HOOK FORMULAS FOR SKEW SHAPES II. COMBINATORIAL PROOFS AND ENUMERATIVE APPLICATIONS

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Abstract. The Naruse hook-length formula is a recent general formula for the number of standard Young tableaux of skew shapes, given as a positive sum over excited diagrams of products of hook-lengths. In [MPP1] we gave two different $q$-analogues of Naruse’s formula: for the skew Schur functions, and for counting reverse plane partitions of skew shapes. In this paper we give an elementary proof of Naruse’s formula based on the case of border strips. For special border strips, we obtain curious new formulas for the Euler and $q$-Euler numbers in terms of certain Dyck path summations.

1. Introduction

In Enumerative Combinatorics, when it comes to fundamental results, one proof is rarely enough, and one is often on the prowl for a better, more elegant or more direct proof. In fact, there is a wide belief in multitude of “proofs from the Book”, rather than a singular best approach. The reasons are both cultural and mathematical: different proofs elucidate different aspects of the underlying combinatorial objects and lead to different extensions and generalizations.

The story of this series of papers is on our effort to understand and generalize the Naruse hook-length formula (NHLF) for the number of standard Young tableaux of a skew shape in terms of excited diagrams. In our previous paper [MPP1], we gave two $q$-analogues of the NHLF, the first with an algebraic proof and the second with a bijective proof. We also gave a (difficult) “mixed” proof of the first $q$-analogue, which combined the bijection with an algebraic argument. Naturally, these provided new proofs of the NHLF, but none which one would call “elementary”.

This paper is the second in the series. Here we consider a special case of border strips which turn out to be extremely fruitful both as a technical tool and as an important object of study. We give two elementary proofs of the NHLF in this case, both inductive: one using weighted paths argument and another using determinant calculation. We then deduce the general case of NHLF for all skew diagrams by using the Lascoux–Pragacz identity for Schur functions. Since the latter has its own elementary proof [HaG] (see also [CYY]), we obtain an elementary proof of the HLF.

But surprises do not stop here. For the special cases of the zigzag strips, our approach gives a number of curious new formulas for the Euler and two types of $q$-Euler numbers, the second of which seems to be new. Because the excited diagrams correspond to Dyck paths in this case, the resulting summations have Catalan number of terms. Despite their strong “classical feel”, all these formulas are new and quite mysterious.

1.1. Hook formulas for straight and skew shapes. Let us recall the main result from the first paper [MPP1] in this series. We assume here the reader is familiar with the basic definitions, which are postponed until the next two sections.

Key words and phrases. Hook-length formula, excited tableau, standard Young tableau, flagged tableau, reverse plane partition, alternating permutation, Dyck path, Euler numbers, Catalan numbers, factorial Schur function.

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The standard Young tableaux (SYT) of straight and skew shapes are central objects in enumerative and algebraic combinatorics. The number \( f_\lambda = |\text{SYT}(\lambda)| \) of standard Young tableaux of shape \( \lambda \) has the celebrated hook-length formula (HLF):

**Theorem 1.1** (HLF; Frame–Robinson–Thrall [FRT]). Let \( \lambda \) be a partition of \( n \). We have:

\[
(f_{\lambda}) = \frac{n!}{\prod_{u \in [\lambda]} h(u)},
\]

where \( h(u) = \lambda_i - i + \lambda_j - j + 1 \) is the hook-length of the square \( u = (i, j) \).

Most recently, Naruse generalized \( (f_{\lambda}) \) as follows. For a skew shape \( \lambda/\mu \), an excited diagram is a subset of the Young diagram \([\lambda]\) of size \( |\mu| \), obtained from the Young diagram \([\mu]\) by a sequence of excited moves:

\[
\begin{array}{c|c|c|c|}
& & & \\
& & & \\
& & & \\
& & & \\
\end{array} 
\rightarrow
\begin{array}{c|c|c|c|}
& & & \\
& & & \\
& & & \\
& & & \\
\end{array}
\]

Such move \((i, j) \rightarrow (i + 1, j + 1)\) is allowed only if cells \((i, j + 1), (i + 1, j)\) and \((i + 1, j + 1)\) in \([\lambda]\) are unoccupied (see the precise definition and an example in §3.1). We use \( E(\lambda/\mu) \) to denote the set of excited diagrams of \( \lambda/\mu \).

**Theorem 1.2** (NHLF; Naruse [Naru]). Let \( \lambda, \mu \) be partitions, such that \( \mu \subset \lambda \). We have:

\[
(f_{\lambda/\mu}) = \frac{|\lambda/\mu|!}{\sum_{D \in E(\lambda/\mu)} \prod_{u \in [\lambda]\setminus D} \frac{1}{h(u)}},
\]

When \( \mu = \emptyset \), there is a unique excited diagram \( D = \emptyset \), and we obtain the usual HLF.

The NHLF has two natural \( q \)-analogues which were proved in the previous paper in the series.

**Theorem 1.3** ([MPPI]). We have:

(\( q \)-NHLF)

\[
(s_{\lambda/\mu}(1, q, q^2, \ldots)) = \sum_{\gamma} \prod_{(i,j) \in [\lambda]\setminus S} \frac{q^{\lambda_j - i}}{1 - q^{h(i,j)}}.
\]

**Theorem 1.4** ([MPPI]). We have:

(\( q \)-NHLF)

\[
\sum_{\pi \in \mathcal{P}(\lambda/\mu)} q^{\sigma_\pi} = \sum_{S \in \mathcal{E}(\lambda/\mu)} \prod_{u \in S} \frac{q^{h(u)}}{1 - q^{h(u)}},
\]

where \( \mathcal{P}(\lambda/\mu) \) is the set of pleasant diagrams (see Definition 4.1).

1.2. Combinatorial proofs. Our approach to the combinatorial proof of the NHLF in Section 5-7 is as follows. We start by proving the case of border strips (connected skew shapes with no \( 2 \times 2 \) square).

In this case the NHLF is more elegant,

\[
\frac{f_{\lambda/\mu}}{|\lambda/\mu|!} = \sum_{\gamma} \prod_{(i,j) \in \gamma} \frac{1}{h(i,j)},
\]

where the sum is over lattice paths \( \gamma \) from \((\lambda'_1, 1)\) to \((1, \lambda_1)\) that stay inside \([\lambda]\). We give two self contained inductive proofs of this case. The first proof in Section 6 is based on showing a multivariate identity of paths. The second proof in Section 7 uses determinants to show that a multivariate identity of paths equals a ratio of factorial Schur functions.
We then use a corollary of the Lascoux–Pragacz identity for skew Schur functions: if \((\theta_1, \ldots, \theta_k)\) is a decomposition of the shape \(\lambda/\mu\) into outer border strips \(\theta_i\) (see Section 7.5) then

\[
\frac{f^{\lambda/\mu}}{[\lambda/\mu]!} = \det \left[ \frac{f^{\theta_i \# \theta_j}}{[\theta_i \# \theta_j]!} \right]_{i,j=1}^k,
\]

where \(\theta_i \# \theta_j\) is a certain substrip of the outer border strip of \(\lambda\).

Combining the case for border strips and this determinantal identity we get

\[
\frac{f^{\lambda/\mu}}{[\lambda/\mu]!} = \det \left[ \sum_{\gamma \subseteq \lambda} \prod_{(r,s) \in \gamma} \frac{1}{h(r,s)} \right]_{i,j=1}^k,
\]

where \((a_j, b_j)\) and \((c_i, d_i)\) are the endpoints of the border strip \(\theta_i \# \theta_j\). Lastly, using the Lindström–Gessel–Viennot lemma this determinant is written as a weighted sum over non-intersecting lattice paths in \(\lambda\). By an explicit characterization of excited diagrams in Section 3 the supports of such paths are exactly the complements of excited diagrams. The NHLF then follows.

A similar approach is used in Section 5 to give a combinatorial proof of the first \(q\)-NHLF for all skew shapes given in [MPP1]. The Hillman–Grassl inspired bijection in [MPP1] remains the only combinatorial proof of the second \(q\)-NHLF.

**Remark 1.5.** We should mention that our inductive proof is involutive, but basic enough to allow “bijectification”, i.e. an involution principle proof of the NHLF. We refer to [K1, Rem, Zei] for the involution principle proofs of the (usual) HLF.

### 1.3. Enumerative applications.

In sections 8 and 9 we give enumerative formulas which follow from NHLF. They involve \(q\)-analogues of Catalan, Euler and Schröder numbers. We highlight several of these formulas.

Let \(\text{Alt}(n) = \{\sigma(1) < \sigma(2) > \sigma(3) < \sigma(4) > \ldots\} \subset S_n\) be the set of alternating permutations. The number \(E_n = |\text{Alt}(n)|\) is the \(n\)-th Euler number (see [S3] and [OEIS A000111]), with the generating function

\[
(1.1) \quad \sum_{n=0}^{\infty} E_n \frac{x^n}{n!} = \tan(x) + \sec(x).
\]

Let \(\delta_n = (n-1, n-2, \ldots, 2, 1)\) denote the staircase shape and observe that \(E_{2n+1} = f^{\delta_{n+2}/\delta_n}\). Thus, the NHLF relates Euler numbers with excited diagrams of \(\delta_{n+2}/\delta_n\). It turns out that these excited diagrams are in correspondence with the set \(\text{Dyck}(n)\) of Dyck paths of length \(2n\) (see Corollary 8.1). More precisely,

\[
|\mathcal{E}(\delta_{n+2}/\delta_n)| = |\text{Dyck}(n)| = C_n = \frac{1}{n+1} \binom{2n}{n},
\]

where \(C_n\) is the \(n\)-th Catalan number, and \(\text{Dyck}(n)\) is the set of lattice paths from \((0,0)\) to \((2n,0)\) with steps \((1,1)\) and \((1,-1)\) that stay on or above the \(x\)-axis (see e.g. [S5]). Now the NHLF implies the following identity.

**Corollary 1.6.** We have:

\[
(\text{EC}) \quad \sum_{p \in \text{Dyck}(n)} \prod_{(a,b) \in p} \frac{1}{2b+1} = \frac{E_{2n+1}}{(2n+1)!},
\]

where \((a,b) \in p\) denotes a point \((a,b)\) of the Dyck path \(p\).

Consider the following two \(q\)-analogues of \(E_n\), the first of which is standard in the literature:

\[
E_n(q) := \sum_{\sigma \in \text{Alt}(n)} q^{\maj(\sigma^{-1})} \quad \text{and} \quad E_n^*(q) := \sum_{\sigma \in \text{Alt}(n)} q^{\maj(\sigma^{-1}\kappa)},
\]
where \( \text{maj}(\sigma) \) is the major index of permutation \( \sigma \) in \( S_n \) and \( \kappa \) is the permutation \( \kappa = (13254 \ldots) \). See examples [3,6] and [9,5] for the initial values.

Now, for the skew shape \( \delta_{n+2}/\delta_n \), Theorem 1.3 gives the following \( q \)-analogue of Corollary 1.6.

**Corollary 1.7.** We have:

\[
\sum_{p \in \text{Dyck}(n)} \prod_{(a,b) \in p} \frac{q^k}{1 - q^{2b+1}} = \frac{E_{2n+1}(q)}{(1-q)(1-q^2) \cdots (1-q^{2n+1})},
\]

Similarly, Theorem 1.4 in this case gives a different \( q \)-analogue.

**Corollary 1.8.** We have:

\[
\sum_{p \in \text{Dyck}(n)} q^{H(p)} \prod_{(a,b) \in p} \frac{1}{1 - q^{2b+1}} = \frac{E^*_2(q)}{(1-q)(1-q^2) \cdots (1-q^{2n+1})},
\]

where

\[
H(p) = \sum_{(c,d) \in \mathcal{HP}(p)} (2d + 1),
\]

and \( \mathcal{HP}(p) \) denotes the set of peaks \( (c,d) \) in \( p \) with height \( d > 1 \).

All three corollaries are derived in sections 8 and 9.

Section 8 considers the special case when \( \lambda/\mu \) is a thick strip shape \( \delta_{n+2k}/\delta_n \), which gives the connection with Euler and Catalan numbers. In Section 9, we consider the pleasant diagrams of the thick strip shapes, establishing a connection with Schröder numbers. We also state conjectures on certain determinantal formulas. We conclude with final remarks and open problems in Section 10.

2. Notation and Background

2.1. Young diagrams. Let \( \lambda = (\lambda_1, \ldots, \lambda_r) \), \( \mu = (\mu_1, \ldots, \mu_s) \) denote integer partitions of length \( \ell(\lambda) = r \) and \( \ell(\mu) = s \). The size of the partition is denoted by \( |\lambda| \) and \( \lambda' \) denotes the conjugate partition of \( \lambda \). We use \( [\lambda] \) to denote the Young diagram of the partition \( \lambda \). The hook length \( h_{ij} = \lambda_i - i + \lambda'_j - j + 1 \) of a square \( u = (i,j) \in [\lambda] \) is the number of squares directly to the right and directly below \( u \) in \( [\lambda] \) including \( u \). The Durfee square \( \square^\lambda \) is the largest square of the form \( \{(i,j), 1 \leq i,j \leq k\} \) inside \( [\lambda] \). Let \( \square^\lambda_k \) be the largest \( i \times (i+k) \) rectangle that fits inside the Young diagram starting at \( (1,1) \). For \( k = 0 \), the rectangle \( \square^\lambda_0 = \square^\lambda \) is the Durfee square of \( \lambda \).

