_\ell$ are positive integers. Then, we define a symmetric function $h_\lambda \in \Lambda$ by

$$h_\lambda = h_{\lambda_1} h_{\lambda_2} \cdots h_{\lambda_\ell}.$$

From [GriRei20, Corollary 2.5.17(a)], we know that the families $(h_\lambda)_{\lambda \in \mathrm{Par}}$ and $(m_\lambda)_{\lambda \in \mathrm{Par}}$ are dual bases with respect to the Hall inner product. Thus,

$$(h_\lambda, m_\mu) = \delta_{\lambda,\mu} \qquad \text{for any } \lambda \in \mathrm{Par} \text{ and } \mu \in \mathrm{Par}. \tag{13}$$

Let us record a slightly different way to express h_λ:

Proposition 3.2. Let λ be a partition. Then,

$$h_\lambda = h_{\lambda_1} h_{\lambda_2} h_{\lambda_3} \cdots .$$

(Here, the infinite product $h_{\lambda_1} h_{\lambda_2} h_{\lambda_3} \cdots$ is well-defined, since every sufficiently high positive integer i satisfies $\lambda_i = 0$ and thus $h_{\lambda_i} = h_0 = 1$.)

This is how h_λ is defined in [Macdon95, Section I.2].

Proof of Proposition 3.2. This is an easy consequence of $h_0 = 1$. □

3.2. Proofs of Proposition 1.2 and Proposition 1.3

Proof of Proposition 1.2. There are myriad ways to prove this. Here is perhaps the simplest one: Let us use the notation h_λ as defined in Definition 3.1. Thus, $h_{(n)} = h_n$ (since n is a positive integer). Applying (13) to $\lambda = (n)$ and $\mu = (n)$, we obtain $\left(h_{(n)}, m_{(n)}\right) = \delta_{(n),(n)} = 1$. In view of $h_{(n)} = h_n$ and $m_{(n)} = p_n$, this rewrites as $(h_n, p_n) = 1$. This proves Proposition 1.2. □

Proof of Proposition 1.3. This is [GriRei20, Exercise 2.8.8(a)]. But here is a self-contained proof: Proposition 1.1 yields

$$(e_n, p_n) = \left(e_n, \sum_{i=0}^{n-1} (-1)^i s_{\left(n-i,1^i\right)}\right) = \sum_{i=0}^{n-1} (-1)^i \underbrace{\left(e_n, s_{\left(n-i,1^i\right)}\right)}_{\substack{=\left(s_{(1^n)}, s_{\left(n-i,1^i\right)}\right) \\ \text{(since } e_n = s_{(1^n)}\text{)}}}$$

$$= \sum_{i=0}^{n-1} (-1)^i \underbrace{\left(s_{(1^n)}, s_{\left(n-i,1^i\right)}\right)}_{\substack{=\delta_{(1^n),\left(n-i,1^i\right)} \\ \text{(since the basis } (s_\lambda)_{\lambda\in\mathrm{Par}} \text{ of } \Lambda \text{ is} \\ \text{orthonormal with respect to} \\ \text{the Hall inner product)}}} = \sum_{i=0}^{n-1} (-1)^i \underbrace{\delta_{(1^n),\left(n-i,1^i\right)}}_{\substack{=\begin{cases} 1, & \text{if } (1^n) = \left(n-i,1^i\right); \\ 0, & \text{if } (1^n) \neq \left(n-i,1^i\right) \end{cases} \\ =\begin{cases} 1, & \text{if } i = n-1; \\ 0, & \text{if } i \neq n-1 \end{cases} \\ \text{(since we have } (1^n)=\left(n-i,1^i\right) \\ \text{if and only if } i=n-1\text{)}}}$$

$$= \sum_{i=0}^{n-1} (-1)^i \begin{cases} 1, & \text{if } i = n-1; \\ 0, & \text{if } i \neq n-1 \end{cases} = (-1)^{n-1}.$$

□

3.3. Skew Schur functions

Let us define a classical partial order on Par (see, e.g., [GriRei20, Definition 2.3.1]):

Definition 3.3. Let λ and μ be two partitions.
We say that $\mu \subseteq \lambda$ if each $i \in \{1, 2, 3, \ldots\}$ satisfies $\mu_i \leq \lambda_i$.
We say that $\mu \not\subseteq \lambda$ if we don't have $\mu \subseteq \lambda$.

For example, $(3,2) \subseteq (4,2,1)$, but $(3,2,1) \not\subseteq (4,2)$ (since $(3,2,1)_3 = 1$ is not $\leq$ to $(4,2)_3 = 0$).

For any two partitions λ and μ, a symmetric function $s_{\lambda/\mu}$ called a *skew Schur function* is defined in [GriRei20, Definition 2.3.1] and in [Macdon95, §I.5] (see also [Stanle01, Definition 7.10.1] for the case when $\mu \subseteq \lambda$). We shall not recall its standard definition here, but rather state a few properties.

The first property (which can in fact be used as an alternative definition of $s_{\lambda/\mu}$) is the *first Jacobi–Trudi formula* for skew shapes; it states the following:

Theorem 3.4. Let $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_\ell)$ and $\mu = (\mu_1, \mu_2, \ldots, \mu_\ell)$ be two partitions. Then,

$$s_{\lambda/\mu} = \det\left(\left(h_{\lambda_i - \mu_j - i + j}\right)_{1\leq i\leq \ell,\ 1\leq j\leq \ell}\right). \tag{14}$$

Theorem 3.4 appears (with proof) in [GriRei20, (2.4.12)] and in [Macdon95, Chapter I, (5.4)].

The following properties of skew Schur functions are easy to see:

- If λ is any partition, then $s_{\lambda/\varnothing} = s_\lambda$. (Recall that $\varnothing$ denotes the empty partition.)
- If λ and μ are two partitions satisfying $\mu \not\subseteq \lambda$, then $s_{\lambda/\mu} = 0$.

3.4. A Cauchy-like identity

We shall use the following identity, which connects the skew Schur functions $s_{\lambda/\mu}$, the symmetric functions h_λ from Definition 3.1 and the monomial symmetric functions m_λ:

Theorem 3.5. Recall the symmetric functions h_λ defined in Definition 3.1. Let μ be any partition. Then, in the ring $\mathbf{k}[[\mathbf{x}, \mathbf{y}]]$, we have

$$\sum_{\lambda \in \mathrm{Par}} s_{\lambda/\mu}(\mathbf{x}) s_\lambda(\mathbf{y}) = s_\mu(\mathbf{y}) \cdot \sum_{\lambda \in \mathrm{Par}} h_\lambda(\mathbf{x}) m_\lambda(\mathbf{y}).$$

Here, we are using the notations introduced in Subsection 2.6.

Proof of Theorem 3.5. A well-known identity (proved, e.g., in [Macdon95, Chapter I, (4.2)] and in [GriRei20, proof of Proposition 2.5.15]) says that

$$\prod_{i,j=1}^{\infty} \left(1 - x_i y_j\right)^{-1} = \sum_{\lambda \in \mathrm{Par}} h_\lambda(\mathbf{x}) m_\lambda(\mathbf{y}). \tag{15}$$

(Here, the product sign " $\prod_{i,j=1}^{\infty}$ " means " $\prod_{(i,j) \in \{1,2,3,\ldots\}^2}$ ".)

Another well-known identity (proved, e.g., in [Macdon95, §I.5, example 26] and in [GriRei20, Exercise 2.5.11(a)]) says that

$$\sum_{\lambda \in \mathrm{Par}} s_\lambda(\mathbf{x}) s_{\lambda/\mu}(\mathbf{y}) = s_\mu(\mathbf{x}) \cdot \prod_{i,j=1}^{\infty} \left(1 - x_i y_j\right)^{-1}.$$

If we swap the roles of $\mathbf{x} = (x_1, x_2, x_3, \ldots)$ and $\mathbf{y} = (y_1, y_2, y_3, \ldots)$ in this identity, then we obtain

$$\sum_{\lambda \in \mathrm{Par}} s_\lambda(\mathbf{y}) s_{\lambda/\mu}(\mathbf{x}) = s_\mu(\mathbf{y}) \cdot \prod_{i,j=1}^{\infty} \left(1 - y_i x_j\right)^{-1}.$$

In view of

$$\sum_{\lambda \in \mathrm{Par}} \underbrace{s_\lambda(\mathbf{y}) s_{\lambda/\mu}(\mathbf{x})}_{= s_{\lambda/\mu}(\mathbf{x}) s_\lambda(\mathbf{y})} = \sum_{\lambda \in \mathrm{Par}} s_{\lambda/\mu}(\mathbf{x}) s_\lambda(\mathbf{y})$$

and

$$\prod_{i,j=1}^{\infty}\left(1-y_i x_j\right)^{-1} = \underbrace{\prod_{j,i=1}^{\infty}}_{=\prod_{i,j=1}^{\infty}} \left(1-\underbrace{y_j x_i}_{=x_i y_j}\right)^{-1}$$

$$\left(\begin{array}{c}\text{here, we have renamed the index } (i,j) \text{ as } (j,i) \\ \text{in the product}\end{array}\right)$$

$$= \prod_{i,j=1}^{\infty}\left(1-x_i y_j\right)^{-1} = \sum_{\lambda\in\mathrm{Par}} h_\lambda\left(\mathbf{x}\right) m_\lambda\left(\mathbf{y}\right) \qquad \text{(by (15))},$$

this rewrites as

$$\sum_{\lambda\in\mathrm{Par}} s_{\lambda/\mu}\left(\mathbf{x}\right) s_\lambda\left(\mathbf{y}\right) = s_\mu\left(\mathbf{y}\right)\cdot \sum_{\lambda\in\mathrm{Par}} h_\lambda\left(\mathbf{x}\right) m_\lambda\left(\mathbf{y}\right).$$

This proves Theorem 3.5. □

3.5. The k-algebra homomorphism $\alpha_k : \Lambda \to \mathbf{k}$

Recall that the family $(h_n)_{n\geq 1} = (h_1, h_2, h_3, \ldots)$ is algebraically independent and generates Λ as a $\mathbf{k}$-algebra. Thus, Λ can be viewed as a polynomial ring in the (infinitely many) indeterminates $h_1, h_2, h_3, \ldots$. The universal property of a polynomial ring thus shows that if A is any commutative $\mathbf{k}$-algebra, and if $(a_1, a_2, a_3, \ldots)$ is any sequence of elements of A, then there is a unique $\mathbf{k}$-algebra homomorphism from Λ to A that sends h_i to a_i for all positive integers i. We shall refer to this as the *h-universal property of* Λ. It lets us make the following definition:[12]

Definition 3.6. Let k be a positive integer. The h-universal property of Λ shows that there is a unique $\mathbf{k}$-algebra homomorphism $\alpha_k : \Lambda \to \mathbf{k}$ that sends h_i to $[i < k]$ for all positive integers i. Consider this α_k.

We will use this homomorphism α_k several times in what follows; let us thus begin by stating some elementary properties of α_k.

Lemma 3.7. Let k be a positive integer.

(a) We have
$$\alpha_k\left(h_i\right) = [i < k] \qquad \text{for all } i \in \mathbb{N}. \tag{16}$$

(b) We have
$$\alpha_k\left(h_i\right) = [0 \leq i < k] \qquad \text{for all } i \in \mathbb{Z}. \tag{17}$$

[12] We are using the Iverson bracket notation (see Convention 2.4) here.

(c) Let λ be a partition. Define h_λ as in Definition 3.1. Then,

$$\alpha_k\left(h_\lambda\right) = \left[\lambda_i < k \text{ for all } i\right]. \tag{18}$$

(Here, "for all i" means "for all positive integers i".)

Proof of Lemma 3.7. Note that $0 < k$ (since k is positive).

(a) Let $i \in \mathbb{N}$. We must prove that $\alpha_k\left(h_i\right) = \left[i < k\right]$. If $i > 0$, then this follows from the definition of α_k. Thus, we WLOG assume that we don't have $i > 0$. Hence, $i = 0$ (since $i \in \mathbb{N}$). Therefore, $h_i = h_0 = 1$, so that $\alpha_k\left(h_i\right) = \alpha_k\left(1\right) = 1$ (since α_k is a $\mathbf{k}$-algebra homomorphism). On the other hand, $i = 0 < k$, so that $\left[i < k\right] = 1$. Comparing this with $\alpha_k\left(h_i\right) = 1$, we obtain $\alpha_k\left(h_i\right) = \left[i < k\right]$. This proves Lemma 3.7 **(a)**.

(b) Let $i \in \mathbb{Z}$. We must prove that $\alpha_k\left(h_i\right) = \left[0 \leq i < k\right]$. If $i < 0$, then this boils down to $0 = 0$ (since $i < 0$ entails $h_i = 0$ and thus $\alpha_k\left(h_i\right) = \alpha_k\left(0\right) = 0$, but also $\left[0 \leq i < k\right] = 0$). Hence, we WLOG assume that $i \geq 0$. Thus, $i \in \mathbb{N}$. Hence, Lemma 3.7 **(a)** yields $\alpha_k\left(h_i\right) = \left[i < k\right]$. On the other hand, the statement "$0 \leq i < k$" is equivalent to the statement "$i < k$" (since $0 \leq i$ holds automatically[13]); thus, $\left[0 \leq i < k\right] = \left[i < k\right]$. Comparing this with $\alpha_k\left(h_i\right) = \left[i < k\right]$, we obtain $\alpha_k\left(h_i\right) = \left[0 \leq i < k\right]$. This proves Lemma 3.7 **(b)**.

(c) We recall the following simple property of truth values: If $\ell \in \mathbb{N}$, and if $\mathcal{A}_1, \mathcal{A}_2, \ldots, \mathcal{A}_\ell$ are ℓ logical statements, then

$$\begin{aligned}\prod_{i=1}^{\ell}\left[\mathcal{A}_i\right] &= \left[\mathcal{A}_1\right]\left[\mathcal{A}_2\right]\cdots\left[\mathcal{A}_\ell\right] = \left[\mathcal{A}_1 \wedge \mathcal{A}_2 \wedge \cdots \wedge \mathcal{A}_\ell\right] \\ &= \left[\mathcal{A}_i \text{ for all } i \in \left\{1, 2, \ldots, \ell\right\}\right]. \end{aligned} \tag{19}$$

Now, write the partition λ in the form $\lambda = \left(\lambda_1, \lambda_2, \ldots, \lambda_\ell\right)$, where $\lambda_1, \lambda_2, \ldots, \lambda_\ell$ are positive integers. Then, the definition of h_λ yields

$$h_\lambda = h_{\lambda_1} h_{\lambda_2} \cdots h_{\lambda_\ell} = \prod_{i=1}^{\ell} h_{\lambda_i}.$$

Applying the map α_k to both sides of this equality, we find

$$\begin{aligned}\alpha_k\left(h_\lambda\right) &= \alpha_k\left(\prod_{i=1}^{\ell} h_{\lambda_i}\right) = \prod_{i=1}^{\ell} \underbrace{\alpha_k\left(h_{\lambda_i}\right)}_{\substack{=\left[\lambda_i < k\right] \\ \text{(by (16), applied to } \lambda_i \text{ instead of } i\text{)}}} \\ &\qquad \left(\text{since } \alpha_k \text{ is a } \mathbf{k}\text{-algebra homomorphism}\right) \\ &= \prod_{i=1}^{\ell}\left[\lambda_i < k\right] = \left[\lambda_i < k \text{ for all } i \in \left\{1, 2, \ldots, \ell\right\}\right] \\ &\qquad \left(\text{by (19), applied to } \mathcal{A}_i = \left(\text{"}\lambda_i < k\text{"}\right)\right). \end{aligned} \tag{20}$$

[13] because $i \geq 0$

But we have $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_\ell)$ and thus $\lambda_{\ell+1} = \lambda_{\ell+2} = \lambda_{\ell+3} = \cdots = 0$. In other words, we have $\lambda_i = 0$ for all $i \in \{\ell+1, \ell+2, \ell+3, \ldots\}$. Hence, we have $\lambda_i < k$ for all $i \in \{\ell+1, \ell+2, \ell+3, \ldots\}$ (since all these i satisfy $\lambda_i = 0 < k$). Thus, the statement "$\lambda_i < k$ for all i" is equivalent to the statement "$\lambda_i < k$ for all $i \in \{1, 2, \ldots, \ell\}$".

Hence,

$$[\lambda_i < k \text{ for all } i] = [\lambda_i < k \text{ for all } i \in \{1, 2, \ldots, \ell\}] .$$

Comparing this with (20), we obtain $\alpha_k(h_\lambda) = [\lambda_i < k \text{ for all } i]$. Thus, Lemma 3.7 **(c)** is proved. □

3.6. Proof of Lemma 2.7

Lemma 2.7 can be proved directly using Laplace expansion of determinants. But the homomorphism α_k from Definition 3.6 allows for a slicker proof:

Proof of Lemma 2.7. Recall that α_k is a $\mathbf{k}$-algebra homomorphism. Thus, α_k respects determinants; i.e., if $(a_{i,j})_{1 \le i \le m,\ 1 \le j \le m} \in \Lambda^{m \times m}$ is an $m \times m$-matrix, then

$$\begin{aligned} &\alpha_k \left(\det \left((a_{i,j})_{1 \le i \le m,\ 1 \le j \le m} \right) \right) \\ &= \det \left((\alpha_k(a_{i,j}))_{1 \le i \le m,\ 1 \le j \le m} \right) . \end{aligned} \tag{21}$$

Applying α_k to both sides of (14), we obtain

$$\begin{aligned} \alpha_k(s_{\lambda/\mu}) &= \alpha_k \left(\det \left(\left(h_{\lambda_i - \mu_j - i + j} \right)_{1 \le i \le \ell,\ 1 \le j \le \ell} \right) \right) \\ &= \det \left(\left(\underbrace{\alpha_k \left(h_{\lambda_i - \mu_j - i + j} \right)}_{\substack{= [0 \le \lambda_i - \mu_j - i + j < k] \\ \text{(by (17))}}} \right)_{1 \le i \le \ell,\ 1 \le j \le \ell} \right) \\ &\qquad \left(\text{by (21), applied to } m = \ell \text{ and } a_{i,j} = h_{\lambda_i - \mu_j - i + j} \right) \\ &= \det \left(\left([0 \le \lambda_i - \mu_j - i + j < k] \right)_{1 \le i \le \ell,\ 1 \le j \le \ell} \right) . \end{aligned} \tag{22}$$

Thus, $\det \left(\left([0 \le \lambda_i - \mu_j - i + j < k] \right)_{1 \le i \le \ell,\ 1 \le j \le \ell} \right)$ does not depend on the choice of ℓ (since $\alpha_k(s_{\lambda/\mu})$ does not depend on the choice of ℓ). This proves Lemma 2.7. □

We record a useful consequence of the above proof:

Lemma 3.8. Let k be a positive integer. Let λ and μ be two partitions. Then, the homomorphism $\alpha_k : \Lambda \to \mathbf{k}$ from Definition 3.6 satisfies

$$\alpha_k \left(s_{\lambda/\mu} \right) = \operatorname{pet}_k \left(\lambda, \mu \right). \tag{23}$$

Proof of Lemma 3.8. Write the partitions λ and μ in the forms $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_\ell)$ and $\mu = (\mu_1, \mu_2, \ldots, \mu_\ell)$ for some $\ell \in \mathbb{N}$. Then, the equality (22) (which we showed in our proof of Lemma 2.7) yields

$$\alpha_k \left(s_{\lambda/\mu} \right) = \det \left(\left([0 \leq \lambda_i - \mu_j - i + j < k] \right)_{1 \leq i \leq \ell,\ 1 \leq j \leq \ell} \right) = \operatorname{pet}_k \left(\lambda, \mu \right)$$

(by the definition of $\operatorname{pet}_k (\lambda, \mu)$). This proves Lemma 3.8. □

3.7. Proof of Proposition 2.8

Proof of Proposition 2.8. Write the partitions λ and μ in the forms $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_\ell)$ and $\mu = (\mu_1, \mu_2, \ldots, \mu_\ell)$ for some $\ell \in \mathbb{N}$ [14]. The definition of $\operatorname{pet}_k (\lambda, \mu)$ yields

$$\begin{aligned}
\operatorname{pet}_k \left(\lambda, \mu \right) &= \det \left(\left(\left[\underbrace{0 \leq \lambda_i - \mu_j - i + j < k}_{\text{This is equivalent to } \mu_j - j \leq \lambda_i - i < \mu_j - j + k} \right] \right)_{1 \leq i \leq \ell,\ 1 \leq j \leq \ell} \right) \\
&= \det \left(\left([\mu_j - j \leq \lambda_i - i < \mu_j - j + k] \right)_{1 \leq i \leq \ell,\ 1 \leq j \leq \ell} \right).
\end{aligned} \tag{24}$$

Let B be the $\ell \times \ell$-matrix $\left([\mu_j - j \leq \lambda_i - i < \mu_j - j + k] \right)_{1 \leq i \leq \ell,\ 1 \leq j \leq \ell} \in \mathbf{k}^{\ell \times \ell}$. Then, (24) rewrites as follows:

$$\operatorname{pet}_k \left(\lambda, \mu \right) = \det B. \tag{25}$$

We will use the concept of Petrie matrices (see [GorWil74, Theorem 1]). Namely, a *Petrie matrix* is a matrix whose entries all belong to $\{0, 1\}$ and such that the 1's in each column occur consecutively (i.e., as a contiguous block). In other words, a Petrie matrix is a matrix whose each column has the form

$$\left(\underbrace{0, 0, \ldots, 0}_{a \text{ zeroes}}, \underbrace{1, 1, \ldots, 1}_{b \text{ ones}}, \underbrace{0, 0, \ldots, 0}_{c \text{ zeroes}} \right)^T \tag{26}$$

for some nonnegative integers a, b, c (where any of a, b, c can be 0). For example, $\begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$ is a Petrie matrix, but $\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 1 \end{pmatrix}$ is not.

[14] Such an ℓ can always be found, since each of λ and μ has only finitely many nonzero entries.

From [GorWil74, Theorem 1], it follows that if a square matrix A is a Petrie matrix, then

$$\det A \in \{-1, 0, 1\}. \tag{27}$$

Now, we shall show that B is a Petrie matrix.

Indeed, fix some $j \in \{1, 2, \ldots, \ell\}$. We have $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_\ell$ (since λ is a partition) and thus $\lambda_1 - 1 > \lambda_2 - 2 > \cdots > \lambda_\ell - \ell$. In other words, the numbers $\lambda_i - i$ for $i \in \{1, 2, \ldots, \ell\}$ decrease as i increases. Hence, the set of all $i \in \{1, 2, \ldots, \ell\}$ satisfying $\mu_j - j \leq \lambda_i - i < \mu_j - j + k$ is a (possibly empty) integer interval[15]. Let us denote this integer interval by I_j. Therefore, if we let i range over $\{1, 2, \ldots, \ell\}$, then the truth value $\left[\mu_j - j \leq \lambda_i - i < \mu_j - j + k\right]$ will be 1 for all $i \in I_j$, and 0 for all other i. Since I_j is an integer interval, this means that this truth value will be 1 when i lies in a certain integer interval (namely, I_j) and 0 when i lies outside it. In other words, the j-th column of the matrix B has a contiguous (but possibly empty) block of 1's (in the rows corresponding to all $i \in I_j$), while all other entries of this column are 0 (because the entries of the j-th column of B are precisely these truth values $\left[\mu_j - j \leq \lambda_i - i < \mu_j - j + k\right]$ for all $i \in \{1, 2, \ldots, \ell\}$). Therefore, this column has the form (26) for some nonnegative integers a, b, c.

Now, forget that we fixed j. We thus have proved that for each $j \in \{1, 2, \ldots, \ell\}$, the j-th column of B has the form (26) for some nonnegative integers a, b, c. In other words, each column of B has this form. Hence, B is a Petrie matrix (by the definition of a Petrie matrix). Therefore, (27) (applied to $A = B$) yields $\det B \in \{-1, 0, 1\}$. Thus, (25) becomes $\operatorname{pet}_k(\lambda, \mu) = \det B \in \{-1, 0, 1\}$. This proves Proposition 2.8. $\square$

3.8. First proof of Theorem 2.17

We are now ready for our first proof of Theorem 2.17:

First proof of Theorem 2.17. We shall use the notations $\mathbf{k}[[\mathbf{x}]]$, $\mathbf{k}[[\mathbf{x}, \mathbf{y}]]$, $\mathbf{x}$, $\mathbf{y}$, $f(\mathbf{x})$ and $f(\mathbf{y})$ introduced in Subsection 2.6. If R is any commutative ring, then $R[[\mathbf{y}]]$ shall denote the ring $R[[y_1, y_2, y_3, \ldots]]$ of formal power series in the indeterminates $y_1, y_2, y_3, \ldots$ over the ring R. We will identify the ring $\mathbf{k}[[\mathbf{x}, \mathbf{y}]]$ with the ring $(\mathbf{k}[[\mathbf{x}]])[[\mathbf{y}]] = (\mathbf{k}[[x_1, x_2, x_3, \ldots]])[[y_1, y_2, y_3, \ldots]]$. Note that $\Lambda \subseteq \mathbf{k}[[\mathbf{x}]]$ and thus $\Lambda[[\mathbf{y}]] \subseteq (\mathbf{k}[[\mathbf{x}]])[[\mathbf{y}]] = \mathbf{k}[[\mathbf{x}, \mathbf{y}]]$. We equip the rings $\mathbf{k}[[\mathbf{y}]]$, $\Lambda[[\mathbf{y}]]$ and $\mathbf{k}[[\mathbf{x}, \mathbf{y}]]$ with the usual topologies that are defined on rings of power series, where Λ itself is equipped with the discrete topology. This has the somewhat confusing consequence that $\Lambda[[\mathbf{y}]] \subseteq \mathbf{k}[[\mathbf{x}, \mathbf{y}]]$ is an inclusion of rings but not of topological spaces; however, this will not cause us any trouble, since all infinite sums in $\Lambda[[\mathbf{y}]]$ we will consider (such as $\sum\limits_{\lambda \in \operatorname{Par}} s_{\lambda/\mu}(\mathbf{x}) s_\lambda(\mathbf{y})$ and $\sum\limits_{\lambda \in \operatorname{Par}} h_\lambda(\mathbf{x}) m_\lambda(\mathbf{y})$) will converge to the same value in either topology.