A skew shape is denoted by \( \lambda/\mu \). A skew shape can have multiple edge connected components. For an integer \( k \), let \( d_k \) be the diagonal \( \{(i,j) \in \lambda/\mu \mid i - j = k\} \), where \( \mu_k = 0 \) if \( k > \ell(\mu) \). For an integer \( t, 1 \leq t \leq \ell(\lambda) - 1 \) let \( d_t(\mu) \) denote the diagonal \( d_{\mu_t-t} \) where \( \mu_t = 0 \) if \( \ell(\mu) < t \leq \ell(\lambda) \).

Given the skew shape \( \lambda/\mu \), let \( P_{\lambda/\mu} \) be the poset of cells \( (i,j) \) of \( [\lambda/\mu] \) partially ordered by component. This poset is naturally labelled, unless otherwise stated.

2.2. Young tableaux. A reverse plane partition of skew shape \( \lambda/\mu \) is an array \( \pi = (\pi_{ij}) \) of non-negative integers of shape \( \lambda/\mu \) that is weakly increasing in rows and columns. We denote the set of such plane partitions by \( \text{RPP}(\lambda/\mu) \). A semistandard Young tableau of shape \( \lambda/\mu \) is a RPP of shape \( \lambda/\mu \) that is strictly increasing in columns. We denote the set of such tableaux by \( \text{SSYT}(\lambda/\mu) \). A standard Young tableau (SYT) of shape \( \lambda/\mu \) is an array \( T \) of shape \( \lambda/\mu \) with the numbers \( 1, \ldots, n \), where \( n = |\lambda/\mu| \), each \( i \) appearing once, strictly increasing in rows and columns. For example, there are five SYT of shape (32/1):

\[
\begin{array}{cccc}
12 & 13 & 12 & 21 \\
12 & 23 & 31 & 13 \\
12 & 23 & 13 & 12
\end{array}
\]

The size of a RPP or tableau \( T \) is the sum of its entries and is denoted by \( |T| \).
2.3. Skew Schur functions. Let \( s_{\lambda/\mu}(x) \) denote the skew Schur function of shape \( \lambda/\mu \) in variables \( x = (x_0, x_1, x_2, \ldots) \). In particular,
\[
s_{\lambda/\mu}(x) = \sum_{T \in SSYT(\lambda/\mu)} x^T, \quad s_{\lambda/\mu}(1, q, q^2, \ldots) = \sum_{T \in SSYT(\lambda/\mu)} q^{|T|},
\]
where \( x^T = \prod_{x_i \in \text{cutting strip} \theta} x_i^{\#x_i \text{in } (T)} \) and \( \theta \) is a connected skew shape without any 2 squares. The starting point and ending point of a strip are its southwest and northeast endpoints. Given \( \lambda \), the outer border strip is the strip containing all the boxes inside \([\lambda]\) sharing a vertex with the boundary of \( \lambda \), i.e., \( \lambda \setminus (\lambda_2 - 1, \lambda_3 - 1, \ldots) \).

A Lascoux–Pragacz decomposition of \( \lambda/\mu \) is a decomposition of the skew shape into \( k \) maximal outer border strips \( (\theta_1, \ldots, \theta_k) \), where \( \theta_1 \) is the outer border strip of \( \lambda \), \( \theta_2 \) is the outer border strip of the remaining diagram \( \lambda \setminus \theta_1 \), and so on until we start intersecting \( \mu \). In this case, we continue the decomposition with each remaining connected component. The strips are ordered \( \geq \) by the contents of their northeast endpoints. See Figure 1[Left], for an example.

We call the border strip \( \theta_1 \) the cutting strip of the decomposition and denote it by \( \tau \) \cite{CYY}. For integers \( p \) and \( q \), let \( \phi[p, q] \) be the substrip of \( \tau \) consisting of the cells with contents between \( p \) and \( q \). By convention, \( \phi[p, p] = (1) \), \( \phi[p+1, p] = \emptyset \) and \( \phi[p, q] \) with \( p > q + 1 \) is undefined. The strip \( \theta_i \# \theta_j \) is the substrip \( \phi[p(\theta_j), q(\theta_i)] \) of \( \tau \), where \( p(\theta_i) \) and \( q(\theta_i) \) are the contents of the starting point and ending point of \( \theta_i \).

**Theorem 2.1** (Lascoux–Pragacz \cite{LasP}, Hamel–Goulden \cite{HaG}). If \( (\theta_1, \ldots, \theta_k) \) is a Lascoux–Pragacz decomposition of \( \lambda/\mu \), then
\[
s_{\lambda/\mu} = \det \left[ s_{\theta_i \# \theta_j} \right]_{i,j=1}^{k}.
\]

where \( s_{\emptyset} = 1 \) and \( s_{\phi[p, q]} = 0 \) if \( \phi[p, q] \) is undefined.

**Example 2.2.** Figure 1[Right], shows the Lascoux–Pragacz decomposition for the shape \( \lambda/\mu = (5441/21) \) into two strips \( (\theta_1, \theta_2) \) where \( \tau = \theta_1 = (5441/33) \) and \( \theta_2 = (33/21) \). The substrips of \( \tau \) appearing in the matrix of the identity are
\[
\theta_1 \# \theta_1 = \theta_1, \quad \theta_1 \# \theta_2 = \phi[0, 4] = (322/11), \quad \theta_2 \# \theta_1 = \phi[-3, 2] = (441/3), \quad \theta_2 \# \theta_2 = \theta_2.
\]

Then by the Lascoux–Pragacz identity \( s_{(5441/21)} \) can be written as the following \( 2 \times 2 \) determinant
\[
s_{\lambda/\mu} = \det \left[ \frac{s_{\theta_1 \# \theta_1}}{s_{\theta_2 \# \theta_1}}, \frac{s_{\theta_1 \# \theta_2}}{s_{\theta_2 \# \theta_2}} \right] = \det \left[ \frac{s_{5441/33}}{s_{441/3}}, \frac{s_{322/11}}{s_{22/1}} \right].
\]

2.5. Factorial Schur functions. The factorial Schur function (e.g. see \cite{MS}) is defined as
\[
s^{(d)}_{\mu}(x | a) := \frac{\det \left[ (x_i - a_j) \cdots (x_i - a_{\mu_j + d - j}) \right]_{i,j=1}^{d}}{\prod_{1 \leq i < j \leq d} (x_i - x_j)},
\]
where \( x = x_1, \ldots, x_d \) and \( a = a_1, a_2, \ldots \) is a sequence of parameters.
2.6. **Permutations.** We write permutations of \( \{1, 2, \ldots, n\} \) in *one-line notation*: \( w = (w_1w_2 \ldots w_n) \) where \( w_i \) is the image of \( i \). A *descent* of \( w \) is an index \( i \) such that \( w_i > w_{i+1} \). The *major index* \( \text{maj}(w) \) is the sum \( \sum_i \) of all the descents \( i \) of \( w \).

2.7. **Dyck paths.** A *Dyck path* \( p \) of length \( 2n \) is a lattice paths from \((0, 0)\) to \((2n, 0)\) with steps \((1, 1)\) and \((1, -1)\) that stay on or above the \( x \)-axis. We use \( \text{Dyck}(n) \) to denote the set of Dyck paths of length \( 2n \). For a Dyck path \( p \), a *peak* is a point \((c,d)\) such that \((c-1,d-1)\) and \((c+1,d-1)\) are in \( p \). Peak \((c,d)\) is called a *high-peak* if \( d > 1 \).

3. **Excited diagrams**

3.1. **Definition.** Let \( \lambda/\mu \) be a skew partition and \( D \) be a subset of the Young diagram of \( \lambda \). A cell \( u = (i,j) \in D \) is called *active* if \((i+1,j), (i,j+1) \) and \((i+1,j+1) \) are all in \( \lambda \setminus D \). Let \( u \) be an active cell of \( D \), define \( \alpha_u(D) \) to be the set obtained by replacing \((i,j) \) in \( D \) by \((i+1,j+1) \). We call this replacement an *excited move*. An *excited diagram* of \( \lambda/\mu \) is a subdiagram of \( \lambda \) obtained from the Young diagram of \( \mu \) after a sequence of excited moves on active cells. Let \( \mathcal{E}(\lambda/\mu) \) be the set of excited diagrams of \( \lambda/\mu \) and \( e(\lambda/\mu) \) its cardinality. For example, Figure 2 shows the eight excited diagrams of \((5441/21)\) (for the moment ignore the paths in the complement).

3.2. **Flagged tableaux.** Excited diagrams of \( \lambda/\mu \) are in bijection with certain *flagged tableaux* of shape \( \mu \) (see [MPPT][3] and [Kre1][6]). Thus, the number of excited diagrams is given by a determinant, a polynomial in the parts of \( \lambda \) and \( \mu \) as follows.

Consider the diagonal that passes through cell \((i, \mu_i)\), i.e. the last cell of row \( i \) in \( \mu \). Let this diagonal intersect the boundary of \( \lambda \) at a row denoted by \( i_1^{(\lambda/\mu)} \). Let \( \mathcal{F}(\lambda/\mu) \) be the set of SSYT for shape \( \mu \).
with entries in row \( i \) at most \( f_i^{(\lambda/\mu)} \). Such SSYT are called flagged tableaux and \((f_1^{\lambda/\mu}, \ldots, f_t^{\lambda/\mu})\) is called a flag. Given an excited diagram \( D \in \mathcal{E}(\lambda/\mu) \) each \((x, y)\) in \( [\mu] \) corresponds to a cell \((i_x, j_y)\) in \( D \), let \( \varphi(D) := T \) be the tableau of shape \( \mu \) with \( T_{i_x,j_y} = \varphi \). See Figure 5 for an example of \( \varphi \).

**Proposition 3.1** (§3 [MPP1]). We have that \( e(\lambda/\mu) = |F(\lambda/\mu)| \) and \( \varphi \) is a bijection between these two sets.

By the enumeration of flagged tableaux of Wachs [Wac] the next formula follows.

**Proposition 3.2** (§3 [MPP1]). In notation above, we have:

\[
e(\lambda/\mu) = \det \left[ \left( \frac{f_i^{(\lambda/\mu)} + \mu_i - i + j - 1}{f_i^{(\lambda/\mu)} - 1} \right) \right]_{i,j=1}^{\ell(\mu)}.
\]

**Example 3.3.** For the same shape as in Example 2.2 and Figure 2 the number of excited diagrams equals the number of flagged tableaux of shape \((2,1)\) with entries in the first and second row \( \leq 2 \). Thus

\[
e(\lambda/\mu) = \det \begin{bmatrix} 4 & \binom{2}{2} \\ \binom{2}{2} & \binom{5}{2} \end{bmatrix} = \det \begin{bmatrix} 6 & 10 \\ 1 & 3 \end{bmatrix} = 8.
\]

### 3.3. Border strip decomposition formula for \( e(\lambda/\mu) \).

This first determinantal identity for \( e(\lambda/\mu) \) is similar to the Jacobi–Trudi identity for \( s_\mu \). In this section we prove a new determinantal identity for \( e(\lambda/\mu) \) very similar to the Lascoux–Pragacz identity for \( s_{\lambda/\mu} \).

**Theorem 3.4.** If \((\gamma_1, \ldots, \gamma_k)\) is the Lascoux–Pragacz decomposition of \( \lambda/\mu \) into \( k \) maximal outer border strips then

\[
e(\lambda/\mu) = \det \left[ e(\theta_i \# \theta_j) \right]_{i,j=1}^{k},
\]

where \( e(\emptyset) = 1 \) and \( e(\phi[p,q]) = 0 \) if \( \phi[p,q] \) is undefined.

**Example 3.5.** For the same shape \( \lambda/\mu \) as in Example 2.2 and Figure 2 we have

\[
e(\lambda/\mu) = \det \begin{bmatrix} e(5441/33) & e(322/11) \\ e(441/3) & e(22/1) \end{bmatrix} = \det \begin{bmatrix} 10 & 3 \\ 4 & 2 \end{bmatrix} = 8.
\]

In order to prove Theorem 3.4 we show a relation between excited diagrams and certain tuples of non-intersecting paths in the diagram of \( \lambda \). The support of a path are the cells of \([\lambda]\) contained in the path.

For the connected skew shape \( \lambda/\mu \) there is a unique tuple of border-strips (i.e. non-intersecting paths) \((\gamma_1^1, \ldots, \gamma^\ell_1)\) in \( \lambda \) with support \([\lambda/\mu]\), where each border strip \( \gamma_i^\ell \) begins at the southern box \((a_i^\ell, b_i^\ell)\) of a column and ends at the eastern box \((c_i^\ell, d_i^\ell)\) of a row [Kre1, Lemma 5.3]. We call this tuple the Kreiman decomposition of \( \lambda/\mu \). Let \( \mathcal{NT}(\lambda/\mu) \) be the set of \( k \)-tuples \( \Gamma := (\gamma_1, \ldots, \gamma_k) \) of non-intersecting paths contained in \([\lambda]\) with \( \gamma_i : (a_i, b_i) \to (c_i, d_i) \). Kreiman showed that the supports of the paths in \( \mathcal{NT}(\lambda/\mu) \) are exactly the complements of excited diagrams in \( \mathcal{E}(\lambda/\mu) \) [Kre1 §5, §6]. See Figure 2 for an example. We include a proof of this result. The first half of the argument uses a lemma from Kreiman, the rest of the argument is a new proof using pleasant diagrams (see Section 4) instead of the induction on the number of excited moves.

**Proposition 3.6** (Kreiman [Kre1]). The \( k \)-tuples of paths in \( \mathcal{NT}(\lambda/\mu) \) are uniquely determined by their supports in \([\lambda]\) and moreover these supports are exactly the complements of excited diagrams of \( \lambda/\mu \).

**Proof.** The fact that paths are uniquely determined by their support in \([\lambda]\) follows by [Kre1 Lemma 5.2]. By abuse of notation we identify the \( k \)-tuples of paths in \( \mathcal{NT}(\lambda/\mu) \) with their supports. Note that the supports of all \( k \)-tuples of paths in \( \mathcal{NT}(\lambda/\mu) \) have size \(|\lambda/\mu|\).

We now show that the support of \( k \)-tuples in \( \mathcal{NT}(\lambda/\mu) \) correspond to complements of excited diagrams. First, we show that if \( D \in \mathcal{E}(\lambda/\mu) \) then \( |\lambda| \setminus D \in \mathcal{NT}(\lambda/\mu) \) by induction on the number
Figure 3. Example of the correspondence of the border strips of the Lascoux–Pragacz outer decomposition \((\theta_1, \ldots, \theta_5)\) and Kreiman outer decomposition \((\gamma_1^*, \ldots, \gamma_5^*)\) of \(\lambda/\mu\). The contents of the endpoints and the lengths of \(\theta_i\) and \(\gamma_i^*\) are the same.

of excited moves. Given \([\mu] \in \mathcal{E}(\lambda/\mu)\), its complement \([\lambda/\mu]\) corresponds to Kreiman decomposition \((\gamma_1^*, \ldots, \gamma_k^*)\in \mathcal{NI}(\lambda/\mu)\) as mentioned above. Then excited moves on the diagrams correspond to ladder moves on the non-intersecting paths:

The latter do not introduce intersections and preserve the endpoints of the paths. Thus for each \(D \in \mathcal{E}(\lambda/\mu)\), its complement \([\lambda/\mu] \setminus D\) corresponds to a \(k\)-tuple \((\gamma_1, \ldots, \gamma_k)\) of paths in \(\mathcal{NI}(\lambda/\mu)\).

Conversely, consider the support \(S\) of a \(k\)-tuple of paths in \(\mathcal{NI}(\lambda/\mu)\). The set \(S\) has the following property: the subset \(S_k := S \cap \square_\lambda\) has no descending chain bigger than the length of the \(k\)th diagonal of \(\lambda/\mu\). Such sets \(S\) are called pleasant diagram \([\text{MPP1}, \S 6]\) (see Section 4). Since \(|S| = |\lambda/\mu|\), by \([\text{MPP1}, \text{Thm. 6.5}]\) the set \(S\) is the complement of an excited diagram in \(\mathcal{E}(\lambda/\mu)\), as desired. \(\square\)

Corollary 3.7. \(e(\lambda/\mu) = |\mathcal{NI}(\lambda/\mu)|\).

Next, we show a correspondence between the Kreiman decomposition and the Lascoux–Pragacz decomposition of \(\lambda/\mu\).

Lemma 3.8. There is a correspondence between the border strips of the Lascoux–Pragacz and the Kreiman decomposition of \(\lambda/\mu\). This correspondence preserves the lengths and contents of the starting and ending points of the paths/border strips:

\[
p(\theta_i) = b_i - a_i, \quad q(\theta_i) = d_i - c_i.
\]

Proof. Let \((\theta_1, \ldots, \theta_k)\) and \((\gamma_1^*, \ldots, \gamma_k^*)\) be the Lascoux–Pragacz and the Kreiman decomposition of the shape \(\lambda/\mu\). We prove the result by induction on \(k\). Note that \(\theta_1\) and \(\gamma_1^*\) have the same endpoints \((\lambda_1', 1)\) and \((1, \lambda_1)\). Thus the strips have the same length and their endpoints have the same respective contents.

Next, note that the skew shapes \(\lambda/\mu\) with \(\theta_1\) removed and \(\lambda/\mu\) with \(\gamma_1^*\) removed are the same up to shifting. The Lascoux–Pragacz decomposition of this new shape is \((\theta_2, \ldots, \theta_k)\) with the contents of the endpoints unchanged. Similarly, the Kreiman decomposition of this new shape is \((\gamma_2^*, \ldots, \gamma_k^*)\) with the contents of the endpoints unchanged. By induction \(k - 1 = t - 1\) and the strip \(\theta_i\) and \(\gamma_i^*\) for \(i = 2, \ldots, k\) have the same length and their endpoints have the same content. This completes the proof. \(\square\)

Lastly, we need a Lindström–Gessel–Viennot type lemma to count (weighted) non-intersecting paths in \([\lambda]\). To state the Lemma we need some notation. Its proof follows the usual sign-reversing involution on paths that intersect (e.g. see \([\text{S4}, \S 2.7]\)). Let \((a_1, b_1), \ldots, (a_k, b_k)\) and \((c_1, d_1), \ldots, (c_k, d_k)\) be cells in \([\lambda]\) and let

\[
h((a_j, b_j) \rightarrow (c_i, d_i), y) := \sum_{\gamma} \prod_{(r,s) \in \gamma} y_{r,s}.
\]
Combining Corollary 3.7 and Lemma 3.9 with weights $y_{r,s}$, 

$$\text{Proof of Theorem 3.4.}$$ Combining Corollary 3.7 and Lemma 3.9 with weights $y_{r,s} = 1$ it follows that $e(\lambda/\mu)$ can be calculated by the determinant:

$$e(\lambda/\mu) = \det [\#\{ \text{paths } \gamma : \gamma \subseteq \lambda, \gamma : (a_j, b_j) \rightarrow (c_i, d_i) \}]_{i,j=1}^k.$$  

Next, we claim that the substrip $\theta$ of $\theta_1$ described above is precisely the substrip $\theta \# \theta_j$ of the cutting strip $\tau = \theta_1$ from the Lascoux–Pragacz identity $\text{(2.2)}$. This follows from Lemma 3.8 since the starting point $(a_j, b_j)$ of $\gamma_j^\tau$ has the same content as the starting point of $\theta_j$ and the end point $(c_i, d_i)$ of $\gamma_i^\tau$ has the same content as the end point of $\theta_j$, i.e. $p(\theta_j) = b_j - a_j$ and $q(\theta_j) = d_i - c_i$. Thus $\theta = \phi[p(\theta_j), q(\theta_j)] = \theta_j \# \theta_j$ and so the previous equation becomes

$$\#\{ \text{paths } \gamma : \gamma \subseteq \lambda, \gamma : (a_j, b_j) \rightarrow (c_i, d_i) \} = e(\theta \# \theta_j).$$

Finally, the result follows by combining $\text{(3.1)}$ and $\text{(3.2)}$. \hfill $\square$

4. Pleasant diagrams

4.1. Definition and characterization. A descending chain of length $s$ of a set $S \subset [\lambda]$ is a sequence $((i_1, j_1), (i_2, j_2), \ldots, (i_s, j_s))$ of elements in $S$ satisfying $1 \leq i_1 < \cdots < i_s \leq m$ and $1 \leq j_1 < \cdots < j_s \leq n$.

**Definition 4.1** (Pleasant diagrams [MPPI]). A diagram $S \subset [\lambda]$ is a pleasant diagram of $\lambda/\mu$ if for all integers $k$ with $1 - \ell(\lambda) \leq k \leq \lambda_1 - 1$, the subarray $S_k := S \cap \square_k^\lambda$ has no descending chain bigger than the length of the $k$th diagonal of $\lambda/\mu$. We denote the set of pleasant diagrams of $\lambda/\mu$ by $\mathcal{P}(\lambda/\mu)$ and its size by $p(\lambda/\mu)$.  

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{example_diagram.png}
\caption{For the shape $\lambda/\mu = (5441/21)$: on the left the Lascoux–Pragacz decomposition of $\lambda/\mu$ and the border strips of the determinantal identity for $s_{\lambda/\mu}$; on the right the Kreiman decomposition of $\lambda/\mu$ and the corresponding endpoints of the paths in the determinantal identity $\text{(3.1)}$ to calculate $e(\lambda/\mu)$.}
\end{figure}
Example 4.2. The pleasant diagrams of $\lambda/\mu = (22, 1)$ are subsets of $[\lambda] = \{(1, 1), (1, 2), (2, 1), (2, 2)\}$ with no descending chains in $S_{-1}, S_0, S_1$ of sizes $> 1$. Thus, out of the 16 subsets we discard the four containing the descending chain $((1, 1), (2, 2))$, thus $p(22/1) = 12$.

Pleasant diagrams can be characterized in terms of complements of excited diagrams.

Theorem 4.3 (MPP1). A diagram $S \subset [\lambda]$ is a pleasant diagram in $\mathcal{P}(\lambda/\mu)$ if and only if $S \subseteq [\lambda] \setminus D$ for some excited diagram $D \in \mathcal{E}(\lambda/\mu)$.

Recall that by Proposition 3.6 for an excited diagram $D$, its complement corresponds to a tuple of non-intersecting paths in $\mathcal{N}(\lambda/\mu)$ and that such paths are characterized by their support of size $[\lambda/\mu]$. Next, we give a formula for $p(\lambda/\mu)$ from MPP1. In order to state it we need to define a peak statistic for the non-intersecting paths associated to the complement of an excited diagram $D$.

To each tuple $\Gamma$ of non-intersecting paths we associate recursively, via ladder/excited moves, a subset of its support called excited peaks. For the shape $\lambda/\mu$, the pleasant diagrams of $\lambda/\mu$ peaks is $\Lambda(\lambda/\mu)$. For $\alpha \subseteq \lambda/\mu$, let $\alpha_u(\Gamma)$ be the number of excited peaks of $\alpha_u(\Gamma)$ are obtained from those of $\Gamma$ by adding the new peak $(i, j)$ and removing $(i, j + 1)$ and $(i + 1, j)$ if any of the two are peaks in $\Lambda(\Gamma)$. Pictorially:

Where $[\mathcal{E}]$ denotes a peak. Finally, let $\expk(\Gamma) := |\Lambda(\Gamma)|$ be the number of excited peaks of $\Gamma$. Given a set $S$, let $2^S$ denote the subsets of $S$.

Theorem 4.4 (MPP1). For a skew shape $\lambda/\mu$ we have that $\mathcal{P}(\lambda/\mu)$ is given by the disjoint union

$\mathcal{P}(\lambda/\mu) = \bigcup_{\Gamma \in \mathcal{N}(\lambda/\mu)} \left( \Lambda(\Gamma) \times 2^{\mathcal{E}(\lambda/\mu)} \right)$.

Thus

$p(\lambda/\mu) = \sum_{\Gamma \in \mathcal{N}(\lambda/\mu)} 2^{\lambda/\mu - \expk(\Gamma)}$.

Example 4.5. For the shape $\lambda/\mu = (5441, 21)$, Figure 2 shows the eight non-intersecting paths in $\mathcal{N}(\lambda/\mu)$, each with its excited peaks marked by $[\mathcal{E}]$. Thus

$p(5441/21) = 2^{11} + 2 \cdot 2^{10} + 2 \cdot 2^9 + 2^8 + 2^{10} + 2^9 = 6912$.

4.2 Border strip decomposition formula for pleasant diagrams. By Theorem 4.4, the number of pleasant diagrams is given by a weighted sum over non-intersecting paths in $\mathcal{N}(\lambda/\mu)$. Since the number of such paths $|\mathcal{N}(\lambda/\mu)| = e(\lambda/\mu)$ is given by a Lascoux–Pragacz type determinant (Theorem 3.4), one could ask if there also a similar determinantal identity for $p(\lambda/\mu)$. The following example shows that the first guess of such a formula does not work. Later, we will see that Conjecture 9.3 suggests that in some cases there might be a determinantal formula for $p(\lambda/\mu)$.

Example 4.6. For $\lambda/\mu = (5441/21)$ we showed that $p(5441/21) = 6912$, but $p(5441/33)p(22/1) - p(322/11)p(441/3) = 4352$ and the ratio of these two numbers is $27/17$.

Remark 4.7. One difficulty in applying the Lindström–Gessel–Viennot Lemma (Lemma 3.9) in order to write $P(\lambda/\mu)$ as a determinant of $P(\theta_i, p(\lambda/\mu))$ is that the non-intersecting paths corresponding to a pleasant diagram have excited-peaks that depend on the structure of the path and not just on the coordinates of its support. In the proof of the Lemma, the sign-reversing involution of switching the paths that intersect will not respect these local excited peaks.
5. Combinatorial proofs of the NHLF and first q-NHLF

The goal of this section is to give a combinatorial proof of the NHLF. The proof is split into two parts: first, we reduce the claim from all skew shapes to the border strips. We then give two elementary proofs of the NHLF in the border strip case, in the two sections that follow.

5.1. NHLF for border strips. In this case the NHLF is more elegant. We give two proofs of this case in Sections 6 and 7.

**Lemma 5.1 (NHLF for border strips).** For a border strip \( \theta = \lambda/\mu \) with endpoints \((a, b)\) and \((c, d)\) we have

\[
\frac{f^{\theta}}{|\theta|!} = \sum_{\gamma \leq \lambda} \prod_{\gamma \subseteq \lambda} \frac{1}{h(i, j)},
\]

where \( h(i, j) = \lambda_i - i + \lambda_j' - j + 1 \).

Since the endpoints \((a, b)\) and \((c, d)\) are on the boundary of \( \lambda \) without loss of generality we assume that \((a, b) = (\lambda_1', 1)\) and \((c, d) = (1, \lambda_1)\). The proof is based on an identity of the following multivariate function. For a border strip \( \lambda/\mu \) let

\[
F_{\lambda/\mu}(x | y) = F_{\lambda/\mu}(x_1, x_2, \ldots, x_d | y_1, y_2 \ldots, y_n-d) := \sum_{\gamma \subseteq \lambda} \prod_{\gamma \subset \lambda} \frac{1}{x_i - y_j}.
\]

Note if we evaluate \( F_{\lambda/\mu}(x | y) \) at \( x_i = \lambda_i + d - i + 1 \) and \( y_j = d + j - \lambda_j' \) we obtain the RHS of (5.1),

\[
F_{\lambda/\mu}(x | y) |_{x_i=\lambda_i+d-i+1, y_j=d+j-\lambda_j'} = \sum_{\gamma \subset \lambda} \prod_{\gamma \subseteq \lambda} \frac{1}{h(i, j)}.
\]

5.2. From border trips to all skew shapes. We need the analogue of Theorem 2.1 for \( f^{\lambda/\mu} \).

**Lemma 5.2 (Lascoux–Pragacz).** If \((\theta_1, \ldots, \theta_k)\) is a Lascoux–Pragacz decomposition of \( \lambda/\mu \), then

\[
f^{\lambda/\mu}_{/\mu} = \det \left[ \frac{f^{\theta_i, \# \theta_j}}{|\theta_i|!} \right]_{i,j=1}^k,
\]

where \( f^\theta = 1 \) and \( f^{\phi[p,q]} = 0 \) if \( \phi[p,q] \) is undefined.