[15] An *integer interval* means a subset of $\mathbb{Z}$ that has the form $\{a, a+1, \ldots, b\}$ for some $a \in \mathbb{Z}$ and $b \in \mathbb{Z}$. (If $a > b$, then this is the empty set.)

We consider both $\mathbf{k}[[\mathbf{y}]]$ and Λ as subrings of $\Lambda[[\mathbf{y}]]$ (indeed, $\mathbf{k}[[\mathbf{y}]]$ embeds into $\Lambda[[\mathbf{y}]]$ because $\mathbf{k}$ is a subring of Λ, whereas Λ embeds into $\Lambda[[\mathbf{y}]]$ because $\Lambda[[\mathbf{y}]]$ is a ring of power series over Λ).

In this proof, the word "monomial" may refer to a monomial in any set of variables (not necessarily in $x_1, x_2, x_3, \ldots$).

Recall the $\mathbf{k}$-algebra homomorphism $\alpha_k : \Lambda \to \mathbf{k}$ from Definition 3.6. This $\mathbf{k}$-algebra homomorphism $\alpha_k : \Lambda \to \mathbf{k}$ induces a $\mathbf{k}[[\mathbf{y}]]$-algebra homomorphism $\alpha_k[[\mathbf{y}]] : \Lambda[[\mathbf{y}]] \to \mathbf{k}[[\mathbf{y}]]$, which is given by the formula

$$(\alpha_k[[\mathbf{y}]]) \left(\sum_{\substack{\mathfrak{n} \text{ is a monomial} \\ \text{in } y_1, y_2, y_3, \ldots}} f_{\mathfrak{n}} \mathfrak{n} \right) = \sum_{\substack{\mathfrak{n} \text{ is a monomial} \\ \text{in } y_1, y_2, y_3, \ldots}} \alpha_k(f_{\mathfrak{n}}) \mathfrak{n}$$

for any family $(f_{\mathfrak{n}})_{\mathfrak{n} \text{ is a monomial in } y_1, y_2, y_3, \ldots}$ of elements of Λ. This induced $\mathbf{k}[[\mathbf{y}]]$-algebra homomorphism $\alpha_k[[\mathbf{y}]]$ is $\mathbf{k}[[\mathbf{y}]]$-linear and continuous (with respect to the usual topologies on the power series rings $\Lambda[[\mathbf{y}]]$ and $\mathbf{k}[[\mathbf{y}]]$), and thus preserves infinite $\mathbf{k}[[\mathbf{y}]]$-linear combinations. Moreover, it extends α_k (that is, for any $f \in \Lambda$, we have $(\alpha_k[[\mathbf{y}]])(f) = \alpha_k(f)$).

Recall the skew Schur functions $s_{\lambda/\mu}$ defined in Subsection 3.3. Also, recall the symmetric functions h_λ defined in Definition 3.1. Theorem 3.5 yields

$$\begin{aligned} \sum_{\lambda \in \mathrm{Par}} s_{\lambda/\mu}(\mathbf{x}) s_\lambda(\mathbf{y}) &= s_\mu(\mathbf{y}) \cdot \sum_{\lambda \in \mathrm{Par}} h_\lambda(\mathbf{x}) m_\lambda(\mathbf{y}) = \sum_{\lambda \in \mathrm{Par}} s_\mu(\mathbf{y}) \underbrace{h_\lambda(\mathbf{x}) m_\lambda(\mathbf{y})}_{= m_\lambda(\mathbf{y}) h_\lambda(\mathbf{x})} \\ &= \sum_{\lambda \in \mathrm{Par}} s_\mu(\mathbf{y}) m_\lambda(\mathbf{y}) \underbrace{h_\lambda(\mathbf{x})}_{= h_\lambda} = \sum_{\lambda \in \mathrm{Par}} s_\mu(\mathbf{y}) m_\lambda(\mathbf{y}) h_\lambda. \end{aligned}$$

Comparing this with

$$\sum_{\lambda \in \mathrm{Par}} \underbrace{s_{\lambda/\mu}(\mathbf{x}) s_\lambda(\mathbf{y})}_{= s_\lambda(\mathbf{y}) s_{\lambda/\mu}(\mathbf{x})} = \sum_{\lambda \in \mathrm{Par}} s_\lambda(\mathbf{y}) \underbrace{s_{\lambda/\mu}(\mathbf{x})}_{= s_{\lambda/\mu}} = \sum_{\lambda \in \mathrm{Par}} s_\lambda(\mathbf{y}) s_{\lambda/\mu},$$

we obtain

$$\sum_{\lambda \in \mathrm{Par}} s_\lambda(\mathbf{y}) s_{\lambda/\mu} = \sum_{\lambda \in \mathrm{Par}} s_\mu(\mathbf{y}) m_\lambda(\mathbf{y}) h_\lambda.$$

Consider this as an equality in the ring $\Lambda[[\mathbf{y}]] = \Lambda[[y_1, y_2, y_3, \ldots]]$. Apply the map $\alpha_k[[\mathbf{y}]] : \Lambda[[\mathbf{y}]] \to \mathbf{k}[[\mathbf{y}]]$ to both sides of this equality. We obtain

$$(\alpha_k[[\mathbf{y}]]) \left(\sum_{\lambda \in \mathrm{Par}} s_\lambda(\mathbf{y}) s_{\lambda/\mu} \right) = (\alpha_k[[\mathbf{y}]]) \left(\sum_{\lambda \in \mathrm{Par}} s_\mu(\mathbf{y}) m_\lambda(\mathbf{y}) h_\lambda \right).$$

Comparing this with

$$\begin{aligned}
&\left(\alpha_k\left[\left[\mathbf{y}\right]\right]\right)\left(\sum_{\lambda\in\operatorname{Par}} s_\lambda\left(\mathbf{y}\right)s_{\lambda/\mu}\right) \\
&= \sum_{\lambda\in\operatorname{Par}} s_\lambda\left(\mathbf{y}\right)\cdot \underbrace{\left(\alpha_k\left[\left[\mathbf{y}\right]\right]\right)\left(s_{\lambda/\mu}\right)}_{\substack{=\alpha_k\left(s_{\lambda/\mu}\right)\\ \text{(since } \alpha_k[[\mathbf{y}]] \text{ extends } \alpha_k\text{)}}} \\
&\qquad \left(\text{since the map } \alpha_k\left[\left[\mathbf{y}\right]\right] \text{ preserves infinite } \mathbf{k}\left[\left[\mathbf{y}\right]\right]\text{-linear combinations}\right) \\
&= \sum_{\lambda\in\operatorname{Par}} s_\lambda\left(\mathbf{y}\right)\cdot \underbrace{\alpha_k\left(s_{\lambda/\mu}\right)}_{\substack{=\operatorname{pet}_k(\lambda,\mu)\\ \text{(by (23))}}} = \sum_{\lambda\in\operatorname{Par}} s_\lambda\left(\mathbf{y}\right)\cdot\operatorname{pet}_k\left(\lambda,\mu\right) = \sum_{\lambda\in\operatorname{Par}} \operatorname{pet}_k\left(\lambda,\mu\right)\cdot s_\lambda\left(\mathbf{y}\right),
\end{aligned}$$

we obtain

$$\begin{aligned}
&\sum_{\lambda\in\operatorname{Par}} \operatorname{pet}_k\left(\lambda,\mu\right)\cdot s_\lambda\left(\mathbf{y}\right) \\
&= \left(\alpha_k\left[\left[\mathbf{y}\right]\right]\right)\left(\sum_{\lambda\in\operatorname{Par}} s_\mu\left(\mathbf{y}\right)m_\lambda\left(\mathbf{y}\right)h_\lambda\right) = \sum_{\lambda\in\operatorname{Par}} s_\mu\left(\mathbf{y}\right)m_\lambda\left(\mathbf{y}\right) \underbrace{\left(\alpha_k\left[\left[\mathbf{y}\right]\right]\right)\left(h_\lambda\right)}_{\substack{=\alpha_k(h_\lambda)\\ \text{(since } \alpha_k[[\mathbf{y}]] \text{ extends } \alpha_k\text{)}}} \\
&\qquad \left(\text{since the map } \alpha_k\left[\left[\mathbf{y}\right]\right] \text{ preserves infinite } \mathbf{k}\left[\left[\mathbf{y}\right]\right]\text{-linear combinations}\right) \\
&= \sum_{\lambda\in\operatorname{Par}} s_\mu\left(\mathbf{y}\right)m_\lambda\left(\mathbf{y}\right) \underbrace{\alpha_k\left(h_\lambda\right)}_{\substack{=[\lambda_i<k \text{ for all } i]\\ \text{(by (18))}}} = \sum_{\lambda\in\operatorname{Par}} s_\mu\left(\mathbf{y}\right)m_\lambda\left(\mathbf{y}\right)\cdot\left[\lambda_i<k \text{ for all } i\right] \\
&= \sum_{\lambda\in\operatorname{Par}} \left[\lambda_i<k \text{ for all } i\right]\cdot s_\mu\left(\mathbf{y}\right)m_\lambda\left(\mathbf{y}\right).
\end{aligned}$$

Renaming the indeterminates $\mathbf{y} = (y_1, y_2, y_3, \ldots)$ as $\mathbf{x} = (x_1, x_2, x_3, \ldots)$ on both sides of this equality, we obtain

$$\begin{aligned}
&\sum_{\lambda\in\operatorname{Par}} \operatorname{pet}_k\left(\lambda,\mu\right)\cdot s_\lambda\left(\mathbf{x}\right) \\
&= \sum_{\lambda\in\operatorname{Par}} \left[\lambda_i<k \text{ for all } i\right]\cdot \underbrace{s_\mu\left(\mathbf{x}\right)}_{=s_\mu}\underbrace{m_\lambda\left(\mathbf{x}\right)}_{=m_\lambda} = \sum_{\lambda\in\operatorname{Par}} \left[\lambda_i<k \text{ for all } i\right]\cdot s_\mu m_\lambda \\
&= \sum_{\substack{\lambda\in\operatorname{Par};\\ \lambda_i<k \text{ for all } i}} \underbrace{\left[\lambda_i<k \text{ for all } i\right]}_{\substack{=1\\ \text{(since } \lambda_i<k \text{ for all } i\text{)}}} \cdot s_\mu m_\lambda + \sum_{\substack{\lambda\in\operatorname{Par};\\ \text{not } (\lambda_i<k \text{ for all } i)}} \underbrace{\left[\lambda_i<k \text{ for all } i\right]}_{\substack{=0\\ \text{(since we don't have ``}\lambda_i<k \text{ for all } i\text{'')}}} \cdot s_\mu m_\lambda \\
&\qquad \left(\text{since any } \lambda\in\operatorname{Par} \text{ satisfies either } \left(\lambda_i<k \text{ for all } i\right) \text{ or not } \left(\lambda_i<k \text{ for all } i\right)\right) \\
&= \sum_{\substack{\lambda\in\operatorname{Par};\\ \lambda_i<k \text{ for all } i}} s_\mu m_\lambda + \underbrace{\sum_{\substack{\lambda\in\operatorname{Par};\\ \text{not } (\lambda_i<k \text{ for all } i)}} 0 s_\mu m_\lambda}_{=0} = \sum_{\substack{\lambda\in\operatorname{Par};\\ \lambda_i<k \text{ for all } i}} s_\mu m_\lambda .
\end{aligned}$$

Comparing this with

$$G(k)\cdot s_\mu = s_\mu \cdot \underbrace{G(k)}_{\substack{=\sum\limits_{\substack{\lambda\in\mathrm{Par};\\ \lambda_i<k \text{ for all } i}} m_\lambda \\ \text{(by Proposition 2.3 (b))}}} = s_\mu \cdot \sum_{\substack{\lambda\in\mathrm{Par};\\ \lambda_i<k \text{ for all } i}} m_\lambda = \sum_{\substack{\lambda\in\mathrm{Par};\\ \lambda_i<k \text{ for all } i}} s_\mu m_\lambda,$$

we obtain

$$G(k)\cdot s_\mu = \sum_{\lambda\in\mathrm{Par}} \mathrm{pet}_k(\lambda,\mu)\cdot \underbrace{s_\lambda(\mathbf{x})}_{=s_\lambda} = \sum_{\lambda\in\mathrm{Par}} \mathrm{pet}_k(\lambda,\mu)\, s_\lambda.$$

This proves Theorem 2.17. □

3.9. Second proof of Theorem 2.17

Our second proof of Theorem 2.17 will rely on [GriRei20, §2.6] and specifically on the notion of alternants. We shall give only a sketch of it; the reader can consult [Grinbe20b] for the full version.

Second proof of Theorem 2.17 (sketched). If $f \in \mathbf{k}[[x_1,x_2,x_3,\ldots]]$ is any formal power series, and if $\ell \in \mathbb{N}$, then $f(x_1,x_2,\ldots,x_\ell)$ shall denote the formal power series

$$f(x_1,x_2,\ldots,x_\ell,0,0,0,\ldots) \in \mathbf{k}[[x_1,x_2,\ldots,x_\ell]]$$

that is obtained by substituting $0,0,0,\ldots$ for the variables $x_{\ell+1},x_{\ell+2},x_{\ell+3},\ldots$ in f. Equivalently, $f(x_1,x_2,\ldots,x_\ell)$ can be obtained from f by removing all monomials that contain any of the variables $x_{\ell+1},x_{\ell+2},x_{\ell+3},\ldots$. This makes it clear that any $f\in\mathbf{k}[[x_1,x_2,x_3,\ldots]]$ satisfies

$$f = \lim_{\ell\to\infty} f(x_1,x_2,\ldots,x_\ell) \tag{28}$$

(where the limit is taken with respect to the usual topology on $\mathbf{k}[[x_1,x_2,x_3,\ldots]]$).

Let $\ell(\mu)$ denote the number of parts of μ. Fix an $\ell\in\mathbb{N}$ such that $\ell \geq \ell(\mu)$. We shall show that

$$\begin{aligned}&(G(k))(x_1,x_2,\ldots,x_\ell)\cdot s_\mu(x_1,x_2,\ldots,x_\ell)\\ &= \sum_{\lambda\in\mathrm{Par}} \mathrm{pet}_k(\lambda,\mu)\, s_\lambda(x_1,x_2,\ldots,x_\ell).\end{aligned} \tag{29}$$

Once this is done, the usual "let ℓ tend to ∞" argument (analogous to [GriRei20, proof of Corollary 2.6.11]) will yield the validity of Theorem 2.17.

Let P_ℓ denote the set of all partitions with at most ℓ parts. Any partition $\lambda\in P_\ell$ satisfies $\lambda=(\lambda_1,\lambda_2,\ldots,\lambda_\ell)$, and thus can be regarded as an ℓ-tuple of nonnegative integers. In other words, $P_\ell\subseteq\mathbb{N}^\ell$. More precisely, the partitions $\lambda\in P_\ell$ are precisely the ℓ-tuples $(\lambda_1,\lambda_2,\ldots,\lambda_\ell)\in\mathbb{N}^\ell$ satisfying $\lambda_1\geq\lambda_2\geq\cdots\geq\lambda_\ell$.

Define the ℓ-tuple $\rho = (\ell - 1, \ell - 2, \ldots, 0) \in \mathbb{N}^\ell$.

For any ℓ-tuple $\alpha \in \mathbb{N}^\ell$ and each $i \in \{1, 2, \ldots, \ell\}$, we shall write α_i for the i-th entry of α.

For any ℓ-tuple $\alpha \in \mathbb{N}^\ell$, we let $\mathbf{x}^\alpha$ denote the monomial $x_1^{\alpha_1} x_2^{\alpha_2} \cdots x_\ell^{\alpha_\ell}$.

Let $\mathfrak{S}_\ell$ denote the symmetric group of the set $\{1, 2, \ldots, \ell\}$. This group $\mathfrak{S}_\ell$ acts by $\mathbf{k}$-algebra homomorphisms on the polynomial ring $\mathbf{k}[x_1, x_2, \ldots, x_\ell]$. It also acts on the set $\mathbb{N}^\ell$ by permuting the entries of an ℓ-tuple; namely,

$$\sigma \cdot \beta = \left(\beta_{\sigma^{-1}(1)}, \beta_{\sigma^{-1}(2)}, \ldots, \beta_{\sigma^{-1}(\ell)}\right) \qquad \text{for any } \sigma \in \mathfrak{S}_\ell \text{ and } \beta \in \mathbb{N}^\ell.$$

For any $\sigma \in \mathfrak{S}_\ell$, we let $(-1)^\sigma$ denote the sign of the permutation σ.

If $\alpha \in \mathbb{N}^\ell$ is any ℓ-tuple, then we define the polynomial $a_\alpha \in \mathbf{k}[x_1, x_2, \ldots, x_\ell]$ (called the *α-alternant*) by

$$a_\alpha = \sum_{\sigma \in \mathfrak{S}_\ell} (-1)^\sigma \sigma(\mathbf{x}^\alpha) = \det\left(\left(x_j^{\alpha_i}\right)_{1 \le i \le \ell,\ 1 \le j \le \ell}\right).$$

We define addition of ℓ-tuples $\alpha \in \mathbb{N}^\ell$ entrywise (so that $(\alpha + \beta)_i = \alpha_i + \beta_i$ for every $\alpha, \beta \in \mathbb{N}^\ell$ and $i \in \{1, 2, \ldots, \ell\}$). Thus, $\lambda + \rho \in \mathbb{N}^\ell$ for each $\lambda \in P_\ell$ (since $\lambda \in P_\ell \subseteq \mathbb{N}^\ell$).

It is known ([GriRei20, Corollary 2.6.7]) that

$$s_\lambda(x_1, x_2, \ldots, x_\ell) = \frac{a_{\lambda+\rho}}{a_\rho} \tag{30}$$

for every $\lambda \in P_\ell$.

The partition μ has at most ℓ parts (since $\ell \ge \ell(\mu)$). In other words, $\mu \in P_\ell$.

Now, define $\alpha \in \mathbb{N}^\ell$ by $\alpha = \mu + \rho$. Proposition 2.3 **(b)** yields

$$G(k) = \prod_{i=1}^{\infty} \left(x_i^0 + x_i^1 + \cdots + x_i^{k-1}\right).$$

Substituting $0, 0, 0, \ldots$ for $x_{\ell+1}, x_{\ell+2}, x_{\ell+3}, \ldots$ in this equality, we obtain

$$
\begin{aligned}
& (G(k))(x_1, x_2, \ldots, x_\ell) \\
& = \left(\prod_{i=1}^{\ell} \left(x_i^0 + x_i^1 + \cdots + x_i^{k-1} \right) \right) \cdot \left(\prod_{i=\ell+1}^{\infty} \underbrace{\left(0^0 + 0^1 + \cdots + 0^{k-1} \right)}_{\substack{=1 \\ \text{(since } 0^0=1 \text{ and } 0^j=0 \text{ for all } j>0)}} \right) \\
& = \prod_{i=1}^{\ell} \left(x_i^0 + x_i^1 + \cdots + x_i^{k-1} \right) \qquad (31) \\
& = \sum_{(j_1, j_2, \ldots, j_\ell) \in \{0,1,\ldots,k-1\}^\ell} x_1^{j_1} x_2^{j_2} \cdots x_\ell^{j_\ell} \qquad \text{(by the product rule)} \\
& = \sum_{\substack{\beta \in \mathbb{N}^\ell; \\ \beta_i < k \text{ for all } i}} \mathbf{x}^\beta \qquad (32) \\
& \qquad \left(\text{here, we have substituted } \beta \text{ for } (j_1, j_2, \ldots, j_\ell) \text{ in the sum} \right).
\end{aligned}
$$

(Here and in the rest of this proof, "for all i" means "for all $i \in \{1, 2, \ldots, \ell\}$".)

From (31), we see that $(G(k))(x_1, x_2, \ldots, x_\ell)$ is a polynomial in $\mathbf{k}[x_1, x_2, \ldots, x_\ell]$ (not merely a power series). From (31), we moreover see that this polynomial $(G(k))(x_1, x_2, \ldots, x_\ell) \in \mathbf{k}[x_1, x_2, \ldots, x_\ell]$ is invariant under the action of $\mathfrak{S}_\ell$.

But from $a_\alpha = \sum_{\sigma\in\mathfrak{S}_\ell} (-1)^\sigma \sigma(\mathbf{x}^\alpha)$, we obtain

$$\begin{aligned}
(G(k))(x_1,x_2,\ldots,x_\ell)\cdot a_\alpha &= (G(k))(x_1,x_2,\ldots,x_\ell)\cdot \sum_{\sigma\in\mathfrak{S}_\ell} (-1)^\sigma \sigma(\mathbf{x}^\alpha) \\
&= \sum_{\sigma\in\mathfrak{S}_\ell} (-1)^\sigma \underbrace{(G(k))(x_1,x_2,\ldots,x_\ell)}_{\substack{=\sigma((G(k))(x_1,x_2,\ldots,x_\ell)) \\ \text{(since the polynomial } (G(k))(x_1,x_2,\ldots,x_\ell) \\ \text{is invariant under the action of } \mathfrak{S}_\ell)}} \cdot\sigma(\mathbf{x}^\alpha) \\
&= \sum_{\sigma\in\mathfrak{S}_\ell} (-1)^\sigma \underbrace{\sigma((G(k))(x_1,x_2,\ldots,x_\ell))\cdot\sigma(\mathbf{x}^\alpha)}_{\substack{=\sigma((G(k))(x_1,x_2,\ldots,x_\ell)\cdot\mathbf{x}^\alpha) \\ \text{(since } \mathfrak{S}_\ell \text{ acts on } \mathbf{k}[x_1,x_2,\ldots,x_\ell] \\ \text{by } \mathbf{k}\text{-algebra homomorphisms)}}} \\
&= \sum_{\sigma\in\mathfrak{S}_\ell} (-1)^\sigma \sigma((G(k))(x_1,x_2,\ldots,x_\ell)\cdot\mathbf{x}^\alpha) \\
&= \sum_{\sigma\in\mathfrak{S}_\ell} (-1)^\sigma \sigma\left(\sum_{\substack{\beta\in\mathbb{N}^\ell; \\ \beta_i<k \text{ for all } i}} \mathbf{x}^\beta\cdot\mathbf{x}^\alpha \right) \qquad \text{(by (32))} \\
&= \sum_{\substack{\beta\in\mathbb{N}^\ell; \\ \beta_i<k \text{ for all } i}} \sum_{\sigma\in\mathfrak{S}_\ell} (-1)^\sigma \sigma\left(\underbrace{\mathbf{x}^\beta\cdot\mathbf{x}^\alpha}_{\substack{=\mathbf{x}^\alpha\cdot\mathbf{x}^\beta \\ =\mathbf{x}^{\alpha+\beta}}} \right) \\
&= \sum_{\substack{\beta\in\mathbb{N}^\ell; \\ \beta_i<k \text{ for all } i}} \underbrace{\sum_{\sigma\in\mathfrak{S}_\ell} (-1)^\sigma \sigma\left(\mathbf{x}^{\alpha+\beta}\right)}_{\substack{=a_{\alpha+\beta} \\ \text{(by the definition of } a_{\alpha+\beta})}} = \sum_{\substack{\beta\in\mathbb{N}^\ell; \\ \beta_i<k \text{ for all } i}} a_{\alpha+\beta} \\
&= \sum_{\substack{\gamma\in\mathbb{N}^\ell; \\ 0\le\gamma_i-\alpha_i<k \text{ for all } i}} a_\gamma
\end{aligned} \tag{33}$$

(here, we have substituted γ for $\alpha+\beta$ in the sum).

It is well-known (and easy to check using the properties of determinants[16]) that if an ℓ-tuple $\gamma\in\mathbb{N}^\ell$ has two equal entries, then

$$a_\gamma = 0. \tag{34}$$

Moreover, any ℓ-tuple $\gamma\in\mathbb{N}^\ell$ and any $\sigma\in\mathfrak{S}_\ell$ satisfy

$$a_{\sigma\cdot\gamma} = (-1)^\sigma\cdot a_\gamma. \tag{35}$$

(This, too, follows from the properties of determinants[17].)

[16]specifically: using the fact that a square matrix with two equal rows always has determinant 0

[17]specifically: using the fact that permuting the rows of a square matrix results in its determinant getting multiplied by the sign of the permutation

Let SP_ℓ denote the set of all ℓ-tuples $\delta \in \mathbb{N}^\ell$ such that $\delta_1 > \delta_2 > \cdots > \delta_\ell$. Then, the map

$$\begin{aligned} P_\ell &\to SP_\ell, \\ \lambda &\mapsto \lambda + \rho \end{aligned} \tag{36}$$

is a bijection.

If an ℓ-tuple $\gamma \in \mathbb{N}^\ell$ has no two equal entries, then γ can be uniquely written in the form $\sigma \cdot \delta$ for some $\sigma \in \mathfrak{S}_\ell$ and some $\delta \in SP_\ell$ (indeed, δ is the result of sorting γ into decreasing order, while σ is the permutation that achieves this sorting). In other words, the map

$$\begin{aligned} \mathfrak{S}_\ell \times SP_\ell &\to \left\{\gamma \in \mathbb{N}^\ell \mid \text{ the } \ell\text{-tuple } \gamma \text{ has no two equal entries}\right\}, \\ (\sigma, \delta) &\mapsto \sigma \cdot \delta \end{aligned} \tag{37}$$

is a bijection.