**Proof.** The result follows by doing the stable principal specialization in (2.2), using the theory of \( P \)-partitions [54] Thm. 3.15.7] and letting \( q \to 1 \).

**Proof of Theorem 5.2.** Combining Lemma 5.1 and Lemma 5.2 we have

\[
f^{\lambda/\mu} = |\lambda/\mu|! \cdot \det \left[ \sum_{\gamma \subseteq \lambda} \prod_{\gamma \subseteq \lambda} \frac{1}{h(r, s)} \right]_{i,j=1}^k.
\]

Note that the weight \( 1/h(r, s) \) of each step in the path only depends on the coordinate \((r, s)\) and the fixed partition \( \lambda \). By the weighted Lindström–Gessel–Viennot lemma (Lemma 2.9), with \( y_{r,s} = 1/h(r, s) \), we rewrite the RHS of (5.4) as a weighted sum over \( k \)-tuples of non-intersecting paths \( \Gamma \) in \( \mathcal{N}(\lambda/\mu) \). That is,

\[
f^{\lambda/\mu} = |\lambda/\mu|! \cdot \sum_{(\gamma_1, \ldots, \gamma_k) \in \mathcal{N}(\lambda/\mu)} \prod_{(r, s) \in (\gamma_1, \ldots, \gamma_k)} \frac{1}{h(r, s)}.
\]

Finally, by Proposition 3.6 the supports of these non-intersecting paths are precisely the complements of excited diagrams of \( \lambda/\mu \). This finishes the proof of NHLF.
5.3. Proof of the first $q$-NHLF. In this case too the SSYT $q$-analogue of NHLF is elegant and can be stated as follows.

**Lemma 5.3.** For a border strip $\theta = \lambda/\mu$ with end points $(a, b)$ and $(c, d)$ we have

\[
s_\theta(1, q, q^2, \ldots) = \sum_{\gamma: (a_j, b_j) \rightarrow (c_i, d_i), (i, j) \in \gamma} \prod_{(i, j) \in \gamma} \frac{q^{\lambda'_i - r}}{1 - q^{h(r, s)}}.
\]

The proof is postponed to Section 7.4.

**Lemma 5.4** (Lascoux–Pragacz).

\[
s_{\lambda/\mu}(1, q, q^2, \ldots) = \det \left[ s_{\theta, \theta}(1, q, q^2, \ldots) \right]_{i, j=1}^k,
\]

where $s_{\emptyset} = 1$ and $s_{[p, q]} = 0$ if $\theta[p, q]$ is undefined.

**Proof.** The result follows by doing a stable principal specialization in (2.2). \hfill $\square$

**Proof of Theorem 1.3.** Combining Lemma 5.4 and Lemma 5.3 we have

\[
s_{\lambda/\mu}(1, q, q^2, \ldots) = \det \left[ \sum_{\gamma: (a_j, b_j) \rightarrow (c_i, d_i), (i, j) \in \gamma} \prod_{(i, j) \in \gamma} \frac{q^{\lambda'_i - r}}{1 - q^{h(r, s)}} \right]_{i, j=1}^k.
\]

Note that the weight of each step $(r, s)$ in the path is $q^{\lambda'_i - r}/(1 - q^{h(r, s)})$ which only depends on the coordinate $(r, s)$ and the fixed partition $\lambda$. By the weighted Lindström–Gessel–Viennot lemma (Lemma 3.9), with $y_{r, s} = q^{\lambda'_i - r}/(1 - q^{h(r, s)})$, we rewrite the RHS of (5.8) as a weighted sum of $k$-tuples of non-intersecting paths in $[\lambda]$. That is,

\[
s_{\lambda/\mu}(1, q, q^2, \ldots) = \sum_{(\gamma_1, \ldots, \gamma_k) \in \mathcal{NT}(\lambda/\mu)} \prod_{(r, s) \in (\gamma_1, \ldots, \gamma_k)} \frac{q^{\lambda'_i - r}}{1 - q^{h(r, s)}},
\]

Finally, by Proposition 3.6 the supports of these non-intersecting paths are precisely the complements of excited diagrams of $\lambda/\mu$. Thus we obtain Equation (first $q$-NHLF). \hfill $\square$

6. First proof of NHLF for border strips

In this section we give a proof of the NHLF for border strips based on a multivariate identity of the weighted sum of paths $F_\theta(x | y)$. We show that this weighted sum satisfies a recurrence for SYT.

6.1. Multivariate lemma. For any connected skew shape $\lambda/\mu$, the entry 1 in a standard Young tableau $T$ of shape $\lambda/\mu$ will be in an inner corner of $\lambda/\mu$. The remaining entries $2, 3, \ldots, n$ form a standard Young tableau $T'$ of shape $\lambda/\mu$ where $\mu \rightarrow \nu$. Conversely, given a standard Young tableau $T'$ of shape $\lambda/\nu$ where $\mu \rightarrow \nu$, by filling the new cell with 0 we obtain a standard Young tableau of shape $\lambda/\mu$. Thus

\[
f^{\lambda/\mu} = \sum_{\mu \rightarrow \nu} f^{\lambda/\nu}.
\]

We show combinatorially that for border strips $\lambda/\mu$ the multivariate rational function $F_{\lambda/\mu}(x | y)$ satisfies this type of relation.

**Lemma 6.1** (Pieri–Chevalley formula for border strips).

\[
F_{\lambda/\mu}(x | y) = \frac{1}{x_1 - y_1} \sum_{\mu \rightarrow \nu} F_{\lambda/\nu}(x | y).
\]
We have started with some notation that will help us in the proof. Our proof for border strips is different than these two proofs. See Section 10.2 for more details.

6.2. Proof of multivariate lemma. The rest of the section is devoted to the proof of Lemma 6.1. We start with some notation that will help us in the proof.

Remark 6.2. A very similar multivariate relation holds for general skew shapes (the only difference is a different linear factor on the RHS of (6.2)), a fact proved by Ikeda and Naruse [IN] algebraically and combinatorially by Konvalinka [Kon]. Our proof for border strips is different than these two proofs.

Example 6.3. Consider $\lambda = (2, 2)$ and $\mu = (1)$, the shape (2, 2)/(1) has inner corners (1, 2) and (2, 1). We have

$$F((2, 1) \to (1, 2)) = \frac{1}{(x_2 - y_1)(x_2 - y_2)(x_1 - y_2)} + \frac{1}{(x_2 - y_1)(x_1 - y_1)(x_1 - y_2)}$$

$$= \frac{1}{x_1 - y_1 + x_2 - y_2} \left( \frac{1}{(x_2 - y_1)(x_2 - y_2)} + \frac{1}{(x_2 - y_2)(x_1 - y_2)} \right),$$

which equals $[F((1, 2) \to (2, 1)^*) + F((1, 2)^* \to (2, 1))] / (x_1 - y_1)$, thus proving the relation.

We prove (6.3) by induction on the total length of the path between $A$ and $B$. The base case $\lambda = (1)$ and $\mu = \emptyset$ since $F(A \to B) = 1 / (x_1 - y_1)$ and (1, 1) is the only inner corner so $F(A \to C^* \to B) = 1$. The next sublemma will be useful in the inductive step later.

Lemma 6.4. For cells $A = (d, r)$ and $B = (1, s)$ in $[\lambda]$ with $r \leq s$, we have

$$(x_1 - x_d)F(A \to B) = \sum_C F(A \to C^* \to B),$$

where the sum is over inner corners $C$ of $\lambda / \mu$.

Proof. We can write $x_k - x_{k-1} = (x_k - y_j) - (x_{k-1} - y_j)$ for any $j$. Let $\gamma$ be a path from $A$ to $B$, and suppose that it crosses from row $k$ to row $k - 1$ in column $j$ for some $j$. Then both points $(k, j) \in \gamma$ and $(k - 1, j) \in \gamma$.

$$(x_k - x_{k-1})H(\gamma) = (x_k - y_j)H(\gamma) - (x_{k-1} - y_j)H(\gamma) = H(\gamma \setminus (k, j)) - H(\gamma \setminus (k - 1, j)).$$
Since every path from \(A\) to \(B\) crosses from row \(k\) to row \(k - 1\) at some cell, denoted by \(C = (k, j)\), by \((6.4)\) then we have the following:

\[
(x_k - x_{k-1})F(A \rightarrow B) = \sum_{C \in R_k(\lambda)} \left( F(A \rightarrow C^*)F(C \rightarrow B) - F(A \rightarrow C)F(C^* \rightarrow B) \right) = \sum_{C \in R_k(\lambda)} F(A \rightarrow C^* \rightarrow C \rightarrow B) - \sum_{C \in R_{k-1}(\lambda)} F(A \rightarrow C \rightarrow C^* \rightarrow B) =: \oplus
\]

where in the last line we denote \(C_1 = C - \) a box in row \(k - 1\). Note that the existence of the boxes below and above is implicit in the specified path functions \(F\).

Let us now rewrite the RHS. In the last equation in a different way. Note that the paths \(A \rightarrow C^* \rightarrow C \rightarrow B\) can be thought of as paths from \(A\) to \(B\) without their outer corner on row \(k\), and, likewise, the paths \(A \rightarrow C_1 \rightarrow C_1^* \rightarrow B\) are paths \(A \rightarrow B\) without the inner corner on row \(k - 1\). However, they can both be thought of as composed of two paths, \(A \rightarrow A_1\) and \(B_1 \rightarrow B\), where \(A_1\) is the last box on row \(k\) (or row \(k + 1\) if \(C\) was the only cell on row \(k\)), \(B_1\) is the first box on row \(k - 1\) (or the box above \(C\), in row \(k - 2\)) and \(A_1\)’s top right vertex is the same as \(B_1\)’s bottom left (i.e. the boxes have that common vertex), or as in the second case \(B_1\) is one box above \(A_1\). In the case of \(A \rightarrow C^* \rightarrow C \rightarrow B = A \rightarrow A_1, B_1 \rightarrow B\), we must have that \(A_1\) is not the last box in the row (for \(C\) to exist), and for \(A \rightarrow C_1 \rightarrow C_1^* \rightarrow B = A \rightarrow A_1, B_1 \rightarrow B\) there are no restrictions. Thus

\[
(x_k - x_{k-1})F(A \rightarrow B) = \oplus
\]

where all terms cancel except for the cases where \(A_1, C, B_1\) are in the same column, and when \(C\) is an outer corner of \(\lambda\) on row \(k\), denoted by \(D_k\) (if such corner exists).

Finally, since \(x_d - x_1 = \sum_k (x_k - x_{k-1})\), we have

\[
(x_d - x_1)F(A \rightarrow B) = \sum_k (x_k - x_{k-1})F(A \rightarrow B)
\]

\[
= \sum_{k,j; A_1 = (k+1,j), B_1 = (k,j)} F(A \rightarrow A_1)F(B_1 \rightarrow B) - \sum_{k,j; A_1 = (k,j), B_1 = (k-2,j)} \left( F(A \rightarrow A_1)F(B_1 \rightarrow B) - F(A \rightarrow D_k^* \rightarrow B) \right),
\]

which all terms cancel across the various values for \(k\), and we obtain the desired identity. \(\square\)

We continue with the proof of Lemma \((6.1)\). In a path \(\gamma : A \rightarrow B\) the first step from \(A\) is either right to cell \(A_r\) or up to cell \(A_u\). Note that in the first case \(A\) is then an inner corner of \(\lambda/\mu\). Thus

\[
F(A \rightarrow B) = \frac{1}{x_d - y_1} \left( F(A_r \rightarrow B) + F(A_u \rightarrow B) \right).
\]

By induction the term \(F(A_u \rightarrow B)\) becomes

\[
F(A \rightarrow B) = \frac{1}{x_d - y_1} \left( F(A_r \rightarrow B) + \frac{1}{x_1 - y_1} \sum_C F(A_u \rightarrow C^* \rightarrow B) \right).
\]
On the other hand, since a step to \( A_r \) indicates that \( A \) is an inner corner then the RHS of (6.3) equals

\[
\frac{1}{x_1 - y_1} \sum_{C} F(A \to C^* \to B) = \frac{1}{x_1 - y_1} \left[ F(A_r \to B) + \frac{1}{x_d - y_1} \sum_{C} F(A^* \to C^* \to B) \right].
\]

Again, depending on the first step of the paths we split \( F(A^* \to C^* \to B) \) into \( F(A_r \to C^\ast \to B) \) and \( F(A_u \to C^* \to B) \) so the above equation becomes

\[
(6.6) \quad \frac{1}{x_1 - y_1} \sum_{C} F(A \to C^* \to B)
= \frac{1}{x_1 - y_1} \left[ F(A_r \to B) + \frac{1}{x_d - y_1} \left( F(A_r \to C^* \to B) + F(A_u \to C^* \to B) \right) \right].
\]

Finally, by (6.5) and (6.6) if we subtract the LHS and RHS of (6.3) the terms with \( A_u \to C^* \to B \) cancel. Collecting the terms with \( A_r \to B \) we obtain

\[
(6.7) \quad F(A \to B) - \frac{1}{x_1 - y_1} \sum_{C} F(A \to C^* \to B)
= \frac{x_1 - x_d}{(x_1 - y_1)(x_d - y_1)} F(A_r \to B) - \frac{1}{(x_1 - y_1)(x_d - y_1)} \sum_{C} F(A_r \to C^* \to B_1).
\]

Lastly, the RHS above is zero since by Lemma 6.4 we have

\[
(x_1 - x_d) F(A_r \to B) = \sum_{C} F(A_r \to C^* \to B).
\]

Thus the desired relation (6.3) follows.

6.3. **Proof of NHLF for border strips.** In this section we use Lemma 6.1 to prove Theorem 5.1. Let \( H_{\lambda/\mu} \) denote the RHS of (5.2). We prove by induction on \( n = |\lambda/\mu| \) that \( f_{\lambda/\mu} = n! \cdot H_{\lambda/\mu} \).

We start with (6.2) and evaluate \( x_i = \lambda_i + d - i + 1 \) and \( y_j = d + j - \lambda_j' \), by (5.2) we obtain

\[
n \cdot H_{\lambda/\mu} = \sum_{\mu \to \nu} H_{\lambda/\nu}.
\]

Multiplying both sides by \((n - 1)!\) and using induction we obtain

\[
n! \cdot H_{\lambda/\mu} = \sum_{\mu \to \nu} f_{\lambda/\nu}.
\]

By (6.1) the result follows.

7. **Second proof of NHLF for border strips**

In this section we give another proof of the NHLF for border strips based on another multivariate identity involving factorial Schur functions. The proof consists of two steps. First we show that a ratio of an evaluation of factorial Schur functions equals the weighted sum of paths \( F_{\theta}(x \mid y) \). Second we show how the ratio of factorial Schur functions properly specialized equals \( f_{\lambda/\mu} \) and \( s_{\lambda/\mu}(1, q, q^2, \ldots) \).
7. Multivariate lemma. We show combinatorially that the function \( F_{\lambda/\mu}(x | y) \) is an evaluation of a factorial Schur function. Let \( z^\lambda \) be the word of length \( n \) of \( x \)'s and \( y \)'s obtained by reading the horizontal and vertical steps of \( \lambda \) from \((d, 1)\) to \((1, n-d)\): i.e. \( z_{i+d-i+1}^\lambda = x_i \) and \( z_{i+n-d-j+1}^\lambda = y_j \):

\[
\begin{array}{c}
  x_1 \\
  x_2 \\
  \vdots \\
  x_d \\
\end{array}
\begin{array}{c}
  y_1 \\
  y_2 \\
  \vdots \\
  y_{n-d} \\
\end{array}
\]

Example 7.1. For \( d = 4, n = 9 \) and \( \lambda = (5533) \) we have that \( z^\lambda = y_1y_2y_3x_4x_3y_4y_5x_2x_1 \). See the figure in the next example.

Lemma 7.2 ([IN]). For a border strip \( \lambda/\mu \subseteq d \times (n-d) \) we have

\[
(7.1) \quad \frac{s^{(d)}_\mu(x | z^\lambda)}{s^{(d)}_\lambda(x | z^\lambda)} = F_{\lambda/\mu}(x | y).
\]

Before we begin the proof we make a few definitions to simplify notation and a few observations to be used throughout. For any partition \( \nu \subseteq d \times (n-d) \) and a set of variables \( x \) and \( z \) define

\[
D(\nu) := \det[(x_i - z_1) \ldots (x_i - z_{\nu_i + d - j})]_{i,j=1}^d,
\]

so that

\[
(7.2) \quad \frac{s^{(d)}_\mu(x | z^\lambda)}{s^{(d)}_\lambda(x | z^\lambda)} = \frac{D(\mu)}{D(\lambda)}.
\]

Notice also that \( z_{\lambda_i+1+d-j} = x_j \) and so \( (x_i - z_1) \ldots (x_i - z_{\lambda_i+d-j}) = 0 \) if \( j < i \). So the matrix in \( D(\lambda) \) is upper-triangular and

\[
(7.3) \quad D(\lambda) = \prod_{i=1}^d (x_i - z_1) \ldots (x_i - z_{\lambda_i+d-1}).
\]

7.2. Proof of multivariate lemma. To prove Lemma 7.2 we verify that both sides of \((7.1)\) satisfy the following trivial path identity. The first step of a path \( \gamma : (\lambda_1', 1) \to (1, \lambda_1) \) is either \((0,1)\) (up) or \((1,0)\) (right) provided \( \lambda_d > 1 \). So

\[
(7.4) \quad (x_d - y_1)F_{\lambda/\mu}(x | y) = F_{\lambda-\lambda_d/\mu-\mu_d-1}(x_1, \ldots, x_{d-1} | y) + F_{\lambda-1/\mu-1}(x | y_2, \ldots, y_{n-d}),
\]

where the second term on the RHS vanishes if \( \lambda_d = 1 \).

Example 7.3. For the border strip \( \lambda/\mu = (5533/422) \), we have

\[
(x_d - y_1)F_{(5533/422)}(x_1, \ldots, x_4 | y_1, \ldots, y_5) = F_{(5533/422)}(x_1, x_2, x_3 | y_1, \ldots, y_5) + F_{(4422/311)}(x_1, \ldots, x_4 | y_2, \ldots, y_5),
\]

Next we show that the following ratio of factorial Schur functions, satisfies the same relation:

\[
G_{\lambda/\mu}(x | y) := \frac{s^{(d)}_\mu(x | z^\lambda)}{s^{(d)}_\lambda(x | z^\lambda)}.
\]

Lemma 7.4. We have:

\[
(7.5) \quad (x_d - y_1)G_{\lambda/\mu}(x | y) = G_{\lambda-\lambda_d/\mu-\mu_d-1}(x_1, \ldots, x_{d-1} | y) + G_{\lambda-1/\mu-1}(x | y_2, \ldots, y_{n-d}),
\]

where the second term on the RHS vanishes if \( \lambda_d = 1 \).
Proof of Lemma 7.3 We proceed by induction. For the base case \( \lambda = (1) \) and \( \mu = \emptyset \), we directly check that
\[
F_{(1)/\emptyset}(x \mid y) = G_{(1)/\emptyset}(x \mid y) = \frac{1}{x_d - y_1}.
\]
Then by (7.4) and Lemma 7.4 we have \( F_{\lambda/\mu}(x \mid y) \) and \( G_{\lambda/\mu}(x \mid y) \) satisfy the same recurrence. Therefore, we have \( F_{\lambda/\mu}(x \mid y) = G_{\lambda/\mu}(x \mid y) \) as desired. \( \square \)

In the rest of the section we prove Lemma 7.4.

Proof of Lemma 7.4 We denote the shape \((\lambda - \lambda_d)/(\mu - \mu_{d-1})\) by \( \overline{\lambda}/\overline{\mu} \). Removing the first column of \( \lambda \) yields \( z^{\overline{\lambda-1}} = y_2, \ldots = z_2, \ldots \) and removing the last row of \( \lambda \) yields \( z^\lambda = y_1, y_2, \ldots, \overline{x}_d, \ldots = z_1, \ldots, z_{\lambda_d}, z_{\lambda_d+2}, \ldots \), i.e. \( z^\lambda \) with the entry \( x_d \) omitted.

Assume \( \lambda_d \neq 0 \) and \( \mu_d = 0 \), the other case is trivially reduced. If \( \lambda/\mu \) is a border strip \( \mu_j = \lambda_{j+1} - 1 \) for \( j = 1, \ldots, d - 1 \). Hence in the ratio of determinants in (7.2) we have that the first \( d - 1 \) columns of the determinant from \( s^{(d)}_\lambda(\cdot \mid \cdot) \) are the last \( d - 1 \) columns from the determinant for \( s^{(d)}_\lambda(\cdot \mid \cdot) \), and the \( d \)th column from \( s^{(d)}_\mu(\cdot \mid \cdot) \) is ones, since \( \mu_d + d - d = 0 \). Thus in (7.2), upon shifting the \( d \)th column to the first column of the determinant \( D(\mu) \) in the numerator, we obtain
\[
(7.6) \quad G_{\lambda/\mu}(x \mid y) = \frac{(-1)^{d-1}}{D(\lambda)} \det \left[ 1, \begin{array}{c} (x_i - z_1) \cdots (x_i - z_{\lambda_j + d-j}) \end{array} \begin{array}{c} j = 1 \end{array} \begin{array}{c} j > 1 \end{array} \right]_{i,j=1}^d.
\]
Next we have two cases depending on whether \( \lambda_d = 1 \) or \( \lambda_d > 1 \).

Case \( \lambda_d = 1 \): For \( \lambda \) we have \( z^\lambda_1 = y_1 \) and \( z^\lambda_2 = x_d \). The \((d, d)\) entry of the upper triangular matrix of the determinant in \( D(\lambda) \) is \( x_d - y_1 \), so by doing a cofactor expansion on this row we get
\[
D(\lambda) = (x_d - y_1) \det \left[ (x_i - x_d)(x_i - y_1)(x_i - z_3) \cdots (x_i - z_{\lambda_j + d-j}) \right]_{i,j=1}^{d-1}.
\]
By factoring \( x_i - z_2 = x_i - x_d \) from each row above we get
\[
D(\lambda) = (x_d - y_1) \det \left[ (x_i - y_1)(x_i - z_3) \cdots (x_i - z_{\lambda_j + d-j}) \right]_{i,j=1}^{d-1} \prod_{i=1}^{d-1} (x_i - x_d).
\]
Since \( z^\lambda_1 = y_1 \) and \( z^\lambda_j = z^\lambda_{j+1} \) for \( j = 2, \ldots, d - 1 \), then by relabeling we get
\[
(7.7) \quad D(\lambda) = (x_d - y_1) D(\overline{\lambda}) \prod_{i=1}^{d-1} (x_i - x_d).
\]

For \( \mu \) we have \( \mu_d = \mu_{d-1} = 0 \) so the matrix in \( D(\mu) \) has a \( d \)th column of ones
\[
D(\mu) = \det \begin{bmatrix} \cdots & (x_1 - z_1) \cdots (x_1 - z_{\mu_j + d-j}) & \cdots & (x_1 - y_1) & 1 \\ \cdots & (x_2 - z_1) \cdots (x_2 - z_{\mu_j + d-j}) & \cdots & (x_2 - y_1) & 1 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & 0 & (x_d - y_1) & 1 \end{bmatrix}.
\]
Then, by adding \((x_d - y_1)\) to each entry in the \((d - 1)\)th column of the matrix above, the determinant remains unchanged but the last row becomes \( 0 \ldots 01 \). This gives
\[
D(\mu) = \det \begin{bmatrix} 1, \begin{array}{c} j = d \end{array} & \begin{array}{c} j = d - 1 \end{array} \\ x_i - x_d, \begin{array}{c} j = d - 1 \end{array} \\ (x_i - z_1) \cdots (x_i - z_{\mu_j + d-j}), \begin{array}{c} j < d - 1 \end{array} \end{bmatrix}_{i,j=1}^d
\]
Next, we do a cofactor expansion on the last row of this matrix and then we factor \( x_i - z_2 = x_i - x_d \) from each row,

\[
D(\mu) = \det \begin{bmatrix}
  x_i - x_d, & \ (x_i - z_1)(x_i - z_2) \ldots (x_i - z_{\lambda_j + d - j}), & j = d - 1 \\
  (x_i - z_1)(x_i - x_d) \ldots (x_i - z_{\lambda_j + d - j}), & j < d - 1
\end{bmatrix}_{i,j=1}^{d-1}
\]

\[
= \det \begin{bmatrix}
  1, & \ (x_i - z_1)(x_i - x_d) \ldots (x_i - z_{\lambda_j + d - j}), & j = d - 1 \\
  (x_i - z_1)(x_i - x_d) \ldots (x_i - z_{\lambda_j + d - j}), & j < d - 1
\end{bmatrix}_{i,j=1}^{d-1} \prod_{i=1}^{d-1} (x_i - x_d).
\]

Again, since \( z_1^* = y_1 \) and \( z_2^* = z_{j+1}^* \) for \( j = 2, \ldots, d - 1 \), we have by relabeling that

\[
D(\mu) = D(\bar{\mu}) \prod_{i=1}^{d-1} (x_i - x_d).
\]

We now combine (7.7) and (7.8) in \((x_d - y_1)G_{\lambda / \mu}(\cdot \mid \cdot), (7.7)\)

\[
(x_d - y_1)G_{\lambda / \mu}(x \mid y) = (x_d - y_1) \frac{D(\bar{\mu}) \prod_{i=1}^{d-1} (x_i - x_d)}{(x_d - y_1)D(\lambda) \prod_{i=1}^{d-1} (x_i - x_d)} = G_{\lambda / \mu}(x, \ldots, x_{d-1} \mid y),
\]

confirming the desired identity \((7.5)\) in this case since the term \( G_{\lambda - 1 / \mu - 1}(x \mid y) \) is vacuously zero when \( \lambda_d = 1 \).