Now, (33) becomes

$$\begin{aligned}
&(G(k))(x_1, x_2, \ldots, x_\ell) \cdot a_\alpha \\
&= \sum_{\substack{\gamma \in \mathbb{N}^\ell; \\ 0 \leq \gamma_i - \alpha_i < k \text{ for all } i}} a_\gamma \\
&= \sum_{\substack{\gamma \in \mathbb{N}^\ell; \\ 0 \leq \gamma_i - \alpha_i < k \text{ for all } i; \\ \text{the } \ell\text{-tuple } \gamma \text{ has no two equal entries}}} a_\gamma + \sum_{\substack{\gamma \in \mathbb{N}^\ell; \\ 0 \leq \gamma_i - \alpha_i < k \text{ for all } i; \\ \text{the } \ell\text{-tuple } \gamma \text{ has two equal entries}}} \underbrace{a_\gamma}_{\substack{=0 \\ \text{(by (34))}}} \\
&= \sum_{\substack{\gamma \in \mathbb{N}^\ell; \\ 0 \leq \gamma_i - \alpha_i < k \text{ for all } i; \\ \text{the } \ell\text{-tuple } \gamma \text{ has no two equal entries}}} a_\gamma \\
&= \sum_{\substack{\gamma \in \mathbb{N}^\ell; \\ \text{the } \ell\text{-tuple } \gamma \text{ has no two equal entries}}} [0 \leq \gamma_i - \alpha_i < k \text{ for all } i] \cdot a_\gamma \\
&= \underbrace{\sum_{(\sigma,\delta) \in \mathfrak{S}_\ell \times SP_\ell}}_{= \sum_{\delta \in SP_\ell} \sum_{\sigma \in \mathfrak{S}_\ell}} \left[0 \leq \underbrace{(\sigma \cdot \delta)_i}_{=\delta_{\sigma^{-1}(i)}} - \alpha_i < k \text{ for all } i \right] \cdot \underbrace{a_{\sigma \cdot \delta}}_{\substack{=(-1)^\sigma a_\delta \\ \text{(by (35))}}} \\
&\qquad \left(\begin{array}{c} \text{here, we have substituted } \sigma \cdot \delta \text{ for } \gamma \text{ in the sum,} \\ \text{since the map (37) is a bijection} \end{array} \right) \\
&= \sum_{\delta \in SP_\ell} \sum_{\sigma \in \mathfrak{S}_\ell} \underbrace{\left[0 \leq \delta_{\sigma^{-1}(i)} - \alpha_i < k \text{ for all } i \right]}_{\substack{= \prod_{i=1}^{\ell} \left[0 \leq \delta_{\sigma^{-1}(i)} - \alpha_i < k \right] \\ = \prod_{i=1}^{\ell} \left[0 \leq \delta_i - \alpha_{\sigma(i)} < k \right] \\ \text{(here, we have substituted } \sigma(i) \\ \text{for } i \text{ in the product, since } \sigma \text{ is a bijection)}}} \cdot (-1)^\sigma a_\delta \\
&= \sum_{\delta \in SP_\ell} \underbrace{\sum_{\sigma \in \mathfrak{S}_\ell} \left(\prod_{i=1}^{\ell} \left[0 \leq \delta_i - \alpha_{\sigma(i)} < k \right] \right) \cdot (-1)^\sigma}_{\substack{= \sum_{\sigma \in \mathfrak{S}_\ell} (-1)^\sigma \prod_{i=1}^{\ell} \left[0 \leq \delta_i - \alpha_{\sigma(i)} < k \right] \\ = \det \left(\left(\left[0 \leq \delta_i - \alpha_j < k \right] \right)_{1 \leq i \leq \ell,\ 1 \leq j \leq \ell} \right) \\ \text{(by the definition of a determinant)}}} a_\delta \\
&= \sum_{\delta \in SP_\ell} \det \left(\left(\left[0 \leq \delta_i - \alpha_j < k \right] \right)_{1 \leq i \leq \ell,\ 1 \leq j \leq \ell} \right) a_\delta \\
&= \sum_{\lambda \in P_\ell} \det \left(\left(\left[0 \leq (\lambda + \rho)_i - \alpha_j < k \right] \right)_{1 \leq i \leq \ell,\ 1 \leq j \leq \ell} \right) a_{\lambda + \rho} \qquad (38)
\end{aligned}$$

(here, we have substituted $\lambda + \rho$ for δ in the sum, since the map (36) is a bijection).

Using the definitions of ρ and α, it is easy to see that

$$(\lambda + \rho)_i - \alpha_j = \lambda_i - \mu_j - i + j \tag{39}$$

for every $\lambda \in P_\ell$ and every $i, j \in \{1, 2, \ldots, \ell\}$.

Now, (30) (applied to $\lambda = \mu$) yields

$$s_\mu (x_1, x_2, \ldots, x_\ell) = \frac{a_{\mu+\rho}}{a_\rho} = \frac{a_\alpha}{a_\rho}$$

(since $\mu + \rho = \alpha$). Multiplying this equality by $(G(k))(x_1, x_2, \ldots, x_\ell)$, we find

$$\begin{aligned}
&(G(k))(x_1, x_2, \ldots, x_\ell) \cdot s_\mu (x_1, x_2, \ldots, x_\ell) \\
&= (G(k))(x_1, x_2, \ldots, x_\ell) \cdot \frac{a_\alpha}{a_\rho} \\
&= \frac{1}{a_\rho} \cdot \underbrace{(G(k))(x_1, x_2, \ldots, x_\ell) \cdot a_\alpha}_{\substack{= \sum_{\lambda \in P_\ell} \det\left(\left([0 \le (\lambda+\rho)_i - \alpha_j < k] \right)_{1 \le i \le \ell,\ 1 \le j \le \ell} \right) a_{\lambda+\rho} \\ \text{(by (38))}}} \\
&= \sum_{\lambda \in P_\ell} \det \left(\left(\left[0 \le \underbrace{(\lambda+\rho)_i - \alpha_j}_{\substack{= \lambda_i - \mu_j - i + j \\ \text{(by (39))}}} < k \right] \right)_{1 \le i \le \ell,\ 1 \le j \le \ell} \right) \underbrace{\frac{a_{\lambda+\rho}}{a_\rho}}_{\substack{= s_\lambda (x_1, x_2, \ldots, x_\ell) \\ \text{(by (30))}}} \\
&= \sum_{\lambda \in P_\ell} \underbrace{\det \left(\left([0 \le \lambda_i - \mu_j - i + j < k] \right)_{1 \le i \le \ell,\ 1 \le j \le \ell} \right)}_{\substack{= \operatorname{pet}_k(\lambda, \mu) \\ \text{(by the definition of } \operatorname{pet}_k(\lambda,\mu))}} \cdot s_\lambda (x_1, x_2, \ldots, x_\ell) \\
&= \sum_{\lambda \in P_\ell} \operatorname{pet}_k(\lambda, \mu)\, s_\lambda (x_1, x_2, \ldots, x_\ell) = \sum_{\lambda \in \operatorname{Par}} \operatorname{pet}_k(\lambda, \mu)\, s_\lambda (x_1, x_2, \ldots, x_\ell),
\end{aligned}$$

where the last equality sign is owed to the well-known fact (see, e.g., [GriRei20, Exercise 2.3.8(b)]) that every $\lambda \in \operatorname{Par} \setminus P_\ell$ (that is, every partition λ having more than ℓ parts) satisfies $s_\lambda (x_1, x_2, \ldots, x_\ell) = 0$. Thus, (29) has been proved.

Forget that we fixed ℓ. Thus, we have proved (29) for each $\ell \in \mathbb{N}$ that satisfies $\ell \ge \ell(\mu)$. As we mentioned above, we can now use a standard limiting argument (using (28)) to obtain the claim of Theorem 2.17. $\square$

3.10. Proofs of Corollary 2.18, Theorem 2.9 and Corollary 2.10

Having proved Theorem 2.17, we can now obtain Corollary 2.18, Theorem 2.9 and Corollary 2.10 as easy consequences:

Proof of Corollary 2.18. Proposition 2.3 **(a)** yields that the m-th degree homogeneous component of $G(k)$ is $G(k,m)$. Hence, the $(m+|\mu|)$-th degree homogeneous component of $G(k) \cdot s_\mu$ is $G(k,m) \cdot s_\mu$ (because s_μ is homogeneous of degree $|\mu|$).

Theorem 2.17 yields

$$G(k) \cdot s_\mu = \sum_{\lambda \in \mathrm{Par}} \mathrm{pet}_k(\lambda, \mu) s_\lambda.$$

Taking the $(m+|\mu|)$-th degree homogeneous components on both sides of this equality, we obtain

$$G(k,m) \cdot s_\mu = \sum_{\lambda \in \mathrm{Par}_{m+|\mu|}} \mathrm{pet}_k(\lambda, \mu) s_\lambda$$

(because each Schur function s_λ is homogeneous of degree $|\lambda|$, whereas the $(m+|\mu|)$-th degree homogeneous component of $G(k) \cdot s_\mu$ is $G(k,m) \cdot s_\mu$). This proves Corollary 2.18. $\square$

Proof of Theorem 2.9. Theorem 2.17 (applied to $\mu = \varnothing$) yields

$$G(k) \cdot s_\varnothing = \sum_{\lambda \in \mathrm{Par}} \mathrm{pet}_k(\lambda, \varnothing) s_\lambda.$$

Comparing this with $G(k) \cdot \underbrace{s_\varnothing}_{=1} = G(k)$, we obtain

$$G(k) = \sum_{\lambda \in \mathrm{Par}} \mathrm{pet}_k(\lambda, \varnothing) s_\lambda.$$

This proves Theorem 2.9. $\square$

Proof of Corollary 2.10. Corollary 2.18 (applied to $\mu = \varnothing$) yields

$$G(k,m) \cdot s_\varnothing = \sum_{\lambda \in \mathrm{Par}_{m+|\varnothing|}} \mathrm{pet}_k(\lambda, \varnothing) s_\lambda.$$

In view of $G(k,m) \cdot \underbrace{s_\varnothing}_{=1} = G(k,m)$ and $m + \underbrace{|\varnothing|}_{=0} = m$, we can rewrite this as

$$G(k,m) = \sum_{\lambda \in \mathrm{Par}_m} \mathrm{pet}_k(\lambda, \varnothing) s_\lambda.$$

This proves Corollary 2.10. $\square$

3.11. Proof of Theorem 2.15

Our proof of Theorem 2.15 will depend on two lemmas about determinants:

Lemma 3.9. Let $m \in \mathbb{N}$. Let R be a commutative ring. Let $\left(a_{i,j}\right)_{1\leq i\leq m,\ 1\leq j\leq m} \in R^{m\times m}$ be an $m \times m$-matrix.

(a) If τ is any permutation of $\{1,2,\ldots,m\}$, then

$$\det\left(\left(a_{\tau(i),j}\right)_{1\leq i\leq m,\ 1\leq j\leq m}\right) = (-1)^{\tau} \cdot \det\left(\left(a_{i,j}\right)_{1\leq i\leq m,\ 1\leq j\leq m}\right).$$

Here, $(-1)^{\tau}$ denotes the sign of the permutation τ.

(b) Let $u_1, u_2, \ldots, u_m$ be m elements of R. Let $v_1, v_2, \ldots, v_m$ be m elements of R. Then,

$$\det\left(\left(u_i v_j a_{i,j}\right)_{1\leq i\leq m,\ 1\leq j\leq m}\right) = \left(\prod_{i=1}^{m}\left(u_i v_i\right)\right) \cdot \det\left(\left(a_{i,j}\right)_{1\leq i\leq m,\ 1\leq j\leq m}\right).$$

Proof of Lemma 3.9. **(a)** This is just the well-known fact that if the rows of a square matrix are permuted using a permutation τ, then the determinant of this matrix gets multiplied by $(-1)^{\tau}$.

(b) This follows easily from the definition of the determinant. $\square$

Lemma 3.10. Let k be a positive integer. Let $\gamma_1, \gamma_2, \ldots, \gamma_{k-1}$ be $k-1$ elements of the set $\{1,2,\ldots,k\}$.

Let G be the $(k-1)\times(k-1)$-matrix

$$\left((-1)^{(\gamma_i+j)\%k}\left[(\gamma_i+j)\%k \in \{0,1\}\right]\right)_{1\leq i\leq k-1,\ 1\leq j\leq k-1}.$$

(a) If the $k-1$ numbers $\gamma_1, \gamma_2, \ldots, \gamma_{k-1}$ are not distinct, then

$$\det G = 0.$$

(b) If $\gamma_1 > \gamma_2 > \cdots > \gamma_{k-1}$, then

$$\det G = (-1)^{(\gamma_1+\gamma_2+\cdots+\gamma_{k-1})-(1+2+\cdots+(k-1))}.$$

(c) Assume that the $k-1$ numbers $\gamma_1, \gamma_2, \ldots, \gamma_{k-1}$ are distinct. Let

$$g = \left|\left\{(i,j) \in \{1,2,\ldots,k-1\}^2 \mid i < j \text{ and } \gamma_i < \gamma_j\right\}\right|.$$

Then,

$$\det G = (-1)^{g+(\gamma_1+\gamma_2+\cdots+\gamma_{k-1})-(1+2+\cdots+(k-1))}.$$

Proof of Lemma 3.10. **(a)** Assume that the $k-1$ numbers $\gamma_1, \gamma_2, \ldots, \gamma_{k-1}$ are not distinct. In other words, there exist two elements u and v of $\{1,2,\ldots,k-1\}$ such that $u < v$ and $\gamma_u = \gamma_v$. Consider these u and v. Now, from $\gamma_u = \gamma_v$, we conclude that the u-th and the v-th rows of the matrix G are equal (by the construction of G). Hence, the matrix G has two equal rows (since $u < v$). Thus, $\det G = 0$. This proves Lemma 3.10 **(a)**.

(b) Assume that $\gamma_1 > \gamma_2 > \cdots > \gamma_{k-1}$. Thus, $\gamma_1, \gamma_2, \ldots, \gamma_{k-1}$ are distinct. Hence, $\{\gamma_1, \gamma_2, \ldots, \gamma_{k-1}\}$ is a $(k-1)$-element set. But $\{\gamma_1, \gamma_2, \ldots, \gamma_{k-1}\}$ is a subset of $\{1, 2, \ldots, k\}$ (since $\gamma_1, \gamma_2, \ldots, \gamma_{k-1}$ are elements of $\{1, 2, \ldots, k\}$). Therefore, $\{\gamma_1, \gamma_2, \ldots, \gamma_{k-1}\}$ is a $(k-1)$-element subset of $\{1, 2, \ldots, k\}$.

Hence, $\{\gamma_1, \gamma_2, \ldots, \gamma_{k-1}\} = \{1, 2, \ldots, k\} \setminus \{u\}$ for some $u \in \{1, 2, \ldots, k\}$ (since any $(k-1)$-element subset of $\{1, 2, \ldots, k\}$ has such a form). Consider this u. From $\{\gamma_1, \gamma_2, \ldots, \gamma_{k-1}\} = \{1, 2, \ldots, k\} \setminus \{u\}$, we conclude that $\gamma_1, \gamma_2, \ldots, \gamma_{k-1}$ are the $k-1$ elements of the set $\{1, 2, \ldots, k\} \setminus \{u\}$, listed in decreasing order (since $\gamma_1 > \gamma_2 > \cdots > \gamma_{k-1}$). In other words,

$$(\gamma_1, \gamma_2, \ldots, \gamma_{k-1}) = (k, k-1, \ldots, \widehat{u}, \ldots, 2, 1), \tag{40}$$

where the "hat" over the u signifies that u is omitted from the list (i.e., the expression "$(k, k-1, \ldots, \widehat{u}, \ldots, 2, 1)$" is understood to mean the $(k-1)$-element list $(k, k-1, \ldots, u+1, u-1, \ldots, 2, 1)$, which contains all k integers from 1 to k in decreasing order except for u).

Now, we claim that

$$\begin{aligned} &(-1)^{(\gamma_i+j)\%k} \left[(\gamma_i + j) \%k \in \{0, 1\}\right] \\ &= (-1)^{\gamma_i+j-k} \left[\gamma_i + j \in \{k, k+1\}\right] \end{aligned} \tag{41}$$

for any $i \in \{1, 2, \ldots, k-1\}$ and $j \in \{1, 2, \ldots, k-1\}$.

[*Proof of (41):* Let $i \in \{1, 2, \ldots, k-1\}$ and $j \in \{1, 2, \ldots, k-1\}$. We must prove the equality (41).

From $i \in \{1, 2, \ldots, k-1\}$, we obtain $1 \leq i \leq k-1$ and thus $k-1 \geq 1$. Thus, $k > k-1 \geq 1$. Hence, $k+1 < 2k$, so that $(k+1) \%k = 1$.

If we don't have $(\gamma_i + j) \%k \in \{0, 1\}$, then both truth values $[(\gamma_i + j) \%k \in \{0, 1\}]$ and $[\gamma_i + j \in \{k, k+1\}]$ are 0 (indeed, the statement "$\gamma_i + j \in \{k, k+1\}$" is false, since otherwise it would imply $(\gamma_i + j) \%k \in \{0, 1\}$), and therefore the equality (41) simplifies to $(-1)^{(\gamma_i+j)\%k} 0 = (-1)^{\gamma_i+j-k} 0$ in this case, which is obviously true. Hence, for the rest of this proof, we WLOG assume that we do have $(\gamma_i + j) \%k \in \{0, 1\}$.

Adding $\gamma_i \in \{1, 2, \ldots, k\}$ with $j \in \{1, 2, \ldots, k-1\}$, we find $\gamma_i + j \in \{2, 3, \ldots, 2k-1\}$. But if $p \in \{2, 3, \ldots, 2k-1\}$ satisfies $p\%k \in \{0, 1\}$, then $p \in \{k, k+1\}$ (since the only numbers in $\{2, 3, \ldots, 2k-1\}$ that leave the remainders 0 and 1 upon division by k are k and $k+1$). Applying this to $p = \gamma_i + j$, we obtain $\gamma_i + j \in \{k, k+1\}$ (since $\gamma_i + j \in \{2, 3, \ldots, 2k-1\}$ and $(\gamma_i + j) \%k \in \{0, 1\}$). Hence, $k \leq \gamma_i + j < 2k$ (since $k+1 < 2k$), so that $(\gamma_i + j) // k = 1$. But every integer n satisfies $n = (n // k) k + (n\%k)$. Applying this to $n = \gamma_i + j$, we obtain $\gamma_i + j = \underbrace{((\gamma_i + j) // k)}_{=1} k +$

$((\gamma_i + j)\,\%k) = k + ((\gamma_i + j)\,\%k)$. Hence, $(\gamma_i + j)\,\%k = \gamma_i + j - k$. Thus,

$$\underbrace{(-1)^{(\gamma_i+j)\%k}}_{\substack{=(-1)^{\gamma_i+j-k} \\ \text{(since } (\gamma_i+j)\%k=\gamma_i+j-k)}} \quad \underbrace{[(\gamma_i + j)\,\%k \in \{0,1\}]}_{\substack{=1 \\ \text{(since } (\gamma_i+j)\%k\in\{0,1\})}} = (-1)^{\gamma_i+j-k}.$$

Comparing this with

$$(-1)^{\gamma_i+j-k} \underbrace{[\gamma_i + j \in \{k, k+1\}]}_{\substack{=1 \\ \text{(since } \gamma_i+j\in\{k,k+1\})}} = (-1)^{\gamma_i+j-k},$$

we obtain

$$(-1)^{(\gamma_i+j)\%k} [(\gamma_i + j)\,\%k \in \{0,1\}] = (-1)^{\gamma_i+j-k} [\gamma_i + j \in \{k, k+1\}].$$

This proves (41).]

Now, G is a $(k-1) \times (k-1)$-matrix. For each $i \in \{1, 2, \ldots, k-1\}$ and $j \in \{1, 2, \ldots, k-1\}$, we have

$$\begin{aligned}
&(\text{the } (i,j)\text{-th entry of } G) \\
&= (-1)^{(\gamma_i+j)\%k} [(\gamma_i + j)\,\%k \in \{0,1\}] \qquad (\text{by the definition of } G) \\
&= (-1)^{\gamma_i+j-k} [\gamma_i + j \in \{k, k+1\}] \qquad (\text{by (41)}) \\
&= \begin{cases} 1, & \text{if } \gamma_i + j = k; \\ -1, & \text{if } \gamma_i + j = k+1; \\ 0, & \text{otherwise} \end{cases} = \begin{cases} 1, & \text{if } j = k - \gamma_i; \\ -1, & \text{if } j = k - \gamma_i + 1; \\ 0, & \text{otherwise} \end{cases}.
\end{aligned}$$

Thus, we can explicitly describe the matrix G as follows: For each $i \in \{1, 2, \ldots, k-1\}$, the i-th row of G has an entry equal to 1 in position $k - \gamma_i$ if $k - \gamma_i > 0$, and an entry equal to -1 in position $k - \gamma_i + 1$ if $k - \gamma_i + 1 < k$; all remaining entries of this row are 0. Recalling (40), we thus see that G has the following form:[18]

$$G = \left(\begin{array}{ccccc|ccccc}
-1 & & & & & & & & & \\
1 & -1 & & & & & & & & \\
 & 1 & -1 & & & & & & & \\
 & & \ddots & \ddots & & & & & & \\
 & & & 1 & -1 & & & & & \\
\hline
 & & & & & 1 & -1 & & & \\
 & & & & & & 1 & -1 & & \\
 & & & & & & & 1 & -1 & \\
 & & & & & & & & \ddots & \ddots \\
 & & & & & & & & & 1
\end{array}\right),$$

[18] Empty cells are understood to have entry 0.

where the horizontal bar separates the $(k-u)$-th row from the $(k-u+1)$-st row, while the vertical bar separates the $(k-u)$-th column from the $(k-u+1)$-st column. Thus, G can be written as a block-diagonal matrix

$$G = \begin{pmatrix} A & 0_{(k-u)\times(u-1)} \\ 0_{(u-1)\times(k-u)} & B \end{pmatrix}, \qquad (42)$$

where A is a lower-triangular $(k-u)\times(k-u)$-matrix with all diagonal entries equal to -1, and where B is an upper-triangular $(u-1)\times(u-1)$-matrix with all diagonal entries equal to 1. Since the determinant of a block-diagonal matrix equals the product of the determinants of its diagonal blocks, we thus conclude that

$$\begin{aligned} \det G &= \underbrace{\det A}_{\substack{=(-1)^{k-u} \\ \text{(since } A \text{ is a} \\ \text{lower-triangular } (k-u)\times(k-u)\text{-matrix} \\ \text{with all diagonal entries equal to } -1)}} \cdot \underbrace{\det B}_{\substack{=1 \\ \text{(since } B \text{ is an} \\ \text{upper-triangular } (u-1)\times(u-1)\text{-matrix} \\ \text{with all diagonal entries equal to 1)}}} \\ &= (-1)^{k-u}. \end{aligned} \qquad (43)$$

But (40) yields

$$\begin{aligned} \gamma_1+\gamma_2+\cdots+\gamma_{k-1} &= k+(k-1)+\cdots+\widehat{u}+\cdots+2+1 \\ &= \underbrace{(k+(k-1)+\cdots+2+1)}_{\substack{=1+2+\cdots+k \\ =(1+2+\cdots+(k-1))+k}} - u \\ &= (1+2+\cdots+(k-1))+k-u. \end{aligned}$$

Solving this for $k-u$, we find

$$k-u = (\gamma_1+\gamma_2+\cdots+\gamma_{k-1}) - (1+2+\cdots+(k-1)).$$

Hence, (43) rewrites as

$$\det G = (-1)^{(\gamma_1+\gamma_2+\cdots+\gamma_{k-1})-(1+2+\cdots+(k-1))}.$$

This proves Lemma 3.10 **(b)**.

(c) Assume that the $k-1$ numbers $\gamma_1,\gamma_2,\ldots,\gamma_{k-1}$ are distinct. Then, there exists a unique permutation σ of $\{1,2,\ldots,k-1\}$ such that $\gamma_{\sigma(1)} > \gamma_{\sigma(2)} > \cdots > \gamma_{\sigma(k-1)}$ (indeed, this is simply saying that the $(k-1)$-tuple $(\gamma_1,\gamma_2,\ldots,\gamma_{k-1})$ can be sorted into decreasing order by a unique permutation). Consider this σ.

Let τ denote the permutation σ^{-1}. Thus, τ is a permutation of $\{1,2,\ldots,k-1\}$ and satisfies $\sigma\circ\tau = \mathrm{id}$.

Let $\delta_1,\delta_2,\ldots,\delta_{k-1}$ denote the $k-1$ elements $\gamma_{\sigma(1)},\gamma_{\sigma(2)},\ldots,\gamma_{\sigma(k-1)}$ of $\{1,2,\ldots,k\}$. Thus, for each $j\in\{1,2,\ldots,k-1\}$, we have

$$\delta_j = \gamma_{\sigma(j)}. \qquad (44)$$

Hence, the chain of inequalities $\gamma_{\sigma(1)} > \gamma_{\sigma(2)} > \cdots > \gamma_{\sigma(k-1)}$ (which is true) can be rewritten as $\delta_1 > \delta_2 > \cdots > \delta_{k-1}$.

Moreover, from (44), we obtain

$$\begin{aligned} \delta_1 + \delta_2 + \cdots + \delta_{k-1} &= \gamma_{\sigma(1)} + \gamma_{\sigma(2)} + \cdots + \gamma_{\sigma(k-1)} \\ &= \gamma_1 + \gamma_2 + \cdots + \gamma_{k-1} \end{aligned} \tag{45}$$

(since σ is a permutation of $\{1, 2, \ldots, k-1\}$).

Moreover, for each $i \in \{1, 2, \ldots, k-1\}$, we have

$$\begin{aligned} \delta_{\tau(i)} &= \gamma_{\sigma(\tau(i))} \qquad \left(\text{by (44), applied to } j = \tau(i)\right) \\ &= \gamma_i \qquad \left(\text{since } \sigma(\tau(i)) = \underbrace{(\sigma \circ \tau)}_{=\mathrm{id}}(i) = i\right). \end{aligned} \tag{46}$$

Recall that an *inversion* of the permutation τ is defined to be a pair (i, j) of elements of $\{1, 2, \ldots, k-1\}$ satisfying $i < j$ and $\tau(i) > \tau(j)$. Hence,

$$\begin{aligned} &\{\text{the inversions of } \tau\} \\ &= \left\{ (i, j) \in \{1, 2, \ldots, k-1\}^2 \mid i < j \text{ and } \underbrace{\tau(i) > \tau(j)}_{\substack{\text{This is equivalent to } (\delta_{\tau(i)} < \delta_{\tau(j)}) \\ (\text{since } \delta_1 > \delta_2 > \cdots > \delta_{k-1})}} \right\} \\ &= \left\{ (i, j) \in \{1, 2, \ldots, k-1\}^2 \mid i < j \text{ and } \underbrace{\delta_{\tau(i)}}_{\substack{=\gamma_i \\ (\text{by (46)})}} < \underbrace{\delta_{\tau(j)}}_{\substack{=\gamma_j \\ (\text{by (46)})}} \right\} \\ &= \left\{ (i, j) \in \{1, 2, \ldots, k-1\}^2 \mid i < j \text{ and } \gamma_i < \gamma_j \right\}. \end{aligned} \tag{47}$$

Recall that the *length* $\ell(\tau)$ of the permutation τ is defined to be the number of inversions of τ. Thus,

$$\begin{aligned} \ell(\tau) &= (\text{the number of inversions of } \tau) \\ &= |\{\text{the inversions of } \tau\}| \\ &= \left| \left\{ (i, j) \in \{1, 2, \ldots, k-1\}^2 \mid i < j \text{ and } \gamma_i < \gamma_j \right\} \right| \qquad (\text{by (47)}) \\ &= g \qquad (\text{by the definition of } g). \end{aligned}$$

Recall that the *sign* $(-1)^\tau$ of the permutation τ is defined by $(-1)^\tau = (-1)^{\ell(\tau)}$. Hence, $(-1)^\tau = (-1)^{\ell(\tau)} = (-1)^g$ (since $\ell(\tau) = g$).