**Case \( \lambda_d > 1 \):** Using \( z_1 = y_1 \) we have

\[
G_{\lambda - 1 / \mu - 1}(x \mid y_2, \ldots, y_{n-d}) = \frac{(-1)^{d-1}}{D(\lambda - 1)} \det \begin{bmatrix}
  1, & j = 1 \\
  (x_i - z_2) \ldots (x_i - z_{\lambda_j + d - j}), & j > 1
\end{bmatrix}_{i,j=1}^{d}
\]

\[
= \frac{(-1)^{d-1}}{D(\lambda)} \det \begin{bmatrix}
  1, & j = 1 \\
  (x_i - z_2) \ldots (x_i - z_{\lambda_j + d - j}), & j > 1
\end{bmatrix}_{i,j=1}^{d} \prod_{i=1}^{d} (x_i - y_1)
\]

Similarly, we have:

\[
G_{\lambda / \mu}(x_1, \ldots, x_{d-1} \mid y) = \frac{(-1)^{d-2}}{D(\lambda)} \det \begin{bmatrix}
  (x_i - x_d), & j = 1 \\
  (x_i - z_1) \ldots (x_i - z_{\lambda_j + d - j - 1}), & 2 \leq j \leq d - 1
\end{bmatrix}_{i,j=1}^{d-1} \prod_{j=1}^{\lambda_d} (x_d - y_j)
\]

Next, we evaluate the difference of \((x_d - y_1)G_{\lambda / \mu}(\cdot \mid \cdot)\) and \(G_{\lambda - 1 / \mu - 1}(\cdot \mid \cdot)\) using \((7.6)\), with the multilinearity property on the first column, and \((7.9)\) to obtain

\[
(x_d - y_1)G_{\lambda / \mu}(x \mid y) - G_{\lambda - 1 / \mu - 1}(x \mid y_2, \ldots, y_{n-d}) = \frac{(-1)^{d-1}}{D(\lambda)} \times
\]

\[
\left( \det \begin{bmatrix}
  (x_d - y_1), & j = 1 \\
  (x_i - z_1) \ldots (x_i - z_{\lambda_j + d - j}), & j > 1
\end{bmatrix}_{i,j=1}^{d} - \det \begin{bmatrix}
  (x_i - y_1), & j = 1 \\
  (x_i - z_1) \ldots (x_i - z_{\lambda_j + d - j}), & j > 1
\end{bmatrix}_{i,j=1}^{d} \right)
\]

\[
= \frac{(-1)^{d-1}}{D(\lambda)} \det \begin{bmatrix}
  x_d - x_i, & j = 1 \\
  (x_i - z_1) \ldots (x_i - z_{\lambda_j + d - j}), & j > 1
\end{bmatrix}_{i,j=1}^{d} =: (*)
\]
Consider the row \( i = d \) in the last determinant. The entries there are all 0, except when \( j = d \): when \( j = 1 \) we have \( x_d - x_i = 0 \) for \( i = d \), when \( j \in [2, d - 1] \) we have \( \lambda_j + d - j \geq \lambda_d + 1 \), and since \( z_{\lambda_d+1} = x_d \) we have \( \prod_{r=1}^{\lambda_j+d-j}(x_d-z_r) = 0 \). Using the cofactor expansion we compute the determinant in the last equation as the principal minor of the matrix times the \((d, d)\) entry gives

\[
(* \equiv) = \frac{(-1)^{d-1}}{D(\lambda)} \det \begin{cases} x_d - x_i, & j = 1 \\
(x_i - z_1) \ldots (x_i - z_{\lambda_d+d-j}), & j > 1 
\end{cases}_{j,i = 1}^{d-1} \prod_{j=1}^{d-1} (x_d - z_1) \cdots (x_d - z_{\lambda_d}).
\]

We now compare this with equation \((7.10)\), realizing that \( z_1, \ldots, z_{\lambda_d} = y_1, \ldots, y_{\lambda_d} \), so the last expression coincides with \( G_{\lambda/\mu}(x | y) \) as desired. Notice also that if \( j < i \), we have \( \lambda_j + d - j \geq \lambda_i + d - i + 1 \), and since \( x_i = z_{\lambda_i+d-i+1} \), the terms above are 0 when \( j < i \) and \( j \neq 1 \).

### 7.3. Proof of NHLF for border strips.

**Lemma 7.5.** Let \( \mu \subset \lambda \) be two partitions with at most \( d \) parts. Then

\[
\frac{s^{(d)}_{\mu}(x | z^\lambda)}{s^{(d)}_{\lambda}(x | z^\lambda)} \Big|_{x_i = \lambda_i + d - i + 1, \quad y_j = d + j - \lambda'_j} = \frac{f^{\lambda/\mu}}{|\lambda/\mu|!}.
\]

An equivalent form of this statement was announced in \[\text{Naru}\] (see \[\text{MPP1, §8.4}\]) with a different proof.

**Proof.** Let \( x_i = \lambda_i + d - i + 1 \) and \( y_j = d + j - \lambda'_j \); then notice that \( x_i \) and \( y_j \) are exactly the numbers on the horizontal/vertical steps at row \( i \)/column \( j \) of the lattice path determined by \( \lambda \) when writing the numbers \( 1, 2, \ldots \) along the path from the bottom left to the top right end. Thus \( z_\lambda = 1, 2, 3, \ldots \), and so

\[
(x_i - z_1) \cdots (x_i - z_{\mu_j+d-j}) = (\lambda_i + d - i) \cdots (\lambda_i + d - i + 1 - (\mu_j + d - j)) = \frac{(\lambda_i + d - i)!}{(\lambda_i - i - \mu_j + j)!}
\]

whenever \( \lambda_i - i \geq \mu_j - j \) and 0 otherwise. When \( \mu = \lambda \) and \( i = j \), we have \( (x_i - z_1) \cdots (x_i - z_{\lambda_i+d-i}) = (\lambda_i + d - i)! \) and by \((7.3)\) we have

\[
D(\lambda) \Big|_{x_i = \lambda_i + d - i + 1, \quad y_j = d + j - \lambda'_j} = \prod_{i=1}^{d}(\lambda_i + d - i)!
\]

Then, by definition and \((7.2)\), we have

\[
G_{\lambda/\mu}(x | y) \Big|_{x_i = \lambda_i + d - i + 1, \quad y_j = d + j - \lambda'_j} = \frac{D(\mu)}{D(\lambda)} \Big|_{x_i = \lambda_i + d - i + 1, \quad y_j = d + j - \lambda'_j} = \frac{\det[(\lambda_i + d - i)!/(\lambda_i - i - \mu_j + j)]_{i,j=1}^d}{\prod_{i=1}^{d}(\lambda_i + d - i)!} = \det \left[ \frac{1}{(\lambda_i - i - \mu_j + j)!} \right]_{i,j=1}^{d}
\]

Multiplying the last determinant by \(|\lambda/\mu|!\), we recognize the exponential specialization of the Jacobi-Trudi identity for the ordinary \( s_{\lambda/\mu} \) giving \( f^{\lambda/\mu} \) (a formula due to Aitken; see e.g. \[\text{S4, Cor. 7.16.3}\]). Hence we get the desired formula. \(\square\)

**Second proof of Theorem 5.1.** We start with the relation from Lemma 7.2 and evaluate \( x_i = \lambda_i + d - i + 1 \) and \( y_j = d + j - \lambda'_j \). In the RHS by \((5.2)\) we immediately obtain the RHS of \((5.1)\).

Next, we do the same evaluation on the ratio of factorial Schur functions applying Lemma 7.5 that gives the ratio of factorial Schur functions as \( f^{\lambda/\mu} / |\lambda/\mu|! \).

\(\square\)
7.4. SSYT q-analogue for border strips. To wrap up the section we show how the tools developed to prove Theorem 5.1 also yield the SSYT q-analogue for border strips.

Corollary 7.6 (first NHLF for border strips). For a border strip $\theta = \lambda/\mu$ with end points $(a, b)$ and $(c, d)$ we have

$$s_{\theta}(1, q, q^2, \ldots) = \sum_{\gamma: (a, b) \rightarrow (c, d), \gamma \subseteq \lambda} \prod_{\gamma \subseteq \lambda} \frac{q^{\gamma'} - q}{1 - q^{h(i, j)}}.$$  

Proof. We start with (7.1) from Lemma 7.2 and evaluate both sides at $x_i = q^{\lambda_i + d - i + 1}$ and $y_j = q^{d+j-\lambda_j}$. The path series $F_{\lambda/\mu}(x | y)$ gives the RHS of (7.11)

$$F_{\lambda/\mu}(x | y)\bigg|_{x_i=q^{\lambda_i+d-i+1}, y_j=q^{d+j-\lambda_j}} = \sum_{\gamma: (a, b) \rightarrow (c, d), \gamma \subseteq \lambda} \prod_{\gamma \subseteq \lambda} \frac{q^{\gamma'} - q}{1 - q^{h(i, j)}}.$$  

Next, by [MPP1, §4] the evaluation of the ratio of the factorial Schur functions gives the stable principal specialization of the Schur function, the LHS of (7.11)

$$\frac{s_{\lambda}^{(d)}(x | z^\lambda)}{s_{\mu}^{(d)}(x | z^\lambda)}|_{x_i=q^{\lambda_i+d-i+1}, y_j=q^{d+j-\lambda_j}} = s_{\theta}(1, q, q^2, \ldots).$$

\[\Box\]

7.5. Lascoux–Pragacz identity for factorial Schur functions. Lemma 7.2 holds for connected skew shape $\lambda/\mu$ in terms of non-intersecting paths $\Gamma = (\gamma_1, \ldots, \gamma_k)$ in $\mathcal{N}(\lambda/\mu)$ (i.e. complements of excited diagrams).

$$F_{\lambda/\mu}(x | y) := \sum_{\Gamma \in \mathcal{N}(\lambda/\mu)} \prod_{(r,s) \in \Gamma} \frac{1}{x_r - y_s} = \sum_{D \in \mathcal{E}(\lambda/\mu)} \prod_{(r,s) \in D \subseteq |\lambda| \setminus D} \frac{1}{x_r - y_s}.$$  

Ikeda and Naruse [IN] showed algebraically the following identity that we call the multivariate NHLF.

Theorem 7.7 ([IN]). For a connected skew shape $\lambda/\mu \subseteq d \times (n-d)$ we have

$$\frac{s_{\mu}^{(d)}(x | z^\lambda)}{s_{\lambda}^{(d)}(x | z^\lambda)} = F_{\lambda/\mu}(x | y).$$

In Lemma 7.2 we proved combinatorially this result for border strips. We can use the approach from the previous subsections in reverse to obtain a Lascoux–Pragacz type identity for evaluations of factorial Schur functions.

Corollary 8. If $(\theta_1, \ldots, \theta_k)$ is a Lascoux–Pragacz decomposition of $\lambda/\mu \subseteq d \times (n-d)$, then

$$s_{\lambda}^{(d)}(x | z^\lambda) \cdot s_{\mu}^{(d)}(x | z^\lambda)^{k-1} = \det \left[ s_{\lambda \setminus \theta_i \# \theta_j}^{(d)}(x | z^\lambda) \right]_{i,j=1}^k$$

where $\lambda \setminus \theta_i \# \theta_j$ denotes the partition obtained by removing from $\lambda$ the outer substrip $\theta_i \# \theta_j$.

Proof. By the weighted Lindström–Gessel–Viennot lemma (Lemma 3.9) with $y_{r,s} = 1/(x_r - y_s)$, we rewrite the RHS of (7.12) as a determinant.

$$\frac{s_{\mu}^{(d)}(x | z^\lambda)}{s_{\lambda}^{(d)}(x | z^\lambda)} = \det \left[ \sum_{\gamma: (a, b) \rightarrow (c, d), (r,s) \in \gamma} \prod_{\gamma \subseteq \lambda} \frac{1}{x_r - y_s} \right]_{i,j=1}^k = \det \left[ F_{\theta_i \# \theta_j}(x | y) \right]_{i,j=1}^k.$$  

Finally, by Lemma 7.2 each entry of the matrix can be written as the quotient of $s_{\lambda \setminus \theta_i \# \theta_j}^{(d)}(x | z^\lambda)$ and $s_{\lambda}^{(d)}(x | z^\lambda)$. By factoring the denominators out of the matrix we obtain the result.  

\[\Box\]
Calculations suggest that an analogue of (7.13) holds for general factorial Schur functions $s^{(d)}_\mu(x | y)$ and not just for the evaluation $y = z^\lambda$.

**Conjecture 7.9.** If $(\theta_1, \ldots, \theta_k)$ is a Lascoux–Pragacz decomposition of $\lambda/\mu \subset d \times (n - d)$, then
\begin{equation}
(7.14)
  s^{(d)}_\mu(x | y) \cdot s^{(d)}_\lambda(x | y)^{k-1} = \det \left[ s^{(d)}_{\lambda\setminus\theta_i \# \theta_j}(x | y) \right]_{i,j=1}^k
\end{equation}
where $\lambda \setminus \theta_i \# \theta_j$ denotes the partition obtained by removing from $\lambda$ the outer substrip $\theta_i \# \theta_j$.

Since factorial Schur functions reduce to Schur functions when $y = 0$, this conjecture implies an identity of Schur functions.

**Proposition 7.10.** Conjecture (7.9) implies the Schur function identity
\begin{equation}
(7.15)
  s_\mu \cdot s_\lambda^{k-1} = \det \left[ s_{\lambda\setminus\theta_i \# \theta_j}(x | y) \right]_{i,j=1}^k,
\end{equation}
where $(\theta_1, \ldots, \theta_k)$ is a Lascoux–Pragacz decomposition of $\lambda/\mu$.

**Example 7.11.** For the Lascoux–Pragacz decomposition in Example 2.2, (7.15) gives the following identity that indeed holds:
\begin{align*}
  s_{(2,1)} \cdot s_{(5,4,2,1)} &= s_{(3^2)} \cdot s_{(5,3,2,1)}^2 - s_{(3^2,2,1)} \cdot s_{(5,3,2,1)}^\ast.
\end{align*}

**Remark 7.12.** Note that instead of reversing the approach in Section 5 having a combinatorial proof of the identity in Corollary 7.8 would show that the multivariate NHLF (Theorem 7.7) for skew shapes is equivalent to the multivariate NHLF for border strips (Lemma 7.2).