Let H be the $(k-1) \times (k-1)$-matrix

$$\left((-1)^{(\delta_i+j)\%k}\left[(\delta_i+j)\%k \in \{0,1\}\right]\right)_{1\leq i\leq k-1,\ 1\leq j\leq k-1}.$$

Then, we can apply Lemma 3.10 **(b)** to δ_i and H instead of γ_i and G (since $\delta_1, \delta_2, \ldots, \delta_{k-1}$ are $k-1$ elements of $\{1, 2, \ldots, k\}$ and satisfy $\delta_1 > \delta_2 > \cdots > \delta_{k-1}$). We thus obtain

$$\det H = (-1)^{(\delta_1+\delta_2+\cdots+\delta_{k-1})-(1+2+\cdots+(k-1))} = (-1)^{(\gamma_1+\gamma_2+\cdots+\gamma_{k-1})-(1+2+\cdots+(k-1))}$$

(by (45)).

But the definition of G yields

$$\begin{aligned} G &= \left(\underbrace{(-1)^{(\gamma_i+j)\%k}\left[(\gamma_i+j)\%k \in \{0,1\}\right]}_{\substack{=(-1)^{\left(\delta_{\tau(i)}+j\right)\%k}\left[\left(\delta_{\tau(i)}+j\right)\%k\in\{0,1\}\right] \\ \text{(since (46) yields } \gamma_i=\delta_{\tau(i)})}}\right)_{1\leq i\leq k-1,\ 1\leq j\leq k-1} \\ &= \left((-1)^{\left(\delta_{\tau(i)}+j\right)\%k}\left[\left(\delta_{\tau(i)}+j\right)\%k \in \{0,1\}\right]\right)_{1\leq i\leq k-1,\ 1\leq j\leq k-1}. \end{aligned}$$

Hence,

$$\begin{aligned} \det G &= \det\left(\left((-1)^{\left(\delta_{\tau(i)}+j\right)\%k}\left[\left(\delta_{\tau(i)}+j\right)\%k \in \{0,1\}\right]\right)_{1\leq i\leq k-1,\ 1\leq j\leq k-1}\right) \\ &= \underbrace{(-1)^{\tau}}_{=(-1)^g}\det\left(\underbrace{\left((-1)^{(\delta_i+j)\%k}\left[(\delta_i+j)\%k \in \{0,1\}\right]\right)_{1\leq i\leq k-1,\ 1\leq j\leq k-1}}_{\substack{=H \\ \text{(by the definition of } H)}}\right) \\ &\qquad \left(\begin{array}{c}\text{by Lemma 3.9 } \textbf{(a)}\text{, applied to } m=k-1 \\ \text{and } R=\mathbf{k} \text{ and } a_{i,j}=(-1)^{(\delta_i+j)\%k}\left[(\delta_i+j)\%k\in\{0,1\}\right]\end{array}\right) \\ &= (-1)^g \underbrace{\det H}_{=(-1)^{(\gamma_1+\gamma_2+\cdots+\gamma_{k-1})-(1+2+\cdots+(k-1))}} \\ &= (-1)^g (-1)^{(\gamma_1+\gamma_2+\cdots+\gamma_{k-1})-(1+2+\cdots+(k-1))} \\ &= (-1)^{g+(\gamma_1+\gamma_2+\cdots+\gamma_{k-1})-(1+2+\cdots+(k-1))}. \end{aligned}$$

This proves Lemma 3.10 **(c)**. $\square$

Next, we recall a well-known property of symmetric functions:

Lemma 3.11. Consider the ring $\Lambda[[t]]$ of formal power series in one indeterminate t over Λ. In this ring, we have

$$1 = \left(\sum_{n \geq 0} (-1)^n e_n t^n \right) \left(\sum_{n \geq 0} h_n t^n \right). \tag{48}$$

Lemma 3.11 is a well-known identity (see, e.g., [Stanle01, proof of Theorem 7.6.1] or [GriRei20, (2.4.3)]); for the sake of completeness, let us nevertheless give a proof:

Proof of Lemma 3.11. Consider the ring $(\mathbf{k}[[x_1, x_2, x_3, \ldots]])[[t]]$ of formal power series in one indeterminate t over $\mathbf{k}[[x_1, x_2, x_3, \ldots]]$. In this ring, we have the equalities

$$\prod_{i=1}^{\infty} (1 - x_i t)^{-1} = \sum_{n \geq 0} h_n t^n \tag{49}$$

and

$$\prod_{i=1}^{\infty} (1 + x_i t) = \sum_{n \geq 0} e_n t^n. \tag{50}$$

(Indeed, the first of these two equalities is [GriRei20, (2.2.18)], whereas the second is [GriRei20, (2.2.19)].)

Substituting $-t$ for t in the equality (50), and multiplying the resulting equality by (49), we obtain

$$\left(\prod_{i=1}^{\infty} (1 - x_i t) \right) \left(\prod_{i=1}^{\infty} (1 - x_i t)^{-1} \right) = \left(\sum_{n \geq 0} e_n (-t)^n \right) \left(\sum_{n \geq 0} h_n t^n \right).$$

The left hand side of this equality simplifies to 1, while the right hand side is the right hand side of (48). Thus, (48) holds, which proves Lemma 3.11. $\square$

Next, we shall prove yet another evaluation of the homomorphism α_k:

Lemma 3.12. Let k be a positive integer such that $k > 1$. Consider the $\mathbf{k}$-algebra homomorphism $\alpha_k : \Lambda \to \mathbf{k}$ from Definition 3.6. Also, recall Convention 2.4. Let r be an integer such that $r > -k + 1$. Then,

$$\alpha_k (e_r) = (-1)^{r + r\%k} [r\%k \in \{0, 1\}]. \tag{51}$$

Proof of Lemma 3.12. Consider the ring $\Lambda[[t]]$ of formal power series in one indeterminate t over Λ. Consider also the analogous ring $\mathbf{k}[[t]]$ over $\mathbf{k}$.

The map $\alpha_k : \Lambda \to \mathbf{k}$ is a $\mathbf{k}$-algebra homomorphism. Hence, it induces a continuous[19] $\mathbf{k}[[t]]$-algebra homomorphism

$$\alpha_k[[t]] : \Lambda[[t]] \to \mathbf{k}[[t]]$$

that sends each formal power series $\sum_{n\geq 0} a_n t^n \in \Lambda[[t]]$ (with $a_n \in \Lambda$) to $\sum_{n\geq 0} \alpha_k(a_n) t^n$. Consider this $\mathbf{k}[[t]]$-algebra homomorphism $\alpha_k[[t]]$.

Applying the map $\alpha_k[[t]]$ to both sides of the equality (48), we obtain

$$\begin{aligned}
(\alpha_k[[t]])(1) &= (\alpha_k[[t]])\left(\left(\sum_{n\geq 0}(-1)^n e_n t^n\right)\left(\sum_{n\geq 0} h_n t^n\right)\right) \\
&= \underbrace{(\alpha_k[[t]])\left(\sum_{n\geq 0}(-1)^n e_n t^n\right)}_{\substack{=\sum_{n\geq 0}\alpha_k\left((-1)^n e_n\right)t^n \\ \text{(by the definition of } \alpha_k[[t]])}} \cdot \underbrace{(\alpha_k[[t]])\left(\sum_{n\geq 0} h_n t^n\right)}_{\substack{=\sum_{n\geq 0}\alpha_k(h_n)t^n \\ \text{(by the definition of } \alpha_k[[t]])}} \\
&\qquad (\text{since } \alpha_k[[t]] \text{ is a } \mathbf{k}[[t]]\text{-algebra homomorphism}) \\
&= \left(\sum_{n\geq 0}\underbrace{\alpha_k\left((-1)^n e_n\right)}_{\substack{=(-1)^n\alpha_k(e_n) \\ \text{(since } \alpha_k \text{ is } \mathbf{k}\text{-linear)}}} t^n\right)\cdot\left(\sum_{n\geq 0}\underbrace{\alpha_k(h_n)}_{\substack{=[n<k] \\ \text{(by (16))}}} t^n\right) \\
&= \left(\sum_{n\geq 0}(-1)^n \alpha_k(e_n) t^n\right)\cdot \underbrace{\left(\sum_{n\geq 0}[n<k]\, t^n\right)}_{=t^0+t^1+\cdots+t^{k-1}=\dfrac{1-t^k}{1-t}} \\
&= \left(\sum_{n\geq 0}(-1)^n \alpha_k(e_n) t^n\right)\cdot \frac{1-t^k}{1-t}.
\end{aligned}$$

Comparing this with

$$(\alpha_k[[t]])(1) = 1 \qquad (\text{since } \alpha_k[[t]] \text{ is a } \mathbf{k}[[t]]\text{-algebra homomorphism}),$$

we obtain

$$\left(\sum_{n\geq 0}(-1)^n \alpha_k(e_n) t^n\right)\cdot \frac{1-t^k}{1-t} = 1.$$

[19] Continuity is defined with respect to the usual topologies on $\Lambda[[t]]$ and $\mathbf{k}[[t]]$, where we equip both Λ and $\mathbf{k}$ with the discrete topologies.

Hence,

$$\sum_{n\geq 0}(-1)^n \alpha_k(e_n) t^n = \frac{1-t}{1-t^k} = (1-t)\cdot \underbrace{\frac{1}{1-t^k}}_{=1+t^k+t^{2k}+t^{3k}+\cdots}$$
$$= (1-t)\cdot\left(1+t^k+t^{2k}+t^{3k}+\cdots\right)$$
$$= 1-t+t^k-t^{k+1}+t^{2k}-t^{2k+1}+t^{3k}-t^{3k+1}\pm\cdots$$
$$= \sum_{n\geq 0}(-1)^{n\%k}[n\%k\in\{0,1\}] t^n$$

(here, we have used that $k>1$, since for $k=1$ there would be cancellations in the sum $1-t+t^k-t^{k+1}+t^{2k}-t^{2k+1}+t^{3k}-t^{3k+1}\pm\cdots$). Comparing coefficients before t^m on both sides of this equality, we obtain

$$(-1)^m \alpha_k(e_m) = (-1)^{m\%k}[m\%k\in\{0,1\}] \tag{52}$$

for each $m\in\mathbb{N}$.

Multiplying both sides of this equality by $(-1)^m$, we obtain

$$\alpha_k(e_m) = (-1)^{m+m\%k}[m\%k\in\{0,1\}]. \tag{53}$$

We must prove that

$$\alpha_k(e_r) = (-1)^{r+r\%k}[r\%k\in\{0,1\}].$$

If $r\in\mathbb{N}$, then this follows by applying (53) to $m=r$. Hence, for the rest of this proof, we WLOG assume that $r\notin\mathbb{N}$. Thus, r is negative, so that $r\in\{-k+2,-k+3,\ldots,-1\}$ (since $r>-k+1$). Hence, $r\%k\in\{2,3,\ldots,k-1\}$, so that $r\%k\notin\{0,1\}$. Consequently, $[r\%k\in\{0,1\}]=0$. Also, $e_r=0$ (since r is negative) and thus $\alpha_k(e_r)=\alpha_k(0)=0$. Comparing this with $(-1)^{r+r\%k}\underbrace{[r\%k\in\{0,1\}]}_{=0}=0$, we obtain $\alpha_k(e_r)=(-1)^{r+r\%k}[r\%k\in\{0,1\}]$. This concludes the proof of Lemma 3.12.

□

Proof of Theorem 2.15. **(a)** Assume that $\mu_k\neq 0$. But $\mu=\lambda^t$, whence

$$\mu_k = \left(\lambda^t\right)_k = \left|\{j\in\{1,2,3,\ldots\}\ \mid\ \lambda_j\geq k\}\right| \qquad \left(\text{by the definition of } \lambda^t\right).$$

Hence,

$$\left|\{j\in\{1,2,3,\ldots\}\ \mid\ \lambda_j\geq k\}\right| = \mu_k\neq 0.$$

In other words, the set $\{j\in\{1,2,3,\ldots\}\ \mid\ \lambda_j\geq k\}$ is nonempty. Hence, there exists some $j\in\{1,2,3,\ldots\}$ satisfying $\lambda_j\geq k$. Consider this j. We have $\lambda_1\geq\lambda_2\geq\lambda_3\geq$

$\cdots$ (since $\lambda \in \operatorname{Par}$) and thus $\lambda_1 \geq \lambda_j$ (since $1 \leq j$). Hence, $\lambda_1 \geq \lambda_j \geq k$. Thus, Proposition 2.12 yields $\operatorname{pet}_k(\lambda, \varnothing) = 0$. This proves Theorem 2.15 **(a)**.

Now, let us prepare for the proof of parts **(b)** and **(c)**.

Consider the $\mathbf{k}$-algebra homomorphism $\alpha_k : \Lambda \to \mathbf{k}$ from Definition 3.6.

For each $i \in \{1, 2, \ldots, k-1\}$, we have $(\beta_i - 1) \% k \in \{0, 1, \ldots, k-1\}$ (by the definition of a remainder) and thus $\gamma_i \in \{1, 2, \ldots, k\}$ (by (8)). In other words, $\gamma_1, \gamma_2, \ldots, \gamma_{k-1}$ are $k-1$ elements of the set $\{1, 2, \ldots, k\}$.

Assume that $\mu_k = 0$. Thus, $\mu = (\mu_1, \mu_2, \ldots, \mu_{k-1})$ (since $\mu \in \operatorname{Par}$).

It is known that taking the transpose of the transpose of a partition returns the original partition. Thus, $(\lambda^t)^t = \lambda$. In view of $\mu = \lambda^t$, this rewrites as $\mu^t = \lambda$. Hence, $\lambda = \mu^t$. Therefore,

$$s_\lambda = s_{\mu^t} = \det\left(\left(e_{\mu_i - i + j}\right)_{1 \leq i \leq k-1,\ 1 \leq j \leq k-1}\right)$$

(by (6), applied to μ and $k-1$ instead of λ and ℓ), because $\mu = (\mu_1, \mu_2, \ldots, \mu_{k-1})$. Applying the map α_k to both sides of this equality, we find

$$\begin{aligned}
\alpha_k(s_\lambda) &= \alpha_k\left(\det\left(\left(\underbrace{e_{\mu_i - i + j}}_{\substack{= e_{\beta_i + j} \\ \text{(since (7) yields } \mu_i - i = \beta_i)}}\right)_{1 \leq i \leq k-1,\ 1 \leq j \leq k-1}\right)\right) \\
&= \alpha_k\left(\det\left(\left(e_{\beta_i + j}\right)_{1 \leq i \leq k-1,\ 1 \leq j \leq k-1}\right)\right) \\
&= \det\left(\left(\alpha_k\left(e_{\beta_i + j}\right)\right)_{1 \leq i \leq k-1,\ 1 \leq j \leq k-1}\right)
\end{aligned}$$

(since α_k is a $\mathbf{k}$-algebra homomorphism, and thus commutes with taking determinants of matrices). On the other hand,

$$\alpha_k\left(\underbrace{s_\lambda}_{= s_{\lambda / \varnothing}}\right) = \alpha_k(s_{\lambda/\varnothing}) = \operatorname{pet}_k(\lambda, \varnothing)$$

(by (23), applied to $\varnothing$ instead of μ). Comparing these two equalities, we obtain

$$\operatorname{pet}_k(\lambda, \varnothing) = \det\left(\left(\alpha_k\left(e_{\beta_i + j}\right)\right)_{1 \leq i \leq k-1,\ 1 \leq j \leq k-1}\right). \tag{54}$$

But each $i \in \{1, 2, \ldots, k-1\}$ and $j \in \{1, 2, \ldots, k-1\}$ satisfy $k > 1$ [20] and

$$\underbrace{\beta_i}_{\substack{= \mu_i - i \\ \text{(by (7))}}} + j = \underbrace{\mu_i}_{\geq 0} - \underbrace{i}_{\leq k-1} + \underbrace{j}_{> 0} > 0 - (k-1) + 0 = -k + 1$$

[20] Indeed, if $i \in \{1, 2, \ldots, k-1\}$, then $1 \leq i \leq k-1$ and thus $k - 1 \geq 1 > 0$, so that $k > 1$.

and thus

$$\alpha_k\left(e_{\beta_i+j}\right) = (-1)^{(\beta_i+j)+(\beta_i+j)\%k}\left[(\beta_i+j)\,\%k \in \{0,1\}\right] \tag{55}$$

(by (51), applied to $r = \beta_i + j$).

Furthermore, each $i \in \{1,2,\ldots,k-1\}$ and $j \in \{1,2,\ldots,k-1\}$ satisfy

$$\begin{aligned}
&(-1)^{(\beta_i+j)+(\beta_i+j)\%k}\left[(\beta_i+j)\,\%k \in \{0,1\}\right] \\
&= (-1)^{\beta_i}(-1)^j(-1)^{(\gamma_i+j)\%k}\left[(\gamma_i+j)\,\%k \in \{0,1\}\right].
\end{aligned} \tag{56}$$

[*Proof of (56):* Let $i \in \{1,2,\ldots,k-1\}$ and $j \in \{1,2,\ldots,k-1\}$. The definition of γ_i yields

$$\gamma_i = 1 + \underbrace{(\beta_i-1)\,\%k}_{\substack{\equiv\beta_i-1 \bmod k \\ \text{(since } u\%k\equiv u \bmod k \text{ for any } u\in\mathbb{Z})}} \equiv 1 + (\beta_i - 1) = \beta_i \bmod k.$$

Hence, $\underbrace{\gamma_i}_{\equiv\beta_i \bmod k} + j \equiv \beta_i + j \bmod k$. But if $u \in \mathbb{Z}$ and $v \in \mathbb{Z}$ satisfy $u \equiv v \bmod k$, then $u\%k = v\%k$. Applying this to $u = \gamma_i + j$ and $v = \beta_i + j$, we obtain $(\gamma_i + j)\,\%k = (\beta_i + j)\,\%k$. Hence,

$$\begin{aligned}
&(-1)^{\beta_i}(-1)^j(-1)^{(\gamma_i+j)\%k}\left[(\gamma_i+j)\,\%k \in \{0,1\}\right] \\
&= \underbrace{(-1)^{\beta_i}(-1)^j(-1)^{(\beta_i+j)\%k}}_{=(-1)^{(\beta_i+j)+(\beta_i+j)\%k}}\left[(\beta_i+j)\,\%k \in \{0,1\}\right] \\
&= (-1)^{(\beta_i+j)+(\beta_i+j)\%k}\left[(\beta_i+j)\,\%k \in \{0,1\}\right].
\end{aligned}$$

This proves (56).]

Now, (54) becomes

$$\begin{aligned}
&\operatorname{pet}_k(\lambda, \varnothing) \\
&= \det\left(\left(\underbrace{\alpha_k\left(e_{\beta_i+j}\right)}_{\substack{=(-1)^{(\beta_i+j)+(\beta_i+j)\%k}[(\beta_i+j)\%k\in\{0,1\}] \\ \text{(by (55))}}}\right)_{1\leq i\leq k-1,\ 1\leq j\leq k-1}\right) \\
&= \det\left(\left(\underbrace{(-1)^{(\beta_i+j)+(\beta_i+j)\%k}\left[(\beta_i+j)\%k\in\{0,1\}\right]}_{\substack{=(-1)^{\beta_i}(-1)^j(-1)^{(\gamma_i+j)\%k}[(\gamma_i+j)\%k\in\{0,1\}] \\ \text{(by (56))}}}\right)_{1\leq i\leq k-1,\ 1\leq j\leq k-1}\right) \\
&= \det\left(\left((-1)^{\beta_i}(-1)^j(-1)^{(\gamma_i+j)\%k}\left[(\gamma_i+j)\%k\in\{0,1\}\right]\right)_{1\leq i\leq k-1,\ 1\leq j\leq k-1}\right) \\
&= \left(\prod_{i=1}^{k-1}\left((-1)^{\beta_i}(-1)^i\right)\right)\cdot\det\left(\left((-1)^{(\gamma_i+j)\%k}\left[(\gamma_i+j)\%k\in\{0,1\}\right]\right)_{1\leq i\leq k-1,\ 1\leq j\leq k-1}\right)
\end{aligned}$$

(by Lemma 3.9 **(b)**, applied to $m = k-1$ and $R = \mathbf{k}$ and $a_{i,j} = (-1)^{(\gamma_i+j)\%k}\left[(\gamma_i+j)\%k\in\{0,1\}\right]$ and $u_i = (-1)^{\beta_i}$ and $v_j = (-1)^j$).

Define a $(k-1)\times(k-1)$-matrix G as in Lemma 3.10. Then, this becomes

$$\begin{aligned}
&\operatorname{pet}_k(\lambda, \varnothing) \\
&= \left(\prod_{i=1}^{k-1}\left((-1)^{\beta_i}(-1)^i\right)\right)\cdot\det\left(\underbrace{\left((-1)^{(\gamma_i+j)\%k}\left[(\gamma_i+j)\%k\in\{0,1\}\right]\right)_{1\leq i\leq k-1,\ 1\leq j\leq k-1}}_{\substack{=G \\ \text{(by the definition of } G)}}\right) \\
&= \left(\prod_{i=1}^{k-1}\left((-1)^{\beta_i}(-1)^i\right)\right)\cdot\det G. \qquad (57)
\end{aligned}$$

Now, we can readily prove parts **(b)** and **(c)** of Theorem 2.15:

(b) Assume that the $k-1$ numbers $\gamma_1, \gamma_2, \ldots, \gamma_{k-1}$ are not distinct. Then, Lemma 3.10 **(a)** yields $\det G = 0$. Hence, (57) yields

$$\operatorname{pet}_k(\lambda, \varnothing) = \left(\prod_{i=1}^{k-1}\left((-1)^{\beta_i}(-1)^i\right)\right)\cdot\underbrace{\det G}_{=0} = 0.$$

This proves Theorem 2.15 **(b)**.

(c) The equality (57) becomes

$$\begin{aligned}
\operatorname{pet}_k(\lambda,\varnothing) &= \underbrace{\left(\prod_{i=1}^{k-1}\left((-1)^{\beta_i}(-1)^i\right)\right)}_{=\left(\prod_{i=1}^{k-1}(-1)^{\beta_i}\right)\left(\prod_{i=1}^{k-1}(-1)^i\right)} \cdot \underbrace{\det G}_{\substack{=(-1)^{g+(\gamma_1+\gamma_2+\cdots+\gamma_{k-1})-(1+2+\cdots+(k-1))} \\ \text{(by Lemma 3.10 (c))}}} \\
&= \underbrace{\left(\prod_{i=1}^{k-1}(-1)^{\beta_i}\right)}_{=(-1)^{\beta_1+\beta_2+\cdots+\beta_{k-1}}} \underbrace{\left(\prod_{i=1}^{k-1}(-1)^i\right)}_{=(-1)^{1+2+\cdots+(k-1)}} \cdot (-1)^{g+(\gamma_1+\gamma_2+\cdots+\gamma_{k-1})-(1+2+\cdots+(k-1))} \\
&= (-1)^{\beta_1+\beta_2+\cdots+\beta_{k-1}}(-1)^{1+2+\cdots+(k-1)} \cdot (-1)^{g+(\gamma_1+\gamma_2+\cdots+\gamma_{k-1})-(1+2+\cdots+(k-1))} \\
&= (-1)^{(\beta_1+\beta_2+\cdots+\beta_{k-1})+(1+2+\cdots+(k-1))+g+(\gamma_1+\gamma_2+\cdots+\gamma_{k-1})-(1+2+\cdots+(k-1))} \\
&= (-1)^{(\beta_1+\beta_2+\cdots+\beta_{k-1})+g+(\gamma_1+\gamma_2+\cdots+\gamma_{k-1})}.
\end{aligned}$$

This proves Theorem 2.15 **(c)**. □

The proof of Proposition 2.16 relies on the following known fact:

Proposition 3.13. Let $\lambda \in \operatorname{Par}$. Let $\mu = \lambda^t$. Then:

(a) If i and j are two positive integers satisfying $\lambda_i \geq j$, then $\mu_j \geq i$.

(b) If i and j are two positive integers satisfying $\lambda_i < j$, then $\mu_j < i$.

(c) Any two positive integers i and j satisfy $\lambda_i + \mu_j - i - j \neq -1$.

For each positive integer i, set $\alpha_i = \lambda_i - i$. For each positive integer j, set $\beta_j = \mu_j - j$ and $\eta_j = -1 - \beta_j$. Then:

(d) The two sets $\{\alpha_1, \alpha_2, \alpha_3, \ldots\}$ and $\{\eta_1, \eta_2, \eta_3, \ldots\}$ are disjoint, and their union is $\mathbb{Z}$.

(e) Let p be an integer such that $p \geq \lambda_1$. Then, the two sets $\{\alpha_1, \alpha_2, \alpha_3, \ldots\}$ and $\{\eta_1, \eta_2, \ldots, \eta_p\}$ are disjoint, and their union is

$$\{\ldots, p-3, p-2, p-1\} = \{k \in \mathbb{Z} \mid k < p\}.$$

(f) Let p and q be two integers such that $p \geq \lambda_1$ and $q \geq \mu_1$. Then, the two sets $\{\alpha_1, \alpha_2, \ldots, \alpha_q\}$ and $\{\eta_1, \eta_2, \ldots, \eta_p\}$ are disjoint, and their union is

$$\{-q, -q+1, \ldots, p-1\} = \{k \in \mathbb{Z} \mid -q \leq k < p\}.$$

Note that Proposition 3.13 **(f)** is a restatement of [Macdon95, Chapter I, (1.7)].

Proof of Proposition 3.13 (sketched). Left to the reader (see [Grinbe20b] for a detailed proof). The easiest way to proceed is by proving **(a)** and **(b)** first, then deriving **(c)** as their consequence, then deriving **(f)** from it, then concluding **(d)** and **(e)**. □

Proof of Proposition 2.16 (sketched). Let $\mu = \lambda^t$. Then, the number of parts of μ is λ_1. Hence, from $\lambda_1 < k$, we conclude that μ has fewer than k parts. Thus, $\mu_k = 0$.

For each positive integer i, set $\alpha_i = \lambda_i - i$. Hence,

$$\begin{aligned}\{\alpha_1, \alpha_2, \alpha_3, \ldots\} &= \left\{ \underbrace{\alpha_i}_{=\lambda_i - i} \mid i \in \{1, 2, 3, \ldots\} \right\} = \{\lambda_i - i \mid i \in \{1, 2, 3, \ldots\}\} \\ &= B \qquad \text{(by the definition of } B\text{)}.\end{aligned}$$

For each positive integer j, set $\beta_j = \mu_j - j$ and $\eta_j = -1 - \beta_j$. Note that $(\beta_1, \beta_2, \ldots, \beta_{k-1}) \in \mathbb{Z}^{k-1}$ is thus the same $(k-1)$-tuple that was called $(\beta_1, \beta_2, \ldots, \beta_{k-1})$ in Theorem 2.15. It is easy to see that $\beta_1 > \beta_2 > \cdots > \beta_{k-1}$ and $\lambda_1 - 1 > \lambda_2 - 2 > \lambda_3 - 3 > \cdots$.

From $\lambda_1 < k$, we obtain $k - 1 \geq \lambda_1$. Hence, Proposition 3.13 **(e)** (applied to $p = k - 1$) yields that the two sets $\{\alpha_1, \alpha_2, \alpha_3, \ldots\}$ and $\{\eta_1, \eta_2, \ldots, \eta_{k-1}\}$ are disjoint, and their union is

$$\{\ldots, (k-1) - 3, (k-1) - 2, (k-1) - 1\} = \{\text{all integers smaller than } k - 1\} = W.$$

Since $\{\alpha_1, \alpha_2, \alpha_3, \ldots\} = B$, we can restate this as follows: The two sets B and $\{\eta_1, \eta_2, \ldots, \eta_{k-1}\}$ are disjoint, and their union is W. Hence, $\{\eta_1, \eta_2, \ldots, \eta_{k-1}\} = W \setminus B$.

It is also easy to see that $\beta_1 > \beta_2 > \cdots > \beta_{k-1}$, so that $\eta_1 < \eta_2 < \cdots < \eta_{k-1}$. Hence, $\eta_1, \eta_2, \ldots, \eta_{k-1}$ are the elements of the set $\{\eta_1, \eta_2, \ldots, \eta_{k-1}\}$ listed in increasing order (with no repetition).

Let us define a $(k-1)$-tuple $(\gamma_1, \gamma_2, \ldots, \gamma_{k-1}) \in \{1, 2, \ldots, k\}^{k-1}$ as in Theorem

2.15. Now, we have the following chain of logical equivalences:

$$\begin{aligned}
&(\operatorname{pet}_k(\lambda,\varnothing)\neq 0)\\
\Longleftrightarrow\ &(\text{the } k-1 \text{ numbers } \gamma_1,\gamma_2,\ldots,\gamma_{k-1} \text{ are distinct})\\
&\qquad\qquad (\text{by parts } \textbf{(b)} \text{ and } \textbf{(c)} \text{ of Theorem 2.15})\\
\Longleftrightarrow\ &(\text{the } k-1 \text{ numbers } (\beta_1-1)\,\%k, (\beta_2-1)\,\%k,\ldots,(\beta_{k-1}-1)\,\%k \text{ are distinct})\\
&\qquad\qquad (\text{since } \gamma_i = 1+(\beta_i-1)\,\%k \text{ for each } i)\\
\Longleftrightarrow\ &(\text{no two of the } k-1 \text{ numbers } \beta_1-1,\beta_2-1,\ldots,\beta_{k-1}-1 \text{ are congruent modulo } k)\\
\Longleftrightarrow\ &(\text{no two of the } k-1 \text{ numbers } \beta_1,\beta_2,\ldots,\beta_{k-1} \text{ are congruent modulo } k)\\
\Longleftrightarrow\ &(\text{no two of the } k-1 \text{ numbers } -1-\beta_1,-1-\beta_2,\ldots,-1-\beta_{k-1}\\
&\ \text{are congruent modulo } k)\\
\Longleftrightarrow\ &(\text{no two of the } k-1 \text{ numbers } \eta_1,\eta_2,\ldots,\eta_{k-1} \text{ are congruent modulo } k)\\
&\qquad\qquad \left(\text{since } \eta_j = -1-\beta_j \text{ for each } j\right)\\
\Longleftrightarrow\ &(\text{no two of the } k-1 \text{ elements of } \{\eta_1,\eta_2,\ldots,\eta_{k-1}\} \text{ are congruent modulo } k)\\
&\ \left(\begin{array}{c}\text{since } \eta_1,\eta_2,\ldots,\eta_{k-1} \text{ are the elements of the set } \{\eta_1,\eta_2,\ldots,\eta_{k-1}\}\\ \text{listed in increasing order (with no repetition)}\end{array}\right)\\
\Longleftrightarrow\ &(\text{no two of the } k-1 \text{ elements of } W\setminus B \text{ are congruent modulo } k)\\
&\qquad\qquad (\text{since } \{\eta_1,\eta_2,\ldots,\eta_{k-1}\} = W\setminus B)\\
\Longleftrightarrow\ &\left(\text{each congruence class } \bar{i} \text{ has at most 1 element in common with } W\setminus B\right)\\
\Longleftrightarrow\ &\left(\text{each } i\in\{0,1,\ldots,k-1\} \text{ satisfies } \left|\bar{i}\cap(W\setminus B)\right|\leq 1\right)\\
\Longleftrightarrow\ &\left(\text{each } i\in\{0,1,\ldots,k-1\} \text{ satisfies } \left|\left(\bar{i}\cap W\right)\setminus B\right|\leq 1\right)
\end{aligned}$$

(since $\bar{i}\cap(W\setminus B) = \left(\bar{i}\cap W\right)\setminus B$ for each i). This proves Proposition 2.16. □

3.12. Proof of Theorem 2.19

Proof of Theorem 2.19. In this proof, the word "monomial" may refer to a monomial in any set of variables (not necessarily in $x_1, x_2, x_3, \ldots$).

In the following, an *i-monomial* (where $i \in \mathbb{N}$) shall mean a monomial of degree i.

We shall say that a monomial is *k-bounded* if all exponents in this monomial are $< k$. In other words, a monomial is *k-bounded* if it can be written in the form $z_1^{a_1} z_2^{a_2} \cdots z_s^{a_s}$, where $z_1, z_2, \ldots, z_s$ are distinct variables and $a_1, a_2, \ldots, a_s$ are nonnegative integers $< k$. Thus, the k-bounded monomials in the variables $x_1, x_2, x_3, \ldots$ are precisely the monomials of the form $\mathbf{x}^\alpha$ for $\alpha \in \mathrm{WC}$ satisfying ($\alpha_i < k$ for all i). Hence, the k-bounded m-monomials in the variables $x_1, x_2, x_3, \ldots$ are precisely the monomials of the form $\mathbf{x}^\alpha$ for $\alpha \in \mathrm{WC}$ satisfying $|\alpha| = m$ and ($\alpha_i < k$ for all i).

Now, the definition of $G(k,m)$ yields

$$G(k,m) = \sum_{\substack{\alpha\in\mathrm{WC};\\ |\alpha|=m;\\ \alpha_i<k \text{ for all } i}} \mathbf{x}^{\alpha}$$
$$= (\text{the sum of all } k\text{-bounded } m\text{-monomials in the variables } x_1, x_2, x_3, \ldots) \tag{58}$$

(since the k-bounded m-monomials in the variables $x_1, x_2, x_3, \ldots$ are precisely the monomials of the form $\mathbf{x}^{\alpha}$ for $\alpha \in \mathrm{WC}$ satisfying $|\alpha| = m$ and ($\alpha_i < k$ for all i)).

Let us now substitute the variables $x_1, x_2, x_3, \ldots, y_1, y_2, y_3, \ldots$ for the variables $x_1, x_2, x_3, \ldots$ on both sides of the equality (58). (This means that we choose some bijection $\phi : \{x_1, x_2, x_3, \ldots\} \to \{x_1, x_2, x_3, \ldots, y_1, y_2, y_3, \ldots\}$, and substitute $\phi(x_i)$ for each x_i on both sides of (58).) The left hand side of (58) turns into $(G(k,m))(\mathbf{x}, \mathbf{y})$ upon this substitution[21], whereas the right hand side turns into

$$(\text{the sum of all } k\text{-bounded } m\text{-monomials in the variables } x_1, x_2, x_3, \ldots, y_1, y_2, y_3, \ldots)$$

[22]. Thus, our substitution transforms the equality (58) into

$$(G(k,m))(\mathbf{x}, \mathbf{y})$$
$$= (\text{the sum of all } k\text{-bounded } m\text{-monomials in the variables } x_1, x_2, x_3, \ldots, y_1, y_2, y_3, \ldots). \tag{59}$$

But any monomial $\mathfrak{m}$ in the variables $x_1, x_2, x_3, \ldots, y_1, y_2, y_3, \ldots$ can be uniquely written as a product $\mathfrak{n}\mathfrak{p}$, where $\mathfrak{n}$ is a monomial in the variables $x_1, x_2, x_3, \ldots$ and where $\mathfrak{p}$ is a monomial in the variables $y_1, y_2, y_3, \ldots$. Moreover, if $\mathfrak{m}$ is written in this form, then:

- the degree of $\mathfrak{m}$ equals the sum of the degrees of $\mathfrak{n}$ and $\mathfrak{p}$;
- thus, $\mathfrak{m}$ is an m-monomial if and only if there exists some $i \in \{0, 1, \ldots, m\}$ such that $\mathfrak{n}$ is an i-monomial and $\mathfrak{p}$ is an $(m-i)$-monomial;
- furthermore, $\mathfrak{m}$ is k-bounded if and only if both $\mathfrak{n}$ and $\mathfrak{p}$ are k-bounded.

Thus, any k-bounded m-monomial $\mathfrak{m}$ in the variables $x_1, x_2, x_3, \ldots, y_1, y_2, y_3, \ldots$ can be uniquely written as a product $\mathfrak{n}\mathfrak{p}$, where $i \in \{0, 1, \ldots, m\}$, where $\mathfrak{n}$ is a k-bounded i-monomial in the variables $x_1, x_2, x_3, \ldots$ and where $\mathfrak{p}$ is a k-bounded $(m-i)$-monomial in the variables $y_1, y_2, y_3, \ldots$. Conversely, every such product $\mathfrak{n}\mathfrak{p}$

[21] because this is how $(G(k,m))(\mathbf{x}, \mathbf{y})$ was defined

[22] Indeed, the substitution can be regarded as simply renaming the variables $x_1, x_2, x_3, \ldots$ as $x_1, x_2, x_3, \ldots, y_1, y_2, y_3, \ldots$ (in some order). Thus, it turns the k-bounded m-monomials in the variables $x_1, x_2, x_3, \ldots$ into the k-bounded m-monomials in the variables $x_1, x_2, x_3, \ldots, y_1, y_2, y_3, \ldots$.

is a k-bounded m-monomial $\mathfrak{m}$ in the variables $x_1, x_2, x_3, \ldots, y_1, y_2, y_3, \ldots$. Thus, we obtain a bijection

$$\begin{aligned}
&\bigsqcup_{i \in \{0,1,\ldots,m\}} \Big(\{k\text{-bounded } i\text{-monomials in the variables } x_1, x_2, x_3, \ldots\} \\
&\qquad \times \{k\text{-bounded } (m-i)\text{-monomials in the variables } y_1, y_2, y_3, \ldots\} \Big) \\
&\quad \to \{k\text{-bounded } m\text{-monomials in the variables } x_1, x_2, x_3, \ldots, y_1, y_2, y_3, \ldots\}
\end{aligned}$$

that sends each pair $(\mathfrak{n}, \mathfrak{p})$ to $\mathfrak{n}\mathfrak{p}$. Hence,

$$\begin{aligned}
&(\text{the sum of all } k\text{-bounded } m\text{-monomials in the variables } x_1, x_2, x_3, \ldots, y_1, y_2, y_3, \ldots) \\
&= \sum_{i \in \{0,1,\ldots,m\}} \sum_{\substack{\mathfrak{n} \text{ is a } k\text{-bounded} \\ i\text{-monomial in the} \\ \text{variables } x_1, x_2, x_3, \ldots}} \sum_{\substack{\mathfrak{p} \text{ is a } k\text{-bounded} \\ (m-i)\text{-monomial in the} \\ \text{variables } y_1, y_2, y_3, \ldots}} \mathfrak{n}\mathfrak{p} \\
&= \sum_{i \in \{0,1,\ldots,m\}} \left(\sum_{\substack{\mathfrak{n} \text{ is a } k\text{-bounded} \\ i\text{-monomial in the} \\ \text{variables } x_1, x_2, x_3, \ldots}} \mathfrak{n} \right) \left(\sum_{\substack{\mathfrak{p} \text{ is a } k\text{-bounded} \\ (m-i)\text{-monomial in the} \\ \text{variables } y_1, y_2, y_3, \ldots}} \mathfrak{p} \right) \\
&= \sum_{i \in \{0,1,\ldots,m\}} (\text{the sum of all } k\text{-bounded } i\text{-monomials in the variables } x_1, x_2, x_3, \ldots) \\
&\qquad \cdot (\text{the sum of all } k\text{-bounded } (m-i)\text{-monomials in the variables } y_1, y_2, y_3, \ldots) . \qquad (60)
\end{aligned}$$

Now, let $i \in \{0, 1, \ldots, m\}$. The same reasoning that gave us (58) can be applied to i instead of m. Thus we obtain

$$G(k, i) = (\text{the sum of all } k\text{-bounded } i\text{-monomials in the variables } x_1, x_2, x_3, \ldots) . \qquad (61)$$

Also, $i \in \{0, 1, \ldots, m\}$, so that $m - i \in \{0, 1, \ldots, m\} \subseteq \mathbb{N}$. Hence, the same reasoning that gave us (58) can be applied to $m - i$ instead of m. Thus we obtain

$$\begin{aligned}
&G(k, m-i) \\
&= (\text{the sum of all } k\text{-bounded } (m-i)\text{-monomials in the variables } x_1, x_2, x_3, \ldots) .
\end{aligned}$$

Renaming the variables $x_1, x_2, x_3, \ldots$ as $y_1, y_2, y_3, \ldots$ in this equality, we obtain

$$\begin{aligned}
&(G(k, m-i))(\mathbf{y}) \\
&= (\text{the sum of all } k\text{-bounded } (m-i)\text{-monomials in the variables } y_1, y_2, y_3, \ldots) . \qquad (62)
\end{aligned}$$

Forget that we fixed i. We thus have proved (61) and (62) for each $i \in \{0, 1, \ldots, m\}$.

Now, (59) becomes

$$\begin{aligned}
&(G(k,m))(\mathbf{x},\mathbf{y}) \\
&= (\text{the sum of all } k\text{-bounded } m\text{-monomials in the variables } x_1,x_2,x_3,\ldots,y_1,y_2,y_3,\ldots) \\
&= \sum_{i\in\{0,1,\ldots,m\}} \underbrace{(\text{the sum of all } k\text{-bounded } i\text{-monomials in the variables } x_1,x_2,x_3,\ldots)}_{\substack{=G(k,i) \\ (\text{by (61)})}} \\
&\qquad \cdot \underbrace{(\text{the sum of all } k\text{-bounded } (m-i)\text{-monomials in the variables } y_1,y_2,y_3,\ldots)}_{\substack{=(G(k,m-i))(\mathbf{y}) \\ (\text{by (62)})}} \\
&\overset{(\text{by (60)})}{=} \sum_{i\in\{0,1,\ldots,m\}} \underbrace{G(k,i)}_{=(G(k,i))(\mathbf{x})} \cdot (G(k,m-i))(\mathbf{y}) = \sum_{i\in\{0,1,\ldots,m\}} (G(k,i))(\mathbf{x}) \cdot (G(k,m-i))(\mathbf{y}).
\end{aligned}$$

Hence, (10) holds for $f = G(k,m)$, $I = \{0,1,\ldots,m\}$, $(f_{1,i})_{i\in I} = (G(k,i))_{i\in\{0,1,\ldots,m\}}$ and $(f_{2,i})_{i\in I} = (G(k,m-i))_{i\in\{0,1,\ldots,m\}}$. Therefore, (9) (applied to these f, I, $(f_{1,i})_{i\in I}$ and $(f_{2,i})_{i\in I}$) yields

$$\Delta(G(k,m)) = \sum_{i\in\{0,1,\ldots,m\}} G(k,i)\otimes G(k,m-i) = \sum_{i=0}^{m} G(k,i)\otimes G(k,m-i).$$

This proves Theorem 2.19. □

3.13. Proof of Theorem 2.21

Proof of Theorem 2.21. Consider the ring $(\mathbf{k}[[x_1,x_2,x_3,\ldots]])[[t]]$ of formal power series in one indeterminate t over $\mathbf{k}[[x_1,x_2,x_3,\ldots]]$. We equip this ring with the topology that is obtained by identifying it with $\mathbf{k}[[x_1,x_2,x_3,\ldots,t]]$ (or, equivalently, which is obtained by considering $\mathbf{k}[[x_1,x_2,x_3,\ldots]]$ itself as equipped with the standard topology on a ring of formal power series, and then adjoining the extra indeterminate t).

Now, consider the map

$$\begin{aligned}
\mathbf{F}_k : \mathbf{k}[[x_1,x_2,x_3,\ldots]] &\to \mathbf{k}[[x_1,x_2,x_3,\ldots]], \\
a &\mapsto a\left(x_1^k,x_2^k,x_3^k,\ldots\right).
\end{aligned}$$

This map $\mathbf{F}_k$ is a continuous $\mathbf{k}$-algebra homomorphism (since it is an evaluation homomorphism)[23]. Hence, it induces a continuous[24] $\mathbf{k}[[t]]$-algebra homomorphism

$$\mathbf{F}_k[[t]] : (\mathbf{k}[[x_1,x_2,x_3,\ldots]])[[t]] \to (\mathbf{k}[[x_1,x_2,x_3,\ldots]])[[t]]$$

[23]It is well-defined, since k is positive.

[24]Continuity is defined with respect to the topology that we defined on $(\mathbf{k}[[x_1,x_2,x_3,\ldots]])[[t]]$.

that sends each formal power series $\sum\limits_{n\geq 0} a_n t^n \in (\mathbf{k}[[x_1, x_2, x_3, \ldots]])[[t]]$ (with $a_n \in \mathbf{k}[[x_1, x_2, x_3, \ldots]]$) to $\sum\limits_{n\geq 0} \mathbf{F}_k(a_n) t^n$. Consider this $\mathbf{k}[[t]]$-algebra homomorphism $\mathbf{F}_k[[t]]$. In particular, it satisfies

$$(\mathbf{F}_k[[t]])\left(t^i\right) = t^i \qquad \text{for each } i \in \mathbb{N}.$$

The definition of $\mathbf{F}_k$ yields

$$\mathbf{F}_k(x_i) = x_i^k \qquad \text{for each } i \in \{1, 2, 3, \ldots\}. \tag{63}$$

Also, for each $a \in \Lambda$, we have

$$\begin{aligned}\mathbf{F}_k(a) &= a\left(x_1^k, x_2^k, x_3^k, \ldots\right) \qquad &&(\text{by the definition of } \mathbf{F}_k)\\ &= \mathbf{f}_k(a) && (64)\end{aligned}$$

(since the definition of $\mathbf{f}_k$ yields $\mathbf{f}_k(a) = a\left(x_1^k, x_2^k, x_3^k, \ldots\right)$). Thus, in particular, each $n \in \mathbb{N}$ satisfies

$$\mathbf{F}_k(e_n) = \mathbf{f}_k(e_n) \tag{65}$$

(by (64), applied to $a = e_n$).

Applying the map $\mathbf{F}_k[[t]]$ to both sides of the equality (50), we obtain

$$(\mathbf{F}_k[[t]])\left(\prod_{i=1}^{\infty}(1 + x_i t)\right) = (\mathbf{F}_k[[t]])\left(\sum_{n\geq 0} e_n t^n\right) = \sum_{n\geq 0} \mathbf{F}_k(e_n) t^n$$

(by the definition of $\mathbf{F}_k[[t]]$). Hence,

$$\begin{aligned}\sum_{n\geq 0} \mathbf{F}_k(e_n) t^n &= (\mathbf{F}_k[[t]])\left(\prod_{i=1}^{\infty}(1 + x_i t)\right) = \prod_{i=1}^{\infty} \underbrace{(\mathbf{F}_k[[t]])(1 + x_i t)}_{\substack{=1+\mathbf{F}_k(x_i)t \\ (\text{by the definition of } \mathbf{F}_k[[t]])}}\\ &\qquad \left(\begin{array}{c}\text{since } \mathbf{F}_k[[t]] \text{ is a continuous } \mathbf{k}[[t]]\text{-algebra homomorphism,}\\ \text{and thus respects infinite products}\end{array}\right)\\ &= \prod_{i=1}^{\infty}\left(1 + \underbrace{\mathbf{F}_k(x_i)}_{\substack{=x_i^k \\ (\text{by } (63))}} t\right) = \prod_{i=1}^{\infty}\left(1 + x_i^k t\right).\end{aligned}$$

Substituting $-t^k$ for t in this equality, we find

$$\begin{aligned}
\sum_{n\geq 0} \mathbf{F}_k(e_n)\left(-t^k\right)^n &= \prod_{i=1}^{\infty} \underbrace{\left(1+x_i^k\left(-t^k\right)\right)}_{\substack{=1-(x_it)^k \\ =(1-x_it)\left((x_it)^0+(x_it)^1+\cdots+(x_it)^{k-1}\right) \\ \text{(since } 1-u^k=(1-u)\left(u^0+u^1+\cdots+u^{k-1}\right) \\ \text{for any element } u \text{ of any ring)}}} \\
&= \prod_{i=1}^{\infty}\left((1-x_it)\left((x_it)^0+(x_it)^1+\cdots+(x_it)^{k-1}\right)\right) \\
&= \left(\prod_{i=1}^{\infty}(1-x_it)\right)\left(\prod_{i=1}^{\infty}\left((x_it)^0+(x_it)^1+\cdots+(x_it)^{k-1}\right)\right).
\end{aligned}$$

We can divide both sides of this equality by $\prod\limits_{i=1}^{\infty}(1-x_it)$ (since the formal power series $\prod\limits_{i=1}^{\infty}(1-x_it)$ has constant term 1 and thus is invertible), and thus obtain

$$\begin{aligned}
\frac{\sum\limits_{n\geq 0}\mathbf{F}_k(e_n)\left(-t^k\right)^n}{\prod\limits_{i=1}^{\infty}(1-x_it)} &= \prod_{i=1}^{\infty}\underbrace{\left((x_it)^0+(x_it)^1+\cdots+(x_it)^{k-1}\right)}_{=\sum\limits_{u=0}^{k-1}(x_it)^u} = \prod_{i=1}^{\infty}\sum_{u=0}^{k-1}(x_it)^u \\
&= \underbrace{\sum_{\substack{\alpha=(\alpha_1,\alpha_2,\alpha_3,\ldots)\in\{0,1,\ldots,k-1\}^{\infty}; \\ \alpha_i=0 \text{ for all but finitely many } i}}}_{\substack{=\sum\limits_{\substack{\alpha\in\{0,1,\ldots,k-1\}^{\infty} \\ \text{is a weak composition}}} \\ =\sum\limits_{\substack{\alpha\in\mathrm{WC}; \\ \alpha_i<k \text{ for all } i}}}} \underbrace{(x_1t)^{\alpha_1}(x_2t)^{\alpha_2}(x_3t)^{\alpha_3}\cdots}_{=\left(x_1^{\alpha_1}x_2^{\alpha_2}x_3^{\alpha_3}\cdots\right)\left(t^{\alpha_1}t^{\alpha_2}t^{\alpha_3}\cdots\right)} \\
&\qquad \text{(here, we have expanded the product)} \\
&= \sum_{\substack{\alpha\in\mathrm{WC}; \\ \alpha_i<k \text{ for all } i}} \underbrace{\left(x_1^{\alpha_1}x_2^{\alpha_2}x_3^{\alpha_3}\cdots\right)}_{\substack{=\mathbf{x}^{\alpha} \\ \text{(by the definition of } \mathbf{x}^{\alpha})}} \underbrace{\left(t^{\alpha_1}t^{\alpha_2}t^{\alpha_3}\cdots\right)}_{\substack{=t^{\alpha_1+\alpha_2+\alpha_3+\cdots}=t^{|\alpha|} \\ \text{(since } \alpha_1+\alpha_2+\alpha_3+\cdots=|\alpha|)}} \\
&= \sum_{\substack{\alpha\in\mathrm{WC}; \\ \alpha_i<k \text{ for all } i}} \mathbf{x}^{\alpha}t^{|\alpha|}.
\end{aligned}$$