## 8. Excited diagrams and SSYT of border strips and thick strips

In the next two sections we focus on the case of the thick strip $\delta_{n+2k}/\delta_n$ where $\delta_n$ denotes the staircase shape $(n-1, n-2, \ldots, 2, 1)$. We study the excited diagrams $E(\delta_{n+2k}/\delta_n)$ using the results from Section 3.3 and the number of SYT of this shape combining the NHLF, its SSYT $q$-analogue (Theorem 1.3) and the Lascoux–Pragacz identity.

### 8.1. Excited diagrams and Catalan numbers

We start by enumerating the excited diagrams of the shape $\delta_{n+2k}/\delta_n$.

**Corollary 8.1.** We have: $e(\delta_{n+2}/\delta_n) = C_n$, $e(\delta_{n+4}/\delta_n) = C_nC_{n+2} - C_{n+1}^2$, and in general
\begin{equation}
(8.1)
  e(\delta_{n+2k}/\delta_n) = \det[C_{n-2+i+j}^k]_{i,j=1}^{2k + i + j - 1}.
\end{equation}

**Proof.** We start with the case $k = 1$ for the zigzag border strip $\delta_{n+2}/\delta_n$. By Proposition 3.6 the complement of excited diagrams of $\delta_{n+2}/\delta_n$ are paths $\gamma : (n+1,1) \to (1,n+1)$, $\gamma \subseteq \delta_{n+2}$. By rotating these paths $45^\circ$ clockwise one obtain the Dyck paths in Dyck$(n)$ as illustrated in Figure 5. Thus $e(\delta_{n+2}/\delta_n) = C_n$.

For general $k$, the shape $\delta_{n+2k}/\delta_n$ has a Lascoux–Pragacz decomposition into $k$ maximal border strips $(\theta_1, \ldots, \theta_k)$ where $\theta_1$ is the zigzag strip from $(n + 2k - 2i - 1,1)$ to $(1,n+2k-2i-1)$ (see Figure 6). Then by Theorem 3.7 we have
\begin{equation}
  e(\delta_{n+2k}/\delta_n) = \det \left[ e(\theta_i \# \theta_j) \right]_{i,j=1}^k.
\end{equation}

The cutting strip $\tau$ of the decomposition of $\delta_{n+2k}/\delta_n$ is the zigzag $\theta_1$. The strips $\theta_i \# \theta_j$ in the determinant, being substrips of $\theta_1$, are themselves zigzags. The strip $\theta_i \# \theta_j$ in $\theta_1$ consists of the cells with content from $2+2j-n-2k$ to $n+2k-2i-2$. So the strip is a zigzag $\delta_{n+2}/\delta_m$ of size $2m+1$ where $m = n+2k+i+j+2$. Since we already know that the shape $\delta_{m+2}/\delta_m$ has $C_m$ excited diagrams then the above determinant becomes
\begin{equation}
  e(\delta_{n+2k}/\delta_n) = \det \left[ C_{n+2k-i-j-2}^k \right]_{i,j=1}^{n+i+j-2} = \det \left[ C_{n+i+j-2}^k \right]_{i,j=1}^{n+i+j-2}.
\end{equation}
where the last equality is obtained by relabeling the matrix. This proves the first equality of (8.1).

To prove the second equality we use the characterization of excited diagrams as flagged tableaux. By Proposition 3.1, excited diagrams in $\mathcal{E}(\delta_n+2k/\delta_n)$ are in bijection with flagged tableaux of shape $\delta_n$ with flag $(k+1, k+2, \ldots, k+n-1)$. By subtracting $i$ to all entries in row $i$, these tableaux are equivalent to reverse plane partitions of shape $\delta_n$ with entries $\leq k$ which are counted by the given product formula due to Proctor [Pr2].

**Remark 8.2.** Similarly excited diagrams in $\mathcal{E}(\delta_n+2k+1/\delta_n)$ are in correspondence with flagged tableaux of shape $\delta_n$ with flag $(k+1, k+2, \ldots, k+n-1)$, thus $|\mathcal{E}(\delta_n+2k/\delta_n)| = |\mathcal{E}(\delta_n+2k+1/\delta_n)|$. In what follows the formulas for the even case $\delta_n+2k$ are simpler than those of the odd case so we omit the latter.

![Figure 5](image)

**Figure 5.** Correspondence between excited diagrams in $\delta_5/\delta_3$, Dyck paths in Dyck(3) and flagged tableaux of shape $\delta_3$ with flag (2,3).

From the first determinantal formula for $e(\lambda/\mu)$ (Proposition 3.2) we easily obtain the following curious determinantal identity (see also [10.4]).

**Corollary 8.3.** We have:

$$\det \left[ \left( \frac{n-i+j}{i} \right)^{n-1} \right]_{i,j=1} = C_n.$$  

**Proof.** By Corollary 8.1 we have $|\mathcal{E}(\delta_n+2/\delta_n)| = C_n$. We apply Proposition 3.2 to the shape $\delta_n+2/\delta_n$, where the vector $f^{n+2/\delta_n} = (2, 3, \ldots, n)$, see [3.2]. This expresses $|\mathcal{E}(\delta_n+2/\delta_n)|$ as the given determinant, and the identity follows.

Next we give a description of the excited diagrams of the shape $\delta_n+2k/\delta_n$. Let $\text{FanDyck}(k, n)$ be the set of tuples $(p_1, \ldots, p_k)$ of $k$ noncrossing Dyck paths from $(0, 0)$ to $(2n, 0)$ (see Figure 6: Right). We call such tuples $k$-fans of Dyck paths. It is known [SV] that fans of Dyck paths are counted by the determinant of Catalan numbers and the product formula in (8.1).

**Corollary 8.4.** We have $e(\delta_n+2k/\delta_n) = |\text{FanDyck}(k, n)|$ and the complements of the excited diagrams correspond to $k$-fans of paths in $\text{FanDyck}(k, n)$.

**Proof.** By Proposition 3.6 the complements of excited diagrams in $\mathcal{E}(\delta_n+2k/\delta_n)$ correspond to $k$-tuples of nonintersecting paths in $\mathcal{N}(\delta_n+2k/\delta_n)$ (paths obtained via ladder moves from the original paths $(\gamma^*_1, \ldots, \gamma^*_k)$ of the Kreiman outer decomposition of $\delta_n+2k/\delta_n$).

The path $\gamma^*_i$ consists of zigzag path $p^*_i$ of $2n+1$ cells bookended by a vertical and horizontal segment of $k-i$ cells each (see Figure 6: Middle). Because the excited/ladder moves preserve the contents of the cells of $\delta_n$, the path $\gamma_i$ in $(\gamma_1, \ldots, \gamma_k) \in \mathcal{N}(\delta_n+2k/\delta_n)$ will consist of a Dyck path $p_i$ bookended by the same vertical and horizontal segments as in $\gamma^*_i$. Thus the map $(\gamma_1, \ldots, \gamma_k) \mapsto (p_1, \ldots, p_k)$ denoted by $\varphi$ is a correspondence between $\mathcal{N}(\delta_n+2k/\delta_n)$ and $\text{FanDyck}(k, n)$. See Figure 6: right, for an example.

**Remark 8.5.** Fans of Dyck paths in $\text{FanDyck}(k, n)$ are equinumerous with $k$-triangulations of an $(n+2k)$-gon [Jon] (see also [S5, A12] and [SS] for a bijection for general $k$).
8.2. Determinantal identity of Schur functions of thick strips. Observe that SYT of shape \( \delta_{n+2}/\delta_n \) are in bijection with alternating permutations of size \( 2n+1 \). These permutations are counted by the odd Euler number \( E_{2n+1} \). Thus,

\[
f_{\delta_{n+2}/\delta_n} = E_{2n+1}.
\]

Let \( E_n(q) \) be as in the introduction, the \( q \)-analogue of Euler numbers\(^1\).

**Example 8.6.** We have: \( E_1(q) = E_2(q) = 1 \), \( E_3(q) = q^2 + q \), \( E_4(q) = q^4 + q^3 + 2q^2 + q \), and \( E_5(q) = q^8 + 2q^7 + 3q^6 + 4q^5 + 3q^4 + 2q^3 + q^2 \).

By the theory of \((P,\omega)\)-partitions [S3, §2][S4, §7.19], we have:

\[
E_{2n+1}(q) = s_{\delta_{n+2}/\delta_n}(1,q,q^2,\ldots) \cdot \prod_{i=1}^{2n+1} (1 - q^i).
\]

Next we apply the Lascoux–Pragacz identity to the shape \( \delta_{n+2k}/\delta_n \).

**Corollary 8.7** (Lascoux–Pragacz for \( \delta_{n+2k}/\delta_n \)). We have:

\[
s_{\delta_{n+2k}/\delta_n}(x) = \det \left[ s_{\delta_{n+i+j}/\delta_{n-2+i+j}}(x) \right]_{i,j=1}^k.
\]

**Proof.** By Theorem 2.1 for the shape \( \delta_{n+2k}/\delta_n \) we have

\[
s_{\delta_{n+2k}/\delta_n}(x) = \det \left[ s_{\theta_i#\theta_j}(x) \right]_{i,j=1}^k,
\]

where \((\theta_1,\ldots,\theta_k)\) is the decomposition of the shape \( \delta_{n+2k}/\delta_n \) into \( k \) maximal border strips. As in the proof of Corollary 8.1, the strip \( \theta_i#\theta_j \) has zigzag shape \( \delta_{m+2}/\delta_m \) for \( m = n + 2k - i - j + 2 \). Thus, after relabeling the matrix, the above equation becomes the desired expression. \( \square \)

**Corollary 8.8.** We have:

\[
s_{\delta_{n+2k}/\delta_n}(1,q,q^2,\ldots) = \det \left[ \bar{E}_{2(n+i+j)-3}(q) \right]_{i,j=1}^k,
\]

where

\[
\bar{E}_n(q) := \frac{E_n(q)}{(1-q)(1-q^2)\cdots(1-q^n)}.
\]

**Proof.** The result follows from Corollary 8.7 and equation (8.2). \( \square \)

Taking the limit \( q \to 1 \) in Corollary 8.8 we get corresponding identities for \( f_{\delta_{n+2k}/\delta_n} \).

---

\(^1\)In the survey [S3, §2], our \( E_n(q) \) is denoted by \( E^*_n(q) \).
Corollary 8.9. We have:

\[
\frac{f_{n+2k/\delta_n}}{f_{n+2k/\delta_n}} = \det \left[ \frac{\hat{E}_{2(n+i+j)-3}}{i,j=1} \right]^k, \quad \text{where } \hat{E}_n := \frac{E_n}{n!}.
\]

Remark 8.10. Baryshnikov and Romik [BR] gave similar determinantal formulas for the number of standard Young tableaux of skew shape \((n + m - 1, n + m - 2, \ldots, m)/(n - 1, n - 2, \ldots, 1)\), extending the method of Elkies (see e.g. [AR, Ch. 14]).

In a different direction, one can use Corollary 8.9 when \(n = 1, 2\) to obtain the following determinant formulas for Euler numbers in terms of \(f_{2k+1}\) and \(f_{2k}\), which of course can be computed by a HLF (cf. [OEIS A005118]).

Corollary 8.11. We have:

\[
\det \left[ \hat{E}_{2(i+j)-1} \right]_{i,j=1}^k = \frac{f_{2k+1}}{(2k+1)!}, \quad \det \left[ \hat{E}_{2(i+j)+1} \right]_{i,j=1}^k = \frac{f_{2k}}{((2k-1))}.
\]

8.3. SYT and Euler numbers. We use the NHLF to obtain an expression for \(f_{n+2/\delta_n} = E_{2n+1}\) in terms of Dyck paths.

Proof of Corollary 1.6. By the NHLF, we have

\[
f_{n+2/\delta_n} = \frac{|\delta_{n+2}/\delta_n|!}{\prod_{D \in \mathcal{E}(\delta_{n+2}/\delta_n)} \prod_{u \in \overline{D}} \frac{1}{h(u)}},
\]

where \(\overline{D} = [\delta_{n+2}/\delta_n] \setminus D\). Now \(|\delta_{n+2}/\delta_n| = (2n+1)!\) and by Corollary 8.1 (complements of) excited diagrams \(D\) of \(\delta_{n+2}/\delta_n\) correspond to Dyck paths \(\gamma\) in Dyck\((n)\). In this correspondence, if \(u \in \overline{D}\) corresponds to point \((a, b)\) in \(\gamma\) then \(h(u) = 2b+1\) (see Figure 5). Translating from excited diagrams to Dyck paths, (8.3) becomes the desired identity (EC).

Equation (EC) can be generalized to thick strips \(\delta_{n+2k}/\delta_n\).

Corollary 8.12. We have:

\[
\sum_{\mathbf{p} \in \text{FanDyck}(k,n)} \prod_{(a, b) \in \mathbf{p}, \text{ noncrossing}} \frac{1}{2b+4r-3} = \left[ \prod_{r=1}^{k-1} (4r-1)!! \right]^2 \det \left[ \hat{E}_{2(n+i+j)-3} \right]_{i,j=1}^k.
\]

where \(\hat{E}_n = E_n/n!\) and \((a, b) \in \mathbf{p}\) denotes a point of the Dyck path \(\mathbf{p}\).