Hence,

$$\sum_{\substack{\alpha\in\mathrm{WC};\\ \alpha_i<k \text{ for all } i}} \mathbf{x}^\alpha t^{|\alpha|}$$

$$= \frac{\sum\limits_{n\geq 0} \mathbf{F}_k\left(e_n\right)\left(-t^k\right)^n}{\prod\limits_{i=1}^{\infty}\left(1-x_i t\right)} = \left(\sum_{n\geq 0} \underbrace{\mathbf{F}_k\left(e_n\right)}_{\substack{=\mathbf{f}_k(e_n)\\ \text{(by (65))}}} \underbrace{\left(-t^k\right)^n}_{=(-1)^n t^{kn}}\right) \cdot \underbrace{\prod_{i=1}^{\infty}\left(1-x_i t\right)^{-1}}_{\substack{=\sum_{n\geq 0} h_n t^n\\ \text{(by (49))}}}$$

$$= \left(\sum_{n\geq 0} \mathbf{f}_k\left(e_n\right)\left(-1\right)^n t^{kn}\right) \cdot \underbrace{\left(\sum_{n\geq 0} h_n t^n\right)}_{=\sum_{j\geq 0} h_j t^j} = \left(\sum_{n\geq 0} \mathbf{f}_k\left(e_n\right)\left(-1\right)^n t^{kn}\right) \cdot \left(\sum_{j\geq 0} h_j t^j\right)$$

$$= \underbrace{\sum_{n\geq 0}\sum_{j\geq 0}}_{=\sum_{(n,j)\in\mathbb{N}^2}} \mathbf{f}_k\left(e_n\right)\left(-1\right)^n \underbrace{t^{kn} h_j t^j}_{=h_j t^{kn+j}} = \sum_{(n,j)\in\mathbb{N}^2} \mathbf{f}_k\left(e_n\right)\left(-1\right)^n h_j t^{kn+j}.$$

This is an equality between two power series in $\left(\mathbf{k}\left[\left[x_1,x_2,x_3,\ldots\right]\right]\right)\left[\left[t\right]\right]$. If we compare the coefficients of t^m on both sides of it (where $x_1,x_2,x_3,\ldots$ are considered scalars, not monomials), we obtain

$$\sum_{\substack{\alpha\in\mathrm{WC};\\ \alpha_i<k \text{ for all } i;\\ |\alpha|=m}} \mathbf{x}^\alpha = \underbrace{\sum_{\substack{(n,j)\in\mathbb{N}^2;\\ kn+j=m}}}_{=\sum_{n\in\mathbb{N}}\sum_{\substack{j\in\mathbb{N};\\ kn+j=m}}} \mathbf{f}_k\left(e_n\right)\left(-1\right)^n h_j = \sum_{n\in\mathbb{N}} \mathbf{f}_k\left(e_n\right)\left(-1\right)^n \cdot \sum_{\substack{j\in\mathbb{N};\\ kn+j=m}} h_j.$$

Now, the definition of $G\left(k,m\right)$ yields

$$G\left(k,m\right) = \sum_{\substack{\alpha\in\mathrm{WC};\\ |\alpha|=m;\\ \alpha_i<k \text{ for all } i}} \mathbf{x}^\alpha = \sum_{\substack{\alpha\in\mathrm{WC};\\ \alpha_i<k \text{ for all } i;\\ |\alpha|=m}} \mathbf{x}^\alpha = \sum_{n\in\mathbb{N}} \mathbf{f}_k\left(e_n\right)\left(-1\right)^n \cdot \sum_{\substack{j\in\mathbb{N};\\ kn+j=m}} h_j. \tag{66}$$

But the right hand side of this equality can be simplified. Namely, for each $n\in\mathbb{N}$, we have

$$\sum_{\substack{j\in\mathbb{N};\\ kn+j=m}} h_j = h_{m-kn}. \tag{67}$$

[*Proof of (67):* Let $n \in \mathbb{N}$. We must prove the equality (67). If $m - kn < 0$, then $h_{m-kn} = 0$ and $\sum\limits_{\substack{j \in \mathbb{N};\\ kn+j=m}} h_j = (\text{empty sum}) = 0$. Thus, if $m - kn < 0$, then (67) boils down to $0 = 0$, which is obviously true. Therefore, for the rest of the proof of (67), we WLOG assume that $m - kn \geq 0$. Hence, the sum $\sum\limits_{\substack{j \in \mathbb{N};\\ kn+j=m}} h_j$ has exactly one addend, namely the addend for $j = m - kn$. Therefore, $\sum\limits_{\substack{j \in \mathbb{N};\\ kn+j=m}} h_j = h_{m-kn}$. This proves (67).]

Now, (66) becomes

$$\begin{aligned} G(k,m) &= \sum_{n \in \mathbb{N}} \mathbf{f}_k(e_n)(-1)^n \cdot \underbrace{\sum_{\substack{j \in \mathbb{N};\\ kn+j=m}} h_j}_{\substack{=h_{m-kn}\\ \text{(by (67))}}} = \sum_{n \in \mathbb{N}} \mathbf{f}_k(e_n)(-1)^n \cdot h_{m-kn} \\ &= \sum_{n \in \mathbb{N}} (-1)^n h_{m-kn} \cdot \mathbf{f}_k(e_n) = \sum_{i \in \mathbb{N}} (-1)^i h_{m-ki} \cdot \mathbf{f}_k(e_i) \end{aligned}$$

(here, we have renamed the summation index n as i). This proves Theorem 2.21. □

3.14. Proofs of the results from Section 2.8

We shall now prove the results from Section 2.8. We begin with Lemma 2.23. This will rely on the Verschiebung endomorphisms $\mathbf{v}_n$ introduced in Definition 2.25, and on Proposition 2.26 and the equality (11).

Proof of Lemma 2.23. Applying (11) to $n = k$, we obtain

$$\mathbf{v}_k(p_m) = \begin{cases} kp_{m/k}, & \text{if } k \mid m; \\ 0, & \text{if } k \nmid m \end{cases}. \tag{68}$$

Applying Proposition 2.26 to $n = k$, $a = p_m$ and $b = e_j$, we obtain

$$(p_m, \mathbf{f}_k(e_j)) = (\mathbf{v}_k(p_m), e_j). \tag{69}$$

Now, we are in one of the following three cases:

Case 1: We have $m = kj$.

Case 2: We have $k \nmid m$.

Case 3: We have neither $m = kj$ nor $k \nmid m$.

Let us first consider Case 1. In this case, we have $m = kj$. Thus, $k \mid m$ (since $j \in \mathbb{N} \subseteq \mathbb{Z}$) and $m/k = j$. Hence, $j = m/k$, so that the integer j is positive (since m

and k are positive). But (68) becomes

$$\mathbf{v}_k(p_m) = \begin{cases} kp_{m/k}, & \text{if } k \mid m; \\ 0, & \text{if } k \nmid m \end{cases} = kp_{m/k} \qquad (\text{since } k \mid m)$$
$$= kp_j \qquad (\text{since } m/k = j).$$

Thus, (69) becomes

$$\begin{aligned}(p_m, \mathbf{f}_k(e_j)) &= \left(\underbrace{\mathbf{v}_k(p_m)}_{=kp_j}, e_j \right) = (kp_j, e_j) \\ &= (e_j, kp_j) \qquad (\text{since the Hall inner product is symmetric}) \\ &= k \underbrace{(e_j, p_j)}_{\substack{=(-1)^{j-1} \\ (\text{by Proposition 1.3, applied to } n=j)}} = k(-1)^{j-1} = (-1)^{j-1} k.\end{aligned}$$

Comparing this with

$$(-1)^{j-1} \underbrace{[m = kj]}_{\substack{=1 \\ (\text{since } m=kj)}} k = (-1)^{j-1} k,$$

we obtain $(p_m, \mathbf{f}_k(e_j)) = (-1)^{j-1} [m = kj] k$. Thus, Lemma 2.23 is proven in Case 1.

A similar (but simpler) argument can be used to prove Lemma 2.23 in Case 2. The main "idea" here is that $k \nmid m$ implies $m \neq kj$. The details are left to the reader.

Let us finally consider Case 3. In this case, we have neither $m = kj$ nor $k \nmid m$. In other words, we have $m \neq kj$ and $k \mid m$. From $k \mid m$, we conclude that m/k is a positive integer[25]. From $m \neq kj$, we obtain $m/k \neq j$. Thus, the symmetric functions $p_{m/k}$ and e_j are homogeneous of different degrees[26], and therefore satisfy $(p_{m/k}, e_j) = 0$ (by (2), applied to $f = p_{m/k}$ and $g = e_j$).

Now, (68) becomes

$$\mathbf{v}_k(p_m) = \begin{cases} kp_{m/k}, & \text{if } k \mid m; \\ 0, & \text{if } k \nmid m \end{cases} = kp_{m/k} \qquad (\text{since } k \mid m).$$

Thus, (69) becomes

$$(p_m, \mathbf{f}_k(e_j)) = \left(\underbrace{\mathbf{v}_k(p_m)}_{=kp_{m/k}}, e_j \right) = (kp_{m/k}, e_j) = k \underbrace{(p_{m/k}, e_j)}_{=0} = 0.$$

[25]Indeed, it is positive since m and k are positive.

[26]since $p_{m/k}$ is homogeneous of degree m/k, whereas e_j is homogeneous of degree j

Comparing this with

$$(-1)^{j-1} \underbrace{[m = kj]}_{\substack{=0 \\ (\text{since } m \neq kj)}} k = 0,$$

we obtain $(p_m, \mathbf{f}_k(e_j)) = (-1)^{j-1} [m = kj] k$. Thus, Lemma 2.23 is proven in Case 3.

We have thus proven Lemma 2.23 in all three Cases 1, 2 and 3. Thus, Lemma 2.23 always holds. □

Next, let us prove a simple property of Hall inner products:

Lemma 3.14. Let m, α and β be positive integers. Let a be a homogeneous symmetric function of degree α. Let b be a homogeneous symmetric function of degree β. Then, $(p_m, ab) = 0$.

Proof of Lemma 3.14. For each $n \in \mathbb{N}$, let Λ_n denote the n-th homogeneous component of the graded $\mathbf{k}$-algebra Λ. Thus, $a \in \Lambda_\alpha$ and $b \in \Lambda_\beta$ (since a and b are homogeneous symmetric functions of degrees α and β).

But it is known that the family $(h_\lambda)_{\lambda \in \operatorname{Par}}$ is a graded basis of the graded $\mathbf{k}$-module Λ; this means that for each $n \in \mathbb{N}$, its subfamily $(h_\lambda)_{\lambda \in \operatorname{Par}_n}$ is a basis of the $\mathbf{k}$-module Λ_n. [27] Applying this to $n = \alpha$, we conclude that the subfamily $(h_\lambda)_{\lambda \in \operatorname{Par}_\alpha}$ is a basis of Λ_α. Hence, a is a $\mathbf{k}$-linear combination of this family $(h_\lambda)_{\lambda \in \operatorname{Par}_\alpha}$ (since $a \in \Lambda_\alpha$).

We must prove the equality $(p_m, ab) = 0$. Both sides of this equality depend $\mathbf{k}$-linearly on a. Thus, in proving it, we can WLOG assume that a belongs to the family $(h_\lambda)_{\lambda \in \operatorname{Par}_\alpha}$ (because we know that a is a $\mathbf{k}$-linear combination of this family). In other words, we can WLOG assume that $a = h_\lambda$ for some $\lambda \in \operatorname{Par}_\alpha$. Assume this. For similar reasons, we can WLOG assume that $b = h_\mu$ for some $\mu \in \operatorname{Par}_\beta$. Assume this, too. Consider these two partitions λ and μ.

We have $\lambda \in \operatorname{Par}_\alpha$ and thus $|\lambda| = \alpha > 0$, so that $\lambda \neq \varnothing$. Hence, the partition λ has at least one part. Likewise, the partition μ has at least one part.

Now, let $\lambda \sqcup \mu$ be the partition obtained by listing all parts of λ and of μ and sorting the resulting list in weakly decreasing order.[28] Using Definition 3.1, we can easily see that $h_{\lambda \sqcup \mu} = h_\lambda h_\mu$. Comparing this with $\underbrace{a}_{=h_\lambda} \underbrace{b}_{=h_\mu} = h_\lambda h_\mu$, we obtain $ab = h_{\lambda \sqcup \mu}$.

But the partition $\lambda \sqcup \mu$ has as many parts as λ and μ have combined. Thus, the partition $\lambda \sqcup \mu$ has at least 2 parts (since λ has at least one part, and μ has at least one part). Therefore, $\lambda \sqcup \mu \neq (m)$ (since the partition $\lambda \sqcup \mu$ has at least 2 parts, while the partition (m) has only 1 part). Now, recall that $p_m = m_{(m)}$ (where, of

[27] This follows, e.g., from [GriRei20, Corollary 2.5.17(a)] (which shows that $(h_\lambda)_{\lambda \in \operatorname{Par}}$ is a basis of Λ) and from the fact that each h_λ is homogeneous of degree $|\lambda|$.

[28] For example: If $\lambda = (5, 3, 2)$ and $\mu = (6, 4, 3, 1, 1)$, then $\lambda \sqcup \mu = (6, 5, 4, 3, 3, 2, 1, 1)$.

course, the two "m"s in "$m_{(m)}$" mean completely unrelated things). Thus,

$$\begin{aligned}\left(\underbrace{p_m}_{=m_{(m)}}, \underbrace{ab}_{=h_{\lambda\sqcup\mu}}\right) &= \left(m_{(m)}, h_{\lambda\sqcup\mu}\right) = \left(h_{\lambda\sqcup\mu}, m_{(m)}\right) \qquad \left(\begin{array}{c}\text{since the Hall inner product}\\ \text{is symmetric}\end{array}\right) \\ &= \delta_{\lambda\sqcup\mu,(m)} \qquad (\text{by (13)}) \\ &= 0 \qquad (\text{since } \lambda \sqcup \mu \neq (m)).\end{aligned}$$

This proves Lemma 3.14. □

See [Grinbe20b] for a different proof of Lemma 3.14, using the graded dual Λ^o of the Hopf algebra Λ and the primitivity of the element $p_m \in \Lambda$.

We can now prove Proposition 2.24:

Proof of Proposition 2.24. Theorem 2.21 yields $G(k,m) = \sum_{i\in\mathbb{N}} (-1)^i h_{m-ki} \cdot \mathbf{f}_k(e_i)$. Hence,

$$\begin{aligned}(p_m, G(k,m)) &= \left(p_m, \sum_{i\in\mathbb{N}} (-1)^i h_{m-ki} \cdot \mathbf{f}_k(e_i)\right) \\ &= \sum_{i\in\mathbb{N}} (-1)^i \left(p_m, h_{m-ki} \cdot \mathbf{f}_k(e_i)\right) \qquad (70)\end{aligned}$$

(since the Hall inner product is $\mathbf{k}$-bilinear).

Now, we claim that every $i \in \mathbb{N} \setminus \{0, m/k\}$ satisfies

$$(p_m, h_{m-ki} \cdot \mathbf{f}_k(e_i)) = 0. \qquad (71)$$

[*Proof of (71):* Let $i \in \mathbb{N} \setminus \{0, m/k\}$. Thus, $i \in \mathbb{N}$ and $i \notin \{0, m/k\}$. From $i \notin \{0, m/k\}$, we obtain $i \neq 0$ and $i \neq m/k$. From $i \neq m/k$, we obtain $ki \neq m$, so that $m - ki \neq 0$.

We must prove the equality (71). If $m - ki < 0$, then $h_{m-ki} = 0$, and therefore

$$\left(p_m, \underbrace{h_{m-ki}}_{=0} \cdot \mathbf{f}_k(e_i)\right) = (p_m, 0) = 0.$$

Hence, the equality (71) is proven if $m - ki < 0$. Thus, for the rest of this proof, we WLOG assume that $m - ki \geq 0$. Combining this with $m - ki \neq 0$, we obtain $m - ki > 0$. Thus, $m - ki$ is a positive integer. Also, i is a positive integer (since $i \in \mathbb{N}$ and $i \neq 0$), and thus ki is a positive integer (since k is a positive integer).

The map $\mathbf{f}_k : \Lambda \to \Lambda$ operates by replacing each x_i by x_i^k in a symmetric function (by the definition of $\mathbf{f}_k$). Thus, if $g \in \Lambda$ is any homogeneous symmetric function of some degree γ, then $\mathbf{f}_k(g)$ is a homogeneous symmetric function of degree $k\gamma$. Applying this to $g = e_i$ and $\gamma = i$, we conclude that $\mathbf{f}_k(e_i)$ is a homogeneous symmetric function of degree ki (since e_i is a homogeneous symmetric function of degree i). Also, h_{m-ki} is a homogeneous symmetric function of degree $m-ki$.

Hence, Lemma 3.14 (applied to $\alpha = m-ki$, $a = h_{m-ki}$, $\beta = ki$ and $b = \mathbf{f}_k(e_i)$) yields $(p_m, h_{m-ki} \cdot \mathbf{f}_k(e_i)) = 0$. This proves (71).]

Note that $e_0 = 1$ and thus $\mathbf{f}_k(e_0) = \mathbf{f}_k(1) = 1$ (by the definition of $\mathbf{f}_k$).

Note that $m/k > 0$ (since m and k are positive). Hence, $m/k \neq 0$. Now, we are in one of the following two cases:

Case 1: We have $k \mid m$.

Case 2: We have $k \nmid m$.

Let us consider Case 1 first. In this case, we have $k \mid m$. Hence, m/k is a positive integer (since m and k are positive integers). Thus, 0 and m/k are two distinct elements of $\mathbb{N}$ (indeed, they are distinct because $m/k \neq 0$). Lemma 2.23 (applied to $j = m/k$) yields

$$(p_m, \mathbf{f}_k(e_{m/k})) = (-1)^{m/k-1} \underbrace{[m = k(m/k)]}_{\substack{=1 \\ (\text{since } m=k(m/k))}} k = (-1)^{m/k-1} k.$$

Now, (70) becomes

$$\begin{aligned}
&(p_m, G(k,m)) \\
&= \sum_{i\in\mathbb{N}} (-1)^i (p_m, h_{m-ki} \cdot \mathbf{f}_k(e_i)) \\
&= \underbrace{(-1)^0}_{=1} \left(p_m, \underbrace{h_{m-k\cdot 0}}_{=h_m} \cdot \underbrace{\mathbf{f}_k(e_0)}_{=1} \right) + (-1)^{m/k} \left(p_m, \underbrace{h_{m-k\cdot m/k}}_{\substack{=h_0 \\ (\text{since } m-k\cdot m/k=0)}} \cdot \mathbf{f}_k(e_{m/k}) \right) \\
&\qquad + \sum_{i\in\mathbb{N}\setminus\{0,m/k\}} (-1)^i \underbrace{(p_m, h_{m-ki} \cdot \mathbf{f}_k(e_i))}_{\substack{=0 \\ (\text{by (71)})}} \\
&\qquad \left(\begin{array}{c} \text{here, we have split off the addends for } i=0 \text{ and for } i=m/k \\ \text{from the sum (since 0 and } m/k \text{ are two distinct elements of } \mathbb{N}) \end{array} \right) \\
&= \underbrace{(p_m, h_m)}_{\substack{=(h_m,p_m) \\ (\text{since the Hall inner} \\ \text{product is symmetric})}} + (-1)^{m/k} \left(p_m, \underbrace{h_0}_{=1} \cdot \mathbf{f}_k(e_{m/k}) \right) + \underbrace{\sum_{i\in\mathbb{N}\setminus\{0,m/k\}} (-1)^i 0}_{=0} \\
&= \underbrace{(h_m, p_m)}_{\substack{=1 \\ (\text{by Proposition 1.2,} \\ \text{applied to } n=m)}} + (-1)^{m/k} \underbrace{(p_m, \mathbf{f}_k(e_{m/k}))}_{=(-1)^{m/k-1}k} \\
&= 1 + \underbrace{(-1)^{m/k}(-1)^{m/k-1}}_{=-1} k = 1-k.
\end{aligned}$$

Comparing this with

$$1 - \underbrace{[k \mid m]}_{\substack{=1 \\ (\text{since } k|m)}} k = 1 - k,$$

we obtain $(p_m, G(k,m)) = 1 - [k \mid m] \, k$. Hence, Proposition 2.24 is proven in Case 1.

Case 2 is similar to Case 1, but simpler because we no longer need to split off the addend for $i = m/k$ from the sum (since $m/k \notin \mathbb{N}$ in this case). We leave it to the reader.

We have now proven Proposition 2.24 both in Case 1 and in Case 2. Hence, Proposition 2.24 always holds. $\square$

Theorem 2.22 will follow from Proposition 2.24 using the following general criterion for generating sets of Λ:

Proposition 3.15. For each positive integer m, let $v_m \in \Lambda$ be a homogeneous symmetric function of degree m.

Assume that (p_m, v_m) is an invertible element of $\mathbf{k}$ for each positive integer m.

Then, the family $(v_m)_{m \geq 1} = (v_1, v_2, v_3, \ldots)$ is an algebraically independent generating set of the commutative $\mathbf{k}$-algebra Λ.

Proof of Proposition 3.15. Proposition 3.15 is [GriRei20, Exercise 2.5.24]. $\square$

Proof of Theorem 2.22. Let m be a positive integer. Proposition 2.24 yields that

$$(p_m, G(k,m)) = 1 - \underbrace{[k \mid m]}_{= \begin{cases} 1, & \text{if } k \mid m; \\ 0, & \text{if } k \nmid m \end{cases}} k = 1 - \begin{cases} 1, & \text{if } k \mid m; \\ 0, & \text{if } k \nmid m \end{cases} \cdot k$$

$$= \begin{cases} 1 - 1 \cdot k, & \text{if } k \mid m; \\ 1 - 0 \cdot k, & \text{if } k \nmid m \end{cases} = \begin{cases} 1 - k, & \text{if } k \mid m; \\ 1, & \text{if } k \nmid m \end{cases}.$$

Hence, $(p_m, G(k,m))$ is an invertible element of $\mathbf{k}$ (because both $1 - k$ and 1 are invertible elements of $\mathbf{k}$).

Forget that we fixed m. We thus have showed that $(p_m, G(k,m))$ is an invertible element of $\mathbf{k}$ for each positive integer m. Also, clearly, for each positive integer m, the element $G(k,m) \in \Lambda$ is a homogeneous symmetric function of degree m. Thus, Proposition 3.15 (applied to $v_m = G(k,m)$) shows that the family $(G(k,m))_{m \geq 1} = (G(k,1), G(k,2), G(k,3), \ldots)$ is an algebraically independent generating set of the commutative $\mathbf{k}$-algebra Λ. This proves Theorem 2.22. $\square$

3.15. Proof of Theorem 2.29

Proof of Theorem 2.29. The $\mathbf{k}$-Hopf algebra Λ is both commutative and cocommutative (by [GriRei20, Exercise 2.3.7(a)]). Thus, its antipode S is a $\mathbf{k}$-Hopf algebra homomorphism[29].

(a) The map $\mathbf{f}_k$ is a $\mathbf{k}$-Hopf algebra homomorphism (by [GriRei20, Exercise 2.9.9(d)], applied to $n = k$). The map $\mathbf{v}_k$ is a $\mathbf{k}$-Hopf algebra homomorphism (by [GriRei20, Exercise 2.9.10(e)], applied to $n = k$). Thus, we have shown that all three maps $\mathbf{f}_k$, S and $\mathbf{v}_k$ are $\mathbf{k}$-Hopf algebra homomorphisms. Hence, their composition $\mathbf{f}_k \circ S \circ \mathbf{v}_k$ is a $\mathbf{k}$-Hopf algebra homomorphism as well. In other words, U_k is a $\mathbf{k}$-Hopf algebra homomorphism (since $U_k = \mathbf{f}_k \circ S \circ \mathbf{v}_k$). This proves Theorem 2.29 **(a)**.

(b) Recall (from [GriRei20, Exercise 1.5.9(a)]) the following fact:

> *Claim 1:* If H is a $\mathbf{k}$-bialgebra and A is a commutative $\mathbf{k}$-algebra, then the convolution $f \star g$ of any two $\mathbf{k}$-algebra homomorphisms $f, g : H \to A$ is again a $\mathbf{k}$-algebra homomorphism.

The following fact is dual to Claim 1:

> *Claim 2:* If H is a $\mathbf{k}$-bialgebra and C is a cocommutative $\mathbf{k}$-coalgebra, then the convolution $f \star g$ of any two $\mathbf{k}$-coalgebra homomorphisms $f, g : C \to H$ is again a $\mathbf{k}$-coalgebra homomorphism.

(See [GriRei20, solution to Exercise 1.5.9(h)] for why exactly Claim 2 is dual to Claim 1, and how it can be proved.)

Theorem 2.29 **(a)** yields that the map U_k is a $\mathbf{k}$-Hopf algebra homomorphism. Hence, U_k is both a $\mathbf{k}$-algebra homomorphism and a $\mathbf{k}$-coalgebra homomorphism.

Now, recall that Λ is commutative, and that id_Λ and U_k are two $\mathbf{k}$-algebra homomorphisms from Λ to Λ. Hence, Claim 1 (applied to $H = \Lambda$, $A = \Lambda$, $f = \mathrm{id}_\Lambda$ and $g = U_k$) shows that the convolution $\mathrm{id}_\Lambda \star U_k$ is a $\mathbf{k}$-algebra homomorphism. In other words, V_k is a $\mathbf{k}$-algebra homomorphism (since $V_k = \mathrm{id}_\Lambda \star U_k$).

Next, recall that Λ is cocommutative, and that id_Λ and U_k are two $\mathbf{k}$-coalgebra homomorphisms from Λ to Λ. Hence, Claim 2 (applied to $H = \Lambda$, $C = \Lambda$, $f = \mathrm{id}_\Lambda$

[29]*Proof.* The antipode of a Hopf algebra is an algebra anti-endomorphism (by [GriRei20, Proposition 1.4.8]). Thus, S is an algebra anti-endomorphism (since S is the antipode of the Hopf algebra Λ). But since Λ is commutative, an algebra anti-endomorphism of Λ is the same thing as an algebra endomorphism of Λ. Hence, S is an algebra endomorphism of Λ (since S is an algebra anti-endomorphism of Λ).

The antipode of a Hopf algebra is a coalgebra anti-endomorphism (by [GriRei20, Exercise 1.4.25]). Thus, S is a coalgebra anti-endomorphism (since S is the antipode of the Hopf algebra Λ). But since Λ is cocommutative, a coalgebra anti-endomorphism of Λ is the same thing as a coalgebra endomorphism of Λ. Hence, S is a coalgebra endomorphism of Λ (since S is a coalgebra anti-endomorphism of Λ).

We now know that S is an algebra endomorphism of Λ and a coalgebra endomorphism of Λ at the same time. In other words, S is a bialgebra endomorphism of Λ. Hence, S is a $\mathbf{k}$-Hopf algebra endomorphism of Λ. In other words, S is a $\mathbf{k}$-Hopf algebra homomorphism.

and $g = U_k$) shows that the convolution $\mathrm{id}_\Lambda \star U_k$ is a $\mathbf{k}$-coalgebra homomorphism. In other words, V_k is a $\mathbf{k}$-coalgebra homomorphism (since $V_k = \mathrm{id}_\Lambda \star U_k$).

So we know that the map V_k is both a $\mathbf{k}$-algebra homomorphism and a $\mathbf{k}$-coalgebra homomorphism. Thus, V_k is a $\mathbf{k}$-bialgebra homomorphism, thus a $\mathbf{k}$-Hopf algebra homomorphism. This proves Theorem 2.29 **(b)**.

(c) The map $\mathbf{v}_k$ is a $\mathbf{k}$-algebra homomorphism; thus, $\mathbf{v}_k(1) = 1$. Now, we have

$$\mathbf{v}_k(h_m) = \begin{cases} h_{m/k}, & \text{if } k \mid m; \\ 0, & \text{if } k \nmid m \end{cases} \tag{72}$$

for each $m \in \mathbb{N}$. (Indeed, if $m > 0$, then this follows from the definition of $\mathbf{v}_k$. But if $m = 0$, then this follows from $\mathbf{v}_k(1) = 1$, since $h_0 = 1$.)

We have

$$S(h_n) = (-1)^n e_n \qquad \text{for each } n \in \mathbb{N}. \tag{73}$$

(This follows from [GriRei20, Proposition 2.4.1(iii)].)

Each $i \in \mathbb{N}$ satisfies

$$\begin{aligned} \mathbf{v}_k(h_{ki}) &= \begin{cases} h_{ki/k}, & \text{if } k \mid ki; \\ 0, & \text{if } k \nmid ki \end{cases} \qquad (\text{by (72), applied to } m = ki) \\ &= h_{ki/k} \qquad (\text{since } k \mid ki) \\ &= h_i \qquad (\text{since } ki/k = i) \end{aligned} \tag{74}$$

and

$$\begin{aligned} U_k(h_{ki}) &= (\mathbf{f}_k \circ S \circ \mathbf{v}_k)(h_{ki}) \qquad (\text{since } U_k = \mathbf{f}_k \circ S \circ \mathbf{v}_k) \\ &= \mathbf{f}_k\left(S\left(\underbrace{\mathbf{v}_k(h_{ki})}_{\substack{=h_i \\ (\text{by (74)})}}\right)\right) = \mathbf{f}_k\left(\underbrace{S(h_i)}_{\substack{=(-1)^i e_i \\ (\text{by (73)})}}\right) = \mathbf{f}_k\left((-1)^i e_i\right) \\ &= (-1)^i \mathbf{f}_k(e_i) \end{aligned} \tag{75}$$

(since the map $\mathbf{f}_k$ is $\mathbf{k}$-linear).

On the other hand, if $j \in \mathbb{N}$ satisfies $k \nmid j$, then

$$\begin{aligned} \mathbf{v}_k(h_j) &= \begin{cases} h_{j/k}, & \text{if } k \mid j; \\ 0, & \text{if } k \nmid j \end{cases} \qquad (\text{by (72), applied to } m = j) \\ &= 0 \qquad (\text{since } k \nmid j) \end{aligned} \tag{76}$$

and

$$\begin{aligned}
U_k\left(h_j\right) &= \left(\mathbf{f}_k \circ S \circ \mathbf{v}_k\right)\left(h_j\right) \qquad \left(\text{since } U_k = \mathbf{f}_k \circ S \circ \mathbf{v}_k\right) \\
&= \left(\mathbf{f}_k \circ S\right)\left(\underbrace{\mathbf{v}_k\left(h_j\right)}_{\substack{=0 \\ (\text{by (76)})}}\right) = \left(\mathbf{f}_k \circ S\right)(0) \\
&= 0 \qquad (77)
\end{aligned}$$

(since the map $\mathbf{f}_k \circ S$ is $\mathbf{k}$-linear).

Let Δ_Λ be the comultiplication $\Delta : \Lambda \to \Lambda \otimes \Lambda$ of the $\mathbf{k}$-coalgebra Λ. Let $m_\Lambda : \Lambda \otimes \Lambda \to \Lambda$ be the $\mathbf{k}$-linear map sending each pure tensor $a \otimes b \in \Lambda \otimes \Lambda$ to $ab \in \Lambda$. Definition 2.28 then yields $\mathrm{id}_\Lambda \star U_k = m_\Lambda \circ (\mathrm{id}_\Lambda \otimes U_k) \circ \Delta_\Lambda$. Thus,

$$\begin{aligned}
V_k = \mathrm{id}_\Lambda \star U_k &= m_\Lambda \circ \left(\mathrm{id}_\Lambda \otimes U_k\right) \circ \underbrace{\Delta_\Lambda}_{=\Delta} \\
&= m_\Lambda \circ \left(\mathrm{id}_\Lambda \otimes U_k\right) \circ \Delta. \qquad (78)
\end{aligned}$$

Let $m \in \mathbb{N}$ (not to be mistaken for the map m_Λ). Then, [GriRei20, Proposition 2.3.6(iii)] (applied to $n = m$) yields

$$\begin{aligned}
\Delta\left(h_m\right) &= \sum_{i+j=m} h_i \otimes h_j \\
&\qquad \left(\text{where the sum ranges over all pairs } (i,j) \in \mathbb{N} \times \mathbb{N} \text{ with } i+j=m\right) \\
&= \sum_{j=0}^{m} h_{m-j} \otimes h_j
\end{aligned}$$

(here, we have substituted $(m-j, j)$ for (i,j) in the sum). Applying the map $\mathrm{id}_\Lambda \otimes U_k$ to both sides of this equality, we obtain

$$\left(\mathrm{id}_\Lambda \otimes U_k\right)\left(\Delta\left(h_m\right)\right) = \left(\mathrm{id}_\Lambda \otimes U_k\right)\left(\sum_{j=0}^{m} h_{m-j} \otimes h_j\right) = \sum_{j=0}^{m} h_{m-j} \otimes U_k\left(h_j\right).$$

Applying the map m_Λ to both sides of this equality, we find

$$\begin{aligned}
& m_\Lambda \left(\left(\operatorname{id}_\Lambda \otimes U_k \right) \left(\Delta \left(h_m \right) \right) \right) \\
&= m_\Lambda \left(\sum_{j=0}^{m} h_{m-j} \otimes U_k \left(h_j \right) \right) = \sum_{j=0}^{m} h_{m-j} U_k \left(h_j \right) \qquad \text{(by the definition of } m_\Lambda \text{)} \\
&= \underbrace{\sum_{j=0}^{\infty}}_{= \sum_{j \in \mathbb{N}}} h_{m-j} U_k \left(h_j \right) - \sum_{j=m+1}^{\infty} \underbrace{h_{m-j}}_{\substack{=0 \\ \text{(since } m-j<0 \\ \text{(because } j \geq m+1 > m))}} U_k \left(h_j \right) \\
&= \sum_{j \in \mathbb{N}} h_{m-j} U_k \left(h_j \right) - \underbrace{\sum_{j=m+1}^{\infty} 0 U_k \left(h_j \right)}_{=0} \\
&= \sum_{j \in \mathbb{N}} h_{m-j} U_k \left(h_j \right) = \sum_{\substack{j \in \mathbb{N}; \\ k \mid j}} h_{m-j} U_k \left(h_j \right) + \sum_{\substack{j \in \mathbb{N}; \\ k \nmid j}} h_{m-j} \underbrace{U_k \left(h_j \right)}_{\substack{=0 \\ \text{(by (77))}}} \\
& \qquad \text{(since each } j \in \mathbb{N} \text{ satisfies either } k \mid j \text{ or } k \nmid j \text{ (but not both))} \\
&= \sum_{\substack{j \in \mathbb{N}; \\ k \mid j}} h_{m-j} U_k \left(h_j \right) + \underbrace{\sum_{\substack{j \in \mathbb{N}; \\ k \nmid j}} h_{m-j} 0}_{=0} = \sum_{\substack{j \in \mathbb{N}; \\ k \mid j}} h_{m-j} U_k \left(h_j \right) = \sum_{i \in \mathbb{N}} h_{m-ki} \underbrace{U_k \left(h_{ki} \right)}_{\substack{= (-1)^i \mathbf{f}_k (e_i) \\ \text{(by (75))}}} \\
& \qquad \text{(here, we have substituted } ki \text{ for } j \text{ in the sum)} \\
&= \sum_{i \in \mathbb{N}} (-1)^i h_{m-ki} \cdot \mathbf{f}_k \left(e_i \right) .
\end{aligned}$$

Comparing this with

$$G(k, m) = \sum_{i \in \mathbb{N}} (-1)^i h_{m-ki} \cdot \mathbf{f}_k \left(e_i \right) \qquad \text{(by Theorem 2.21)},$$

we obtain

$$G(k, m) = m_\Lambda \left(\left(\operatorname{id}_\Lambda \otimes U_k \right) \left(\Delta \left(h_m \right) \right) \right) = \underbrace{\left(m_\Lambda \circ \left(\operatorname{id}_\Lambda \otimes U_k \right) \circ \Delta \right)}_{\substack{= V_k \\ \text{(by (78))}}} \left(h_m \right) = V_k \left(h_m \right) .$$

This proves Theorem 2.29 **(c)**.

(d) Let us recall a few facts from [GriRei20].

From [GriRei20, Exercise 2.9.10(a)], we know that every positive integers n and m satisfy

$$\mathbf{v}_n \left(p_m \right) = \begin{cases} n p_{m/n}, & \text{if } n \mid m; \\ 0, & \text{if } n \nmid m \end{cases} . \tag{79}$$

On the other hand, it is easy to see (directly using the definition of $\mathbf{f}_n$) that every positive integers n and m satisfy

$$\mathbf{f}_n(p_m) = p_{nm}. \tag{80}$$

Finally, [GriRei20, Proposition 2.4.1(i)] yields that every positive integer n satisfies

$$S(p_n) = -p_n. \tag{81}$$

Now, let n be a positive integer. We first claim the following:

Claim 1: We have $U_k(p_n) = -[k \mid n] k p_n$.

[*Proof of Claim 1:* We are in one of the following two cases:
Case 1: We have $k \mid n$.
Case 2: We have $k \nmid n$.

Let us first consider Case 1. In this case, we have $k \mid n$. Hence, n/k is a positive integer. Now, (79) (applied to k and n instead of n and m) yields

$$\mathbf{v}_k(p_n) = \begin{cases} kp_{n/k}, & \text{if } k \mid n; \\ 0, & \text{if } k \nmid n \end{cases} = kp_{n/k} \qquad (\text{since } k \mid n).$$

Applying the map S to both sides of this equality, we find

$$S(\mathbf{v}_k(p_n)) = S(kp_{n/k}) = k \underbrace{S(p_{n/k})}_{\substack{=-p_{n/k} \\ \text{(by (81),} \\ \text{applied to } n/k \text{ instead of } n)}} \qquad (\text{since the map } S \text{ is } \mathbf{k}\text{-linear})$$
$$= k(-p_{n/k}) = -kp_{n/k}.$$

Applying the map $\mathbf{f}_k$ to both sides of this equality, we find

$$\mathbf{f}_k(S(\mathbf{v}_k(p_n))) = \mathbf{f}_k(-kp_{n/k}) = -k \underbrace{\mathbf{f}_k(p_{n/k})}_{\substack{=p_{k(n/k)} \\ \text{(by (80),} \\ \text{applied to } k \text{ and } n/k \\ \text{instead of } n \text{ and } m)}} \qquad (\text{since the map } \mathbf{f}_k \text{ is } \mathbf{k}\text{-linear})$$
$$= -kp_{k(n/k)} = -kp_n.$$

Now, the definition of U_k yields $U_k = \mathbf{f}_k \circ S \circ \mathbf{v}_k$. Hence,

$$U_k(p_n) = (\mathbf{f}_k \circ S \circ \mathbf{v}_k)(p_n) = \mathbf{f}_k(S(\mathbf{v}_k(p_n))) = -kp_n.$$

Comparing this with

$$-\underbrace{[k \mid n]}_{\substack{=1 \\ (\text{since } k \mid n)}} kp_n = -kp_n,$$

we obtain $U_k(p_n) = -[k \mid n] \, k p_n$. Hence, Claim 1 is proved in Case 1.

Let us now consider Case 2. In this case, we have $k \nmid n$. But (79) (applied to k and n instead of n and m) yields

$$\mathbf{v}_k(p_n) = \begin{cases} k p_{n/k}, & \text{if } k \mid n; \\ 0, & \text{if } k \nmid n \end{cases} = 0 \qquad (\text{since } k \nmid n).$$

But the definition of U_k yields $U_k = \mathbf{f}_k \circ S \circ \mathbf{v}_k$. Hence,

$$U_k(p_n) = (\mathbf{f}_k \circ S \circ \mathbf{v}_k)(p_n) = (\mathbf{f}_k \circ S)\left(\underbrace{\mathbf{v}_k(p_n)}_{=0}\right) = (\mathbf{f}_k \circ S)(0) = 0$$

(since the map $\mathbf{f}_k \circ S$ is $\mathbf{k}$-linear). Comparing this with

$$-\underbrace{[k \mid n]}_{\substack{=0 \\ (\text{since } k \nmid n)}} k p_n = 0,$$

we obtain $U_k(p_n) = -[k \mid n] \, k p_n$. Hence, Claim 1 is proved in Case 2.

We have now proved Claim 1 in both Cases 1 and 2. Thus, Claim 1 always holds.]

Theorem 2.29 **(a)** shows that the map U_k is a $\mathbf{k}$-Hopf algebra homomorphism. Hence, U_k is a $\mathbf{k}$-algebra homomorphism. Thus, $U_k(1) = 1$.

Now, let Δ_Λ be the comultiplication $\Delta : \Lambda \to \Lambda \otimes \Lambda$ of the $\mathbf{k}$-coalgebra Λ. Let $m_\Lambda : \Lambda \otimes \Lambda \to \Lambda$ be the $\mathbf{k}$-linear map sending each pure tensor $a \otimes b \in \Lambda \otimes \Lambda$ to $ab \in \Lambda$. Then, the definition of V_k yields $V_k = \mathrm{id}_\Lambda \star U_k = m_\Lambda \circ (\mathrm{id}_\Lambda \otimes U_k) \circ \Delta_\Lambda$ (by the definition of convolution).

But [GriRei20, Proposition 2.3.6(i)] yields $\Delta_\Lambda(p_n) = 1 \otimes p_n + p_n \otimes 1$. Now,

$$\begin{aligned}
&\underbrace{V_k}_{=m_\Lambda \circ (\mathrm{id}_\Lambda \otimes U_k) \circ \Delta_\Lambda} (p_n) \\
&= (m_\Lambda \circ (\mathrm{id}_\Lambda \otimes U_k) \circ \Delta_\Lambda)(p_n) \\
&= m_\Lambda \left((\mathrm{id}_\Lambda \otimes U_k) \left(\underbrace{\Delta_\Lambda(p_n)}_{=1 \otimes p_n + p_n \otimes 1} \right) \right) \\
&= m_\Lambda \left(\underbrace{(\mathrm{id}_\Lambda \otimes U_k)(1 \otimes p_n + p_n \otimes 1)}_{=\mathrm{id}_\Lambda(1) \otimes U_k(p_n) + \mathrm{id}_\Lambda(p_n) \otimes U_k(1)} \right) \\
&= m_\Lambda \left(\mathrm{id}_\Lambda(1) \otimes U_k(p_n) + \mathrm{id}_\Lambda(p_n) \otimes U_k(1) \right) \\
&= \underbrace{\mathrm{id}_\Lambda(1)}_{=1} \cdot \underbrace{U_k(p_n)}_{\substack{=-[k \mid n] k p_n \\ (\text{by Claim 1})}} + \underbrace{\mathrm{id}_\Lambda(p_n)}_{=p_n} \cdot \underbrace{U_k(1)}_{=1} \qquad (\text{by the definition of } m_\Lambda) \\
&= -[k \mid n] \, k p_n + p_n = (1 - [k \mid n] \, k) \, p_n.
\end{aligned}$$

This proves Theorem 2.29 **(d)**. □

3.16. Proof of Corollary 2.30

Proof of Corollary 2.30. Recall that the family $(h_n)_{n\geq 1} = (h_1, h_2, h_3, \ldots)$ generates Λ as a $\mathbf{k}$-algebra. Hence, each $g \in \Lambda$ can be written as a polynomial in $h_1, h_2, h_3, \ldots$. Applying this to $g = p_n$, we conclude that p_n can be written as a polynomial in $h_1, h_2, h_3, \ldots$. In other words, there exists a polynomial $f \in \mathbf{k}[x_1, x_2, x_3, \ldots]$ such that

$$p_n = f(h_1, h_2, h_3, \ldots). \tag{82}$$

Consider this f. We shall show that this f satisfies (12). This will clearly prove Corollary 2.30.

Consider the map V_k defined in Theorem 2.29. Theorem 2.29 **(c)** yields that $V_k(h_m) = G(k, m)$ for each positive integer m. In other words,

$$(V_k(h_1), V_k(h_2), V_k(h_3), \ldots) = (G(k,1), G(k,2), G(k,3), \ldots). \tag{83}$$

The map V_k is a $\mathbf{k}$-Hopf algebra homomorphism (by Theorem 2.29 **(b)**), and thus is a $\mathbf{k}$-algebra homomorphism. Hence, it commutes with polynomials over $\mathbf{k}$. Thus,

$$\begin{aligned} V_k(f(h_1, h_2, h_3, \ldots)) &= f(V_k(h_1), V_k(h_2), V_k(h_3), \ldots) \\ &= f(G(k,1), G(k,2), G(k,3), \ldots) \qquad (\text{by (83)}). \end{aligned}$$

Now, applying the map V_k to both sides of the equality (82), we obtain

$$V_k(p_n) = V_k(f(h_1, h_2, h_3, \ldots)) = f(G(k,1), G(k,2), G(k,3), \ldots).$$

Comparing this with

$$V_k(p_n) = (1 - [k \mid n] k) p_n \qquad (\text{by Theorem 2.29 } \mathbf{(d)}),$$

we obtain

$$(1 - [k \mid n] k) p_n = f(G(k,1), G(k,2), G(k,3), \ldots).$$

Thus, we have shown that our f satisfies (12). As we said, this proves Corollary 2.30. $\square$

4. Proof of the Liu–Polo conjecture

Let us recall a well-known partial order on the set of partitions of a given $n \in \mathbb{N}$:

Definition 4.1. Let $n \in \mathbb{N}$. We define a binary relation $\trianglerighteq$ on the set Par_n as follows: Two partitions $\lambda, \mu \in \operatorname{Par}_n$ shall satisfy $\lambda \trianglerighteq \mu$ if and only if we have

$$\lambda_1 + \lambda_2 + \cdots + \lambda_k \geq \mu_1 + \mu_2 + \cdots + \mu_k \qquad \text{for each } k \in \{1, 2, \ldots, n\}.$$

This relation $\trianglerighteq$ is the greater-or-equal relation of a partial order on Par_n, which is known as the *dominance order* (or the *majorization order*).

This definition is precisely [GriRei20, Definition 2.2.7]. Note that if we replace "for each $k \in \{1, 2, \ldots, n\}$" by "for each $k \in \{1, 2, 3, \ldots\}$" in this definition, then the relation $\triangleright$ does not change.

Our goal in this section is to prove the conjecture made in [LiuPol19, Remark 1.4.5]. We state this conjecture as follows:[30]

Theorem 4.2. Let n be an integer such that $n > 1$. Then,

$$\sum_{\substack{\lambda \in \operatorname{Par}_{2n-1};\\ (n-1,n-1,1) \triangleright \lambda}} m_\lambda = \sum_{i=0}^{n-2} (-1)^i s_{\left(n-1,n-1-i,1^{i+1}\right)}.$$

Example 4.3. For this example, let $n = 3$. Then, $n - 1 = 2$ and $2n - 1 = 5$. Hence, the left hand side of the equality in Theorem 4.2 is

$$\sum_{\substack{\lambda \in \operatorname{Par}_{2n-1};\\ (n-1,n-1,1) \triangleright \lambda}} m_\lambda = \sum_{\substack{\lambda \in \operatorname{Par}_{5};\\ (2,2,1) \triangleright \lambda}} m_\lambda = m_{(2,2,1)} + m_{(2,1,1,1)} + m_{(1,1,1,1,1)}.$$

Meanwhile, the right hand side of the equality in Theorem 4.2 is

$$\sum_{i=0}^{n-2} (-1)^i s_{\left(n-1,n-1-i,1^{i+1}\right)} = \sum_{i=0}^{1} (-1)^i s_{\left(2,2-i,1^{i+1}\right)} = s_{(2,2,1)} - s_{(2,1,1,1)}.$$

Thus, Theorem 4.2 claims that $m_{(2,2,1)} + m_{(2,1,1,1)} + m_{(1,1,1,1,1)} = s_{(2,2,1)} - s_{(2,1,1,1)}$ in this case.

We will pave our way to the proof of Theorem 4.2 by several lemmas. We begin with a particularly simple one:

Lemma 4.4. Let n be an integer such that $n > 1$. Let $\lambda \in \operatorname{Par}_{2n-1}$. Then, $(n-1, n-1, 1) \triangleright \lambda$ if and only if all positive integers i satisfy $\lambda_i < n$.

Proof. This simple proof (an exercise in following Definition 4.1) is left to the reader. $\square$

The next lemma identifies the left hand side of Theorem 4.2 as the Petrie symmetric function $G(n, 2n-1)$:

Corollary 4.5. Let n be an integer such that $n > 1$. Then,

$$\sum_{\substack{\lambda \in \operatorname{Par}_{2n-1};\\ (n-1,n-1,1) \triangleright \lambda}} m_\lambda = G(n, 2n-1).$$

[30] Note that $(n-1, n-1, 1)$ is a partition whenever $n > 1$ is an integer.

Proof. Proposition 2.3 **(c)** (applied to $k = n$ and $m = 2n - 1$) yields

$$G(n, 2n-1) = \sum_{\substack{\alpha \in \mathrm{WC};\\ |\alpha| = 2n-1;\\ \alpha_i < n \text{ for all } i}} \mathbf{x}^\alpha = \sum_{\substack{\lambda \in \mathrm{Par};\\ |\lambda| = 2n-1;\\ \lambda_i < n \text{ for all } i}} m_\lambda. \tag{84}$$

But Lemma 4.4 yields the following equality of summation signs:

$$\sum_{\substack{\lambda \in \mathrm{Par}_{2n-1};\\ (n-1, n-1, 1) \rhd \lambda}} = \sum_{\substack{\lambda \in \mathrm{Par}_{2n-1};\\ \lambda_i < n \text{ for all } i}} = \sum_{\substack{\lambda \in \mathrm{Par};\\ |\lambda| = 2n-1;\\ \lambda_i < n \text{ for all } i}} .$$

Hence,

$$\sum_{\substack{\lambda \in \mathrm{Par}_{2n-1};\\ (n-1, n-1, 1) \rhd \lambda}} m_\lambda = \sum_{\substack{\lambda \in \mathrm{Par};\\ |\lambda| = 2n-1;\\ \lambda_i < n \text{ for all } i}} m_\lambda.$$

Comparing this with (84), we obtain

$$\sum_{\substack{\lambda \in \mathrm{Par}_{2n-1};\\ (n-1, n-1, 1) \rhd \lambda}} m_\lambda = G(n, 2n-1).$$

This proves Corollary 4.5. □

It was Corollary 4.5 that led the author to introduce and study the Petrie symmetric functions $G(k, m)$ in general, even if little of their general properties has proven relevant to Theorem 4.2.

The next proposition gives a simple formula for certain kinds of Petrie symmetric functions:

Proposition 4.6. Let n be a positive integer. Let $k \in \{0, 1, \ldots, n-1\}$. Then,

$$G(n, n+k) = h_{n+k} - h_k p_n.$$

Proposition 4.6 can be viewed as a particular case of Theorem 2.21 (applied to n and $n+k$ instead of k and m), after realizing that in the sum on the right hand side of Theorem 2.21, only the first two addends will (potentially) be nonzero in this case. However, let us give an independent proof of the proposition.

Proof of Proposition 4.6. From $k \in \{0, 1, \ldots, n-1\}$, we obtain $k < n$ and thus $n + k < n + n$. Thus we conclude:

> *Observation 1:* A monomial of degree $n+k$ cannot have more than one variable appear in it with exponent $\geq n$ (since this would require it to have degree $\geq n + n > n + k$).

Let $\mathfrak{M}_k$ be the set of all monomials of degree k. The definition of h_k shows that h_k is the sum of all monomials of degree k. In other words,

$$h_k = \sum_{\mathfrak{m} \in \mathfrak{M}_k} \mathfrak{m}. \tag{85}$$

Let $\mathfrak{M}_{n+k}$ be the set of all monomials of degree $n+k$. The definition of h_{n+k} shows that h_{n+k} is the sum of all monomials of degree $n+k$. In other words,

$$h_{n+k} = \sum_{\mathfrak{n} \in \mathfrak{M}_{n+k}} \mathfrak{n}. \tag{86}$$

Let $\mathfrak{N}$ be the set of all monomials of degree $n+k$ in which all exponents are $< n$. These monomials are exactly the $\mathbf{x}^\alpha$ for $\alpha \in \mathrm{WC}$ satisfying $|\alpha| = n+k$ and ($\alpha_i < n$ for all i). Hence,

$$\sum_{\mathfrak{n} \in \mathfrak{N}} \mathfrak{n} = \sum_{\substack{\alpha \in \mathrm{WC}; \\ |\alpha| = n+k; \\ \alpha_i < n \text{ for all } i}} \mathbf{x}^\alpha. \tag{87}$$

But Proposition 2.3 **(c)** (applied to n and $n+k$ instead of k and m) yields

$$G(n, n+k) = \sum_{\substack{\alpha \in \mathrm{WC}; \\ |\alpha| = n+k; \\ \alpha_i < n \text{ for all } i}} \mathbf{x}^\alpha = \sum_{\substack{\lambda \in \mathrm{Par}; \\ |\lambda| = n+k; \\ \lambda_i < n \text{ for all } i}} m_\lambda.$$

Hence,

$$G(n, n+k) = \sum_{\substack{\alpha \in \mathrm{WC}; \\ |\alpha| = n+k; \\ \alpha_i < n \text{ for all } i}} \mathbf{x}^\alpha = \sum_{\mathfrak{n} \in \mathfrak{N}} \mathfrak{n} \tag{88}$$

(by (87)).

Clearly, the set $\mathfrak{N}$ is a subset of $\mathfrak{M}_{n+k}$, and furthermore its complement $\mathfrak{M}_{n+k} \setminus \mathfrak{N}$ is the set of all monomials of degree $n+k$ in which at least one exponent is $\geq n$. Hence, the map

$$\begin{aligned} \mathfrak{M}_k \times \{1, 2, 3, \ldots\} &\to \mathfrak{M}_{n+k} \setminus \mathfrak{N}, \\ (\mathfrak{m}, i) &\mapsto \mathfrak{m} \cdot x_i^n \end{aligned}$$

is well-defined (because if $\mathfrak{m}$ is a monomial of degree k, and if $i \in \{1, 2, 3, \ldots\}$, then $\mathfrak{m} \cdot x_i^n$ is a monomial of degree $k+n = n+k$, and the variable x_i appears in it with exponent $\geq n$). This map is furthermore surjective (for simple reasons) and injective (in fact, if $\mathfrak{n} \in \mathfrak{M}_{n+k} \setminus \mathfrak{N}$, then $\mathfrak{n}$ is a monomial of degree $n+k$, and thus Observation 1 yields that there is **at most** one variable x_i that appears in $\mathfrak{n}$ with exponent $\geq n$; but this means that the only preimage of $\mathfrak{n}$ under our map is $\left(\dfrac{\mathfrak{n}}{x_i^n}, i\right)$). Hence, this map is a bijection. We can thus use it to substitute $\mathfrak{m} \cdot x_i^n$ for

$\mathfrak{n}$ in the sum $\sum\limits_{\mathfrak{n}\in\mathfrak{M}_{n+k}\setminus\mathfrak{N}} \mathfrak{n}$. We thus obtain

$$\begin{aligned}\sum_{\mathfrak{n}\in\mathfrak{M}_{n+k}\setminus\mathfrak{N}} \mathfrak{n} &= \sum_{(\mathfrak{m},i)\in\mathfrak{M}_k\times\{1,2,3,\ldots\}} \mathfrak{m}\cdot x_i^n = \underbrace{\left(\sum_{\mathfrak{m}\in\mathfrak{M}_k}\mathfrak{m}\right)}_{\substack{=h_k\\ \text{(by (85))}}} \cdot \underbrace{\sum_{i\in\{1,2,3,\ldots\}} x_i^n}_{=p_n} \\ &= h_k p_n. \end{aligned} \tag{89}$$

But (86) becomes

$$\begin{aligned} h_{n+k} &= \sum_{\mathfrak{n}\in\mathfrak{M}_{n+k}} \mathfrak{n} = \underbrace{\sum_{\mathfrak{n}\in\mathfrak{N}} \mathfrak{n}}_{\substack{=G(n,n+k)\\ \text{(by (88))}}} + \underbrace{\sum_{\mathfrak{n}\in\mathfrak{M}_{n+k}\setminus\mathfrak{N}} \mathfrak{n}}_{\substack{=h_kp_n\\ \text{(by (89))}}} \qquad \left(\text{since } \mathfrak{N}\subseteq\mathfrak{M}_{n+k}\right) \\ &= G(n,n+k) + h_k p_n. \end{aligned}$$

In other words,

$$G(n,n+k) = h_{n+k} - h_k p_n.$$

This proves Proposition 4.6. □

Corollary 4.7. Let n be an integer such that $n > 1$. Then,

$$\sum_{\substack{\lambda\in\operatorname{Par}_{2n-1};\\ (n-1,n-1,1)\triangleright\lambda}} m_\lambda = h_{2n-1} - h_{n-1}p_n.$$

Proof. Corollary 4.5 yields

$$\begin{aligned} \sum_{\substack{\lambda\in\operatorname{Par}_{2n-1};\\ (n-1,n-1,1)\triangleright\lambda}} m_\lambda &= G(n,2n-1) = G(n,n+(n-1)) \qquad (\text{since } 2n-1 = n+(n-1)) \\ &= h_{n+(n-1)} - h_{n-1}p_n \qquad (\text{by Proposition 4.6, applied to } k=n-1) \\ &= h_{2n-1} - h_{n-1}p_n. \end{aligned}$$

□

Our next claim is an easy consequence of Proposition 1.1:

Corollary 4.8. Let n be a positive integer. Then,

$$h_n - p_n = \sum_{i=0}^{n-2} (-1)^i s_{\left(n-1-i,1^{i+1}\right)}.$$

Proof. Proposition 1.1 yields

$$p_n = \sum_{i=0}^{n-1} (-1)^i s_{\left(n-i,1^i\right)} = \underbrace{(-1)^0}_{=1} \underbrace{s_{(n-0,1^0)}}_{=s_{(n-0)}=s_{(n)}=h_n} + \sum_{i=1}^{n-1} (-1)^i s_{\left(n-i,1^i\right)}$$
$$= h_n + \sum_{i=1}^{n-1} (-1)^i s_{\left(n-i,1^i\right)},$$

so that

$$h_n - p_n = -\sum_{i=1}^{n-1} (-1)^i s_{\left(n-i,1^i\right)} = \sum_{i=1}^{n-1} \underbrace{\left(-(-1)^i\right)}_{=(-1)^{i-1}} s_{\left(n-i,1^i\right)} = \sum_{i=1}^{n-1} (-1)^{i-1} s_{\left(n-i,1^i\right)}$$
$$= \sum_{i=0}^{n-2} (-1)^i s_{\left(n-1-i,1^{i+1}\right)}$$

(here, we have substituted $i+1$ for i in the sum). □

We shall use the *skewing operators* $f^\perp : \Lambda \to \Lambda$ for all $f \in \Lambda$ as defined in [GriRei20, §2.8] or in [Macdon95, Chapter I, Section 5, Example 3]. The easiest way to define them (following [Macdon95, Chapter I, Section 5, Example 3]) is as follows: For each $f \in \Lambda$, we let $f^\perp : \Lambda \to \Lambda$ be the $\mathbf{k}$-linear map adjoint to the map $L_f : \Lambda \to \Lambda,\ g \mapsto fg$ (that is, to the map that multiplies every element of Λ by f) with respect to the Hall inner product. That is, $f^\perp$ is the $\mathbf{k}$-linear map from Λ to Λ that satisfies

$$\left(g, f^\perp(a)\right) = (fg, a) \qquad \text{for all } a \in \Lambda \text{ and } g \in \Lambda.$$

It is not hard to show that such an operator $f^\perp$ exists[31]. The definition of $f^\perp$ in [GriRei20, §2.8] is different but equivalent (because of [GriRei20, Proposition 2.8.2(i)]). One of the most important properties of skewing operators is the following fact ([GriRei20, (2.8.2)]):

Lemma 4.9. Let λ and μ be any two partitions. Then,

$$s_\mu^\perp(s_\lambda) = s_{\lambda/\mu}. \tag{90}$$

(Here, $s_{\lambda/\mu}$ is a skew Schur function, defined in Subsection 3.3.)

[31] This is not completely automatic: Not every $\mathbf{k}$-linear map from Λ to Λ has an adjoint with respect to the Hall inner product! (For example, the $\mathbf{k}$-linear map $\Lambda \to \Lambda$ that sends each Schur function s_λ to 1 has none.) The reason why the map $L_f : \Lambda \to \Lambda,\ g \mapsto fg$ has an adjoint is that when f is homogeneous of degree k, this map L_f sends each graded component Λ_m of Λ to Λ_{m+k}, and both of these graded components Λ_m and Λ_{m+k} are $\mathbf{k}$-modules with **finite** bases. (The case when f is not homogeneous can be reduced to the case when f is homogeneous, since each $f \in \Lambda$ is a sum of finitely many homogeneous elements.)

Using skewing operators, we can define another helpful family of operators on Λ:

Definition 4.10. For any $m \in \mathbb{Z}$, we define a map $\mathbf{B}_m : \Lambda \to \Lambda$ by setting

$$\mathbf{B}_m (f) = \sum_{i \in \mathbb{N}} (-1)^i h_{m+i} e_i^{\perp} f \qquad \text{for all } f \in \Lambda.$$

It is known ([GriRei20, Exercise 2.9.1(a)]) that this map $\mathbf{B}_m$ is well-defined and $\mathbf{k}$-linear.

(Actually, the well-definedness of $\mathbf{B}_m$ is easy to check: If $f \in \Lambda$ has degree d, then all integers $i > d$ satisfy $e_i^{\perp} f = 0$ for degree reasons, and thus the sum $\sum\limits_{i \in \mathbb{N}} (-1)^i h_{m+i} e_i^{\perp} f$ has only finitely many nonzero addends. The $\mathbf{k}$-linearity of $\mathbf{B}_m$ is even clearer.)

The operators $\mathbf{B}_m$ for $m \in \mathbb{Z}$ have first appeared in Zelevinsky's [Zelevi81, §4.20] (in the different-looking but secretly equivalent setting of a PSH-algebra), where they are credited to J. N. Bernstein. They have since been dubbed the *Bernstein creation operators* and proved useful in various contexts (e.g., the definition of the "dual immaculate functions" in [BBSSZ13] takes them for inspiration). One of their most fundamental properties is the following fact (which originates in [Zelevi81, 4.20, $(**)$] and appears implicitly in [Macdon95, Chapter I, Section 5, Example 29]):

Proposition 4.11. Let λ be any partition. Let $m \in \mathbb{Z}$ satisfy $m \geq \lambda_1$. Then,

$$\sum_{i \in \mathbb{N}} (-1)^i h_{m+i} e_i^{\perp} s_\lambda = s_{(m, \lambda_1, \lambda_2, \lambda_3, \ldots)}. \tag{91}$$

See [GriRei20, Exercise 2.9.1(b)] for a proof of Proposition 4.11. Thus, if λ is any partition, and if $m \in \mathbb{Z}$ satisfies $m \geq \lambda_1$, then

$$\begin{aligned} \mathbf{B}_m (s_\lambda) &= \sum_{i \in \mathbb{N}} (-1)^i h_{m+i} e_i^{\perp} s_\lambda \qquad (\text{by the definition of } \mathbf{B}_m) \\ &= s_{(m, \lambda_1, \lambda_2, \lambda_3, \ldots)} \qquad (\text{by (91)}) . \end{aligned} \tag{92}$$

Lemma 4.12. Let n be a positive integer. Let $m \in \mathbb{N}$. Then, $\mathbf{B}_m (h_n) = h_m h_n - h_{m+1} h_{n-1}$.

Proof of Lemma 4.12. We have $e_0 = 1$ and thus $e_0^{\perp} = 1^{\perp} = \mathrm{id}$. Hence, $e_0^{\perp} (h_n) = h_n$.

We shall use the notion of skew Schur functions $s_{\lambda / \mu}$ (as in Subsection 3.3). Recall that $s_{\lambda / \mu} = 0$ when $\mu \not\subseteq \lambda$.

From $e_1 = s_{(1)}$ and $h_n = s_{(n)}$, we obtain

$$e_1^{\perp} (h_n) = s_{(1)}^{\perp} \left(s_{(n)} \right) = s_{(n)/(1)} \qquad (\text{by (90)}) .$$

But it is easy to see that $s_{(n)/(1)} = s_{(n-1)}$. (Indeed, this follows from the combinatorial definition of skew Schur functions, since the skew Ferrers diagram of $(n)/(1)$ can be obtained from the Ferrers diagram of $(n-1)$ by parallel shift[32]. Alternatively, this follows easily from Theorem 3.4, because $s_{(n-1)} = h_{n-1}$.)

Thus, we obtain

$$e_1^{\perp}(h_n) = s_{(n)/(1)} = s_{(n-1)} = h_{n-1}.$$

For each integer $i > 1$, we have

$$\begin{aligned} e_i^{\perp}(h_n) &= s_{(1^i)}^{\perp}\left(s_{(n)}\right) && \left(\text{since } e_i = s_{(1^i)} \text{ and } h_n = s_{(n)}\right) \\ &= s_{(n)/(1^i)} && (\text{by (90)}) \\ &= 0 && \left(\text{since } \left(1^i\right) \not\subseteq (n) \ (\text{because } i > 1)\right). \end{aligned} \tag{93}$$

Now, the definition of $\mathbf{B}_m$ yields

$$\begin{aligned} \mathbf{B}_m(h_n) &= \sum_{i\in\mathbb{N}} (-1)^i h_{m+i} e_i^{\perp}(h_n) \\ &= \underbrace{(-1)^0}_{=1} \underbrace{h_{m+0}}_{=h_m} \underbrace{e_0^{\perp}(h_n)}_{=h_n} + \underbrace{(-1)^1}_{=-1} h_{m+1} \underbrace{e_1^{\perp}(h_n)}_{=h_{n-1}} + \sum_{i\geq 2} (-1)^i h_{m+i} \underbrace{e_i^{\perp}(h_n)}_{\substack{=0 \\ (\text{by (93)})}} \\ &= h_m h_n - h_{m+1} h_{n-1}. \end{aligned}$$

□

Corollary 4.13. Let n be a positive integer. Then, $\mathbf{B}_{n-1}(h_n) = 0$.

Proof. Apply Lemma 4.12 to $m = n-1$ and simplify. □

Lemma 4.14. Let $m \in \mathbb{N}$. Let n be a positive integer. Then, $\mathbf{B}_m(p_n) = h_m p_n - h_{m+n}$.

Proof. This is [GriRei20, Exercise 2.9.1(f)]. But here is a more direct proof: We will use the comultiplication $\Delta : \Lambda \to \Lambda \otimes \Lambda$ of the Hopf algebra Λ (see [GriRei20, §2.3]). Here and in the following, the "$\otimes$" sign denotes $\otimes_{\mathbf{k}}$. The power-sum symmetric function p_n is primitive[33] (see [GriRei20, Proposition 2.3.6(i)]); thus,

$$\Delta(p_n) = 1 \otimes p_n + p_n \otimes 1.$$

Hence, for each $i \in \mathbb{N}$, the definition of $e_i^{\perp}$ given in [GriRei20, Definition 2.8.1] (not the equivalent definition we gave above) yields

$$e_i^{\perp}(p_n) = (e_i, 1)\, p_n + (e_i, p_n)\, 1. \tag{94}$$

[32] See [GriRei20, §2.3] for the notions we are using here.

[33] Recall that an element x of a Hopf algebra H is said to be *primitive* if the comultiplication Δ_H of H satisfies $\Delta_H(x) = 1 \otimes x + x \otimes 1$.

Now, the definition of $\mathbf{B}_m$ yields

$$\begin{aligned}
\mathbf{B}_m(p_n) &= \sum_{i\in\mathbb{N}} (-1)^i h_{m+i} \underbrace{e_i^{\perp}(p_n)}_{\substack{=(e_i,1)p_n+(e_i,p_n)1 \\ \text{(by (94))}}} \\
&= \sum_{i\in\mathbb{N}} (-1)^i h_{m+i}\left((e_i,1)\,p_n + (e_i,p_n)\,1\right) \\
&= \underbrace{\sum_{i\in\mathbb{N}} (-1)^i h_{m+i}\cdot(e_i,1)\,p_n}_{\substack{=(-1)^0 h_{m+0}\cdot(e_0,1)p_n \\ \text{(because the Hall inner product } (e_i,1) \\ \text{equals 0 whenever } i\neq 0 \text{ (by (2)),} \\ \text{and thus the only nonzero addend of this} \\ \text{sum is the addend for } i=0)}} + \underbrace{\sum_{i\in\mathbb{N}} (-1)^i h_{m+i}\cdot(e_i,p_n)\,1}_{\substack{=(-1)^n h_{m+n}\cdot(e_n,p_n)1 \\ \text{(because the Hall inner product } (e_i,p_n) \\ \text{equals 0 whenever } i\neq n \text{ (by (2)),} \\ \text{and thus the only nonzero addend of this} \\ \text{sum is the addend for } i=n)}} \\
&= \underbrace{(-1)^0}_{=1}\underbrace{h_{m+0}}_{=h_m}\cdot\underbrace{(e_0,1)}_{=(1,1)=1} p_n + (-1)^n h_{m+n}\cdot \underbrace{(e_n,p_n)}_{\substack{=(-1)^{n-1} \\ \text{(by Proposition 1.3)}}} 1 \\
&= h_m p_n + \underbrace{(-1)^n h_{m+n}\cdot(-1)^{n-1}\,1}_{=-h_{m+n}} = h_m p_n - h_{m+n}.
\end{aligned}$$

□

Lemma 4.15. Let n be a positive integer. Then,

$$\mathbf{B}_{n-1}(h_n - p_n) = h_{2n-1} - h_{n-1}p_n.$$

Proof. The map $\mathbf{B}_{n-1}$ is $\mathbf{k}$-linear. Thus,

$$\begin{aligned}
\mathbf{B}_{n-1}(h_n - p_n) &= \underbrace{\mathbf{B}_{n-1}(h_n)}_{\substack{=0 \\ \text{(by Corollary 4.13)}}} - \underbrace{\mathbf{B}_{n-1}(p_n)}_{\substack{=h_{n-1}p_n-h_{(n-1)+n} \\ \text{(by Lemma 4.14,} \\ \text{applied to } m=n-1)}} \\
&= -\left(h_{n-1}p_n - h_{(n-1)+n}\right) = \underbrace{h_{(n-1)+n}}_{=h_{2n-1}} - h_{n-1}p_n = h_{2n-1} - h_{n-1}p_n.
\end{aligned}$$

□

Lemma 4.16. Let n be a positive integer. Then,

$$\mathbf{B}_{n-1}(h_n - p_n) = \sum_{i=0}^{n-2} (-1)^i s_{\left(n-1,n-1-i,1^{i+1}\right)}.$$

Proof of Lemma 4.16. We have

$$\begin{aligned}
\mathbf{B}_{n-1}\left(h_n - p_n\right) &= \mathbf{B}_{n-1}\left(\sum_{i=0}^{n-2} (-1)^i s_{\left(n-1-i,1^{i+1}\right)}\right) && \text{(by Corollary 4.8)} \\
&= \sum_{i=0}^{n-2} (-1)^i \underbrace{\mathbf{B}_{n-1}\left(s_{\left(n-1-i,1^{i+1}\right)}\right)}_{\substack{=s_{\left(n-1,n-1-i,1^{i+1}\right)} \\ \text{(by (92), applied to } m=n-1 \\ \text{and } \lambda=\left(n-1-i,1^{i+1}\right) \\ \text{(since } n-i\geq n-1-i\text{))}}} && \text{(since } \mathbf{B}_{n-1} \text{ is } \mathbf{k}\text{-linear)} \\
&= \sum_{i=0}^{n-2} (-1)^i s_{\left(n-1,n-1-i,1^{i+1}\right)}.
\end{aligned}$$

$\square$

Now the proof of Theorem 4.2 is a trivial concatenation of equalities:

Proof of Theorem 4.2. Corollary 4.7 yields

$$\begin{aligned}
\sum_{\substack{\lambda\in\operatorname{Par}_{2n-1}; \\ (n-1,n-1,1)\rhd\lambda}} m_\lambda = h_{2n-1} - h_{n-1}p_n &= \mathbf{B}_{n-1}\left(h_n - p_n\right) && \text{(by Lemma 4.15)} \\
&= \sum_{i=0}^{n-2} (-1)^i s_{\left(n-1,n-1-i,1^{i+1}\right)} && \text{(by Lemma 4.16)}.
\end{aligned}$$

$\square$

5. Final remarks

5.1. SageMath code

The SageMath computer algebra system [SageMath] does not (yet) natively know the Petrie symmetric functions $G(k,m)$; but they can be easily constructed in it. For example, the code that follows computes $G(k,n)$ expanded in the Schur basis:

```
Sym = SymmetricFunctions(QQ) # Replace QQ by your favorite base ring.
m = Sym.m() # monomial symmetric functions
s = Sym.s() # Schur functions

def G(k, n): # a Petrie function
  return s(m.sum(m[lam] for lam in Partitions(n, max_part=k-1)))
```

5.2. Understanding the Petrie numbers

Combining Corollary 2.10 with Theorem 2.15 yields an explicit expression of all coefficients in the expansion of a Petrie symmetric function $G(k,m)$ in the Schur basis. It would stand to reason if the identity in Theorem 4.2 (whose left hand side is $G(n,2n-1)$) could be obtained from this expression. Surprisingly, we have been unable to do so, which suggests that the description of $\operatorname{pet}_k(\lambda,\varnothing)$ in Theorem 2.15 might not be optimal.

As to $\operatorname{pet}_k(\lambda,\mu)$, we do not have an explicit description at all, unless we count the recursive one that can be extracted from the proof in [GorWil74].

5.3. MNable symmetric functions

Combining Theorem 2.17 with Proposition 2.8, we conclude that for any $k>0$ and $m\in\mathbb{N}$, the symmetric function $G(k,m)\in\Lambda$ has the following property: For any $\mu\in\operatorname{Par}$, its product $G(k,m)\cdot s_\mu$ with s_μ can be written in the form $\sum\limits_{\lambda\in\operatorname{Par}} u_\lambda s_\lambda$ with $u_\lambda\in\{-1,0,1\}$ for all $\lambda\in\operatorname{Par}$. It has this property in common with the symmetric functions h_m and e_m (according to the Pieri rules) and p_m (according to the Murnaghan–Nakayama rule) as well as several others. The study of symmetric functions having this property – which we call *MNable symmetric functions* (in honor of Murnaghan and Nakayama) – has been initiated in [Grinbe20a, §8], but there is much to be done.

5.4. A conjecture of Per Alexandersson

In February 2020, Per Alexandersson suggested the following conjecture:

Conjecture 5.1. Let k be a positive integer, and $n\in\mathbb{N}$. Then, $G(k,m)\cdot p_2\in\Lambda$ can be written in the form $\sum\limits_{\lambda\in\operatorname{Par}} u_\lambda s_\lambda$ with $u_\lambda\in\{-1,0,1\}$ for all $\lambda\in\operatorname{Par}$.

For example,

$$G(3,4)\cdot p_2 = s_{(1,1,1,1,1,1)} + s_{(2,2,2)} - s_{(3,1,1,1)} - s_{(3,3)} + s_{(4,2)}.$$

Conjecture 5.1 has been verified for all k and n satisfying $k+n\leq 30$.

Note that Conjecture 5.1 becomes false if p_2 is replaced by p_3. For example,

$$G(3,4)\cdot p_3 = -s_{(1,1,1,1,1,1,1,1)} + s_{(2,2,1,1,1)} - 2s_{(2,2,2,1)} + s_{(3,2,1,1)} - s_{(4,1,1,1)} - s_{(4,3)} + s_{(5,2)}.$$

5.5. A conjecture of François Bergeron

An even more mysterious conjecture was suggested by François Bergeron in April 2020:

Conjecture 5.2. Let k and n be positive integers, and $m \in \mathbb{N}$. Let ∇ be the *nabla operator* as defined (e.g.) in [Berger19, §3.2.1]. Then, there exists a sign $\sigma_{n,k,m} \in \{1, -1\}$ such that $\sigma_{n,k,m} \nabla^n (G(k,m))$ is an $\mathbb{N}[q,t]$-linear combination of Schur functions.

Using SageMath, this conjecture has been checked for $n = 1$ and all $k, m \in \{0, 1, \ldots, 9\}$; the signs $\sigma_{1,k,m}$ are given by the following table:

	1	2	3	4	5	6	7	8	9
2	+	+	+	+	+	+	+	+	+
3	+	−	−	−	+	+	+	−	−
4	+	−	+	+	+	−	+	+	+
5	+	−	+	−	−	−	+	−	+
6	+	−	+	−	+	+	+	−	+
7	+	−	+	−	+	−	−	−	+
8	+	−	+	−	+	−	+	+	+
9	+	−	+	−	+	−	+	−	−

(where the entry in the row indexed k and the column indexed m is the sign $\sigma_{1,k,m}$, represented by a "+" sign if it is 1 and by a "−" sign if it is -1). I am not aware of a pattern in these signs, apart from the fact that $\sigma_{1,2,m} = 1$ for all $m \in \mathbb{N}$ (a consequence of Haiman's famous interpretation of $\nabla(e_m)$ as a character), and that $\sigma_{1,k,m}$ appears to be $(-1)^{m-1}$ whenever $1 \leq m < k$ (which would follow from the conjecture that $(-1)^{m-1} \nabla(h_m)$ is an $\mathbb{N}[q,t]$-linear combination of Schur functions for any $m \geq 1$).

5.6. "Petriefication" of Schur functions

Theorem 2.29 shows the existence of a Hopf algebra homomorphism $V_k : \Lambda \to \Lambda$ that sends the complete homogeneous symmetric functions $h_1, h_2, h_3, \ldots$ to the Petrie symmetric functions $G(k,1), G(k,2), G(k,3), \ldots$. It thus is natural to consider the images of all Schur functions s_λ under this homomorphism V_k. Experiments with small λ's may suggest that these images $V_k(s_\lambda)$ all can be written in the form $\sum\limits_{\lambda \in \mathrm{Par}} u_\lambda s_\lambda$ with $u_\lambda \in \{-1, 0, 1\}$. But this is not generally the case; counterexamples include $V_3\left(s_{(4,4,4)}\right)$, $V_4\left(s_{(4,4)}\right)$ and $V_4\left(s_{(5,1,1,1,1)}\right)$. (Of course, it is true when λ is a single row, because of $V_k\left(s_{(m)}\right) = V_k(h_m) = G(k,m)$; and it is also true when λ is a single column, because the Hopf algebra homomorphism V_k commutes with the antipode S that sends $h_m \mapsto (-1)^m e_m$ and $s_\lambda \mapsto (-1)^{|\lambda|} s_{\lambda^t}$.)

Note that these images $V_k(s_\lambda)$ are precisely the *modular Schur functions s'_λ* studied in [Walker94].

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