Proof. For the RHS we use Corollary 8.9 to express \(f_{n+2k/\delta_n}\) in terms of Euler numbers. For the LHS, we first use the NHLF to write \(f_{n+2k/\delta_n}\) as a sum over excited diagrams \(\mathcal{E}(\delta_{n+2k}/\delta_n)\):

\[
f_{n+2k/\delta_n} = \frac{|\delta_{n+2k}/\delta_n|!}{\prod_{D \in \mathcal{E}(\delta_{n+2k}/\delta_n)} \prod_{u \in \overline{D}} \frac{1}{h(u)}},
\]

where \(\overline{D} = [\delta_{n+2k}/\delta_n] \setminus D\). By Corollary 8.4, excited diagrams of \(\delta_{n+2k}/\delta_n\) correspond to \(k\)-tuples of noncrossing Dyck paths in \(\text{FanDyck}(k,n)\) via the map \(\varphi\). Finally, one can check (see Figure 6 right) that if \(\varphi : D \mapsto (p_1, \ldots, p_k)\) then

\[
\prod_{u \in \overline{D}} h(u) = \left[ \prod_{r=1}^{k-1} (4r-1)!! \right]^2 \prod_{(a, b) \in \mathbf{p}} (2b+4r-3),
\]

which gives the desired RHS.

\[\square\]
8.4. **Probabilistic variant of** \((\text{EC})\). Here we present a new identity \((8.6)\) which is a close relative of the curious identity \((\text{EC})\) we proved above.

Let \(\mathcal{BT}(n)\) be the set of *plane full binary trees* \(\tau\) with \(2n + 1\) vertices, i.e. plane binary trees where every vertex has zero or two descendants. These trees are counted by \(|\mathcal{BT}(n)| = C_n\) (see e.g. [SS5 §2]). Given a vertex \(v\) in a tree \(\tau \in \mathcal{BT}(n)\), \(h(v)\) denotes the number of descendants of \(v\) (including itself). An *increasing* labeling of \(\tau\) is a labeling \(\omega(\cdot)\) of the vertices of \(\tau\) with \(\{1, 2, \ldots, 2n + 1\}\) such that if \(u\) is a descendant of \(v\) then \(\omega(v) \leq \omega(u)\). By abuse of notation, let \(f_\tau\) is the number of increasing labelings of \(\tau\). By the HLF for trees (see e.g. [Sag3]), we have:

\[
\begin{align*}
(8.5) 
& \quad f_\tau = \frac{(2n + 1)!}{\prod_{v \in \tau} h(v)}. \\
& \text{Proposition 8.13.} \quad \text{We have:} \\
(8.6) 
& \quad \sum_{\tau \in \mathcal{BT}(n)} \prod_{v \in \tau} \frac{1}{h(v)} = \frac{E_{2n+1}}{(2n + 1)!}. 
\end{align*}
\]

**Proof.** The RHS of \((8.6)\) gives the probability \(E_{2n+1}/(2n + 1)!\) that a permutation \(w \in S_{2n+1}\) is alternating. We use the representation of a permutation \(w\) as an *increasing binary tree* \(T(w)\) with \(2n + 1\) vertices (see e.g. [S4 §1.5]). It is well-known that \(w\) is an *down-up* permutation (equinumerous with up-down/alternating permutations) if and only if \(T(w)\) is an increasing full binary tree [S4 Prop. 1.5.3]. See Figure 7 for an example. We conclude that the probability \(p\) that an increasing binary tree is a full binary tree is given by \(p = E_{2n+1}/(2n + 1)!\).

On the other hand, we have:

\[p = \sum_{\tau \in \mathcal{BT}(n)} \frac{f_\tau}{(2n + 1)!},\]

where \(f_\tau/(2n + 1)!\) is the probability that a labeling of a full binary tree \(\tau\) is increasing. By \((8.5)\), the result follows. \(\square\)

**Figure 7.** The full binary tree corresponding to the alternating permutation \(w = (6273514)\).

**Remark 8.14.** Note the similarities between \((8.6)\) and \((\text{EC})\). They have the same RHS, both are sums over the same number \(C_n\) of Catalan objects of products of \(n\) terms, and both are variations on the (usual) \((\text{HLF})\) for other posets. As the next example shows, these equations are quite different.

**Example 8.15.** For \(n = 2\) there are \(C_2 = 2\) full binary trees with 5 vertices and \(E_5 = 16\). By Equation \((8.6)\)

\[
\frac{1}{3\cdot5} + \frac{1}{3\cdot5} = \frac{16}{5!}.
\]

On the other hand, for the two Dyck paths in \(\text{Dyck}(2)\), Equation \((\text{EC})\) gives

\[
\frac{1}{3\cdot3} + \frac{1}{3\cdot3\cdot5} = \frac{16}{5!}.
\]
8.5. **Identity (EC) for other types.** In this section \( \lambda \) and \( \mu \) are partitions with distinct parts. We consider shifted diagrams of shape \( \lambda \) and skew shape \( \lambda/\mu \) and standard tableaux of shifted shape \( \lambda/\mu \). Along with Theorem 1.2.3, Naruse also announced two formulas for the number \( g^{\lambda/\mu} \) of standard tableaux of skew shifted shape \( \lambda/\mu \), in terms of type \( B \) and type \( D \) excited diagrams. These excited diagrams are obtained from the diagram of \( \mu \) by applying the following excited moves:

- **Type B:**
  
  \[
  \begin{array}{ccc}
  & & \\
  & \rightarrow & \\
  & & \\
  \end{array}
  \quad \text{and} \quad
  \begin{array}{ccc}
  & & \\
  & \rightarrow & \\
  & & \\
  \end{array}
  \]

- **Type D:**
  
  \[
  \begin{array}{ccc}
  & & \\
  & \rightarrow & \\
  & & \\
  \end{array}
  \quad \text{and} \quad
  \begin{array}{ccc}
  & & \\
  & \rightarrow & \\
  & & \\
  \end{array}
  \]

We denote the set of type \( B \) (type \( D \)) excited diagrams of shifted skew shape \( \lambda/\mu \) by \( \mathcal{E}^B(\lambda/\mu) \) (\( \mathcal{E}^D(\lambda/\mu) \)). As in Section 3.2 or [MPP1] §3, type \( B \) (type \( D \)) excited diagrams of \( \lambda/\mu \) are equivalent to certain (subset of) flagged tableaux of shifted shape \( \mu \) and to certain non-intersecting paths (see Figure 9).

Given a shifted shape \( \lambda \), the type \( B \) hook of a cell \((i, i)\) on the diagonal is the cells in row \( i \) of \( \lambda \). The hook of a cell \((i, j)\) for \( i \leq j \) is the cells in row \( i \) right of \((i, j)\), the cells in column \( j \) below \((i, j)\), and if \((j, j)\) is one of these cells below then the hook also includes the cells in the \( j \)th row of \( \lambda \) (overall counting \((j, j)\) twice). The type \( D \) hook is the usual shifted hook (e.g., see [Sag2] Ex. 3.21). The hook-length of \((i, j)\) is the size of the hook of \((i, j)\) and is denoted by \( h^B(i, j) \) (\( h^D(i, j) \)); see Figure 8.

The NHLF then extends verbatim.

**Theorem 8.16 (Naruse [Naru]).** Let \( \lambda, \mu \) be partitions with distinct parts, such that \( \mu \subset \lambda \). We have

\[
\begin{align}
\lambda^{\mu} = \lambda/\mu & = |\lambda/\mu|! \sum_{S \in \mathcal{E}^B(\lambda/\mu)} \prod_{(i, j) \in [\lambda]} \frac{1}{h^B(i, j)}, \\
\lambda^{\mu} & = |\lambda/\mu|! \sum_{S \in \mathcal{E}^D(\lambda/\mu)} \prod_{(i, j) \in [\lambda]} \frac{1}{h^D(i, j)},
\end{align}
\]

where \( h^B(i, j) \) and \( h^D(i, j) \) are the shifted hook-lengths of type \( B \) and type \( D \), respectively.

**Example 8.17** (shifted thick zigzag strip). The shifted analogue of the staircase is the triangle \( \nabla_n = (2n-1, 2n-3, \ldots, 1) \). The analogue of the thick strip is the shifted skew shape \( \nabla_{n+k}/\nabla_n \). The number of type \( B \) excited diagrams of this shape has a product formula analogous to (8.1).

**Proposition 8.18.**

\[
|\mathcal{E}^B(\nabla_{n+k}/\nabla_n)| = \prod_{h=1}^{k} \prod_{i=1}^{n} \prod_{j=1}^{n} \frac{h + i + j - 1}{h + i + j - 2}.
\]

**Proof.** As in the standard shape case, the type \( B \) excited diagrams correspond to shifted flagged tableaux of shape \( \nabla_n \) with entries in row \( i \leq i + k \). By subtracting \( i \) from all entries in row \( i \) of such tableaux they are equivalent to plane partitions of shape \( \nabla_n \) with entries \( \leq k \). By a result of Proctor [Pr1], recently proved bijectively in [HPPW], these are equinumerous with plane partitions in a \( n \times n \times k \) box (see also [HW]). Thus the result follows by MacMahon’s boxed plane partition formula.

\[\square\]
Proof of Corollary 1.7. \[ E(8.10) \]
is just \((EC)\). It would be of interest to find a formula for

Remark 8.21. Suppose \(8.6\).

8.17. counts plane partitions that fit inside the \((8.7)\), we obtain a type

Corollary 8.19. \[ (EC-B) \]
\begin{equation}
\sum_{p \in \text{Dyck}^B(n)} \prod_{(a,b) \in p} \frac{1}{wt(a,b)} = \frac{E_{2n+1}}{(2n+1)!}, \quad \text{where } \text{wt}(a,b) = \begin{cases} b+1 & \text{if } a \leq n, \\ 2b+1 & \text{if } a < n < 2n, \\ 2b+2 & \text{if } a = 2n. \end{cases}
\end{equation}

Example 8.20. Figure 9 shows the \(2^1\) excited diagrams of shape \(\nabla_3/\nabla_2\). By taking their complements and reflecting vertically, we obtain the paths in \(\text{Dyck}^B(2)\). Either using \text{wt}(a,b) on the paths or the hook-lengths for the shape \(\nabla_3/\nabla_2\) (see Figure 8 right), \((EC-B)\) gives

\[
\frac{1}{4 \cdot 3 \cdot 1^3} + \frac{1}{6 \cdot 4 \cdot 3 \cdot 1^2} + \frac{1}{4 \cdot 3^2 \cdot 1} + \frac{1}{6 \cdot 4 \cdot 3^2 \cdot 1} + \frac{1}{8 \cdot 6 \cdot 3^2 \cdot 1} + \frac{1}{8 \cdot 6 \cdot 5 \cdot 3 \cdot 1} = \frac{16}{5!}.
\]

Remark 8.21. The complements of type \(D\) excited diagrams of the shape \(\nabla_{n+1}/\nabla_n\) are just the Dyck paths in \(\text{Dyck}(n)\), thus \(|E^D(\nabla_{n+1}/\nabla_n)| = C_n\). In addition, one can see that \(8.8\) for \(\nabla_{n+1}/\nabla_n\) is just \((EC)\). It would be of interest to find a formula for \(|E^D(\nabla_{n+k}/\nabla_n)|\) analogous to \(8.9\).

8.6. \(q\)-analogue of Euler numbers via SSYT. We use our first \(q\)-analogue of NHLF (Theorem 1.3) to obtain identities for \(s_{\delta_{n+2k}/\delta_n}(1,q,q^2,\ldots)\) in terms of Dyck paths.

Proof of Corollary 1.7. By Theorem 1.3 for the skew shape \(\delta_{n+2}/\delta_n\) and \(8.2\) we have

\[ (8.10) \]

Suppose \(D\) in \(E(\delta_{n+2}/\delta_n)\) corresponds to the Dyck path \(p\) and cell \((i,j)\) in \(D\) corresponds to point \((a,b)\) in \(p\) then \(h(i,j) = 2b+1\) and \(\lambda_j' - i = b\). Using this correspondence, the LHS of \(8.10\) becomes the LHS of the desired expression.

Corollary 8.22.

\[
\sum_{(p_1,\ldots, p_k) \in \text{Dyck}(n)^k} \prod_{r=1}^{k} \prod_{(a,b) \in p_r} \frac{q^{k+2r-2}}{1 - q^{2b+4r-3}} = \left( \prod_{r=1}^{k-1} [4r - 1]!! \right)^2 \det \left[ \frac{E_{2(n+i+j)-3}(q)}{i,j=1} \right]^{k}
\]

where \(E_n(q) := E_n(q)/(1-q)(1-q^2)\cdots(1-q^n)\) and \([2m-1]!! := (1-q)(1-q^3)\cdots(1-q^{2m-1})\).
Proof. For the LHS, use Corollary 8.8 to express \( s_{\delta_n+2k/\delta_n}(1,q,q^2,\ldots) \) in terms of \( q \)-Euler polynomials \( \tilde{E}_m(q) \). For the RHS, first use Theorem 1.3 for the skew shape \( \delta_n+2k/\delta_n \) and then follow the same argument as that of Corollary 8.12. \( \square \)

Remark 8.23. Combinatorial proofs of Corollary 1.6 and Corollary 1.7 are obtained from the proof in Section 5 of (NHLF). Similarly, combinatorial proofs of Corollary 8.12 and Corollary 8.22 are obtained from the proof in Section 5 of (NHLF) and the first \( q \)-NHLF for all shapes, or from Konvalinka’s bijective proof of (NHLF) in [Kon] and the first \( q \)-NHLF for border strips.\(^2\)

9. Pleasant diagrams and RPP of border strips and thick strips

In this section we study pleasant diagrams in \( P(\delta_n+2/\delta_n) \) and our second \( q \)-analogue of NHLF (Theorem 1.4) for RPP of shape \( \delta_n+2/\delta_n \). Recall that \( p(\lambda/\mu) \) denotes the number of pleasant diagrams of shape \( \lambda/\mu \).

9.1. Pleasant diagrams and Schröder numbers. Let \( s_n \) be the \( n \)-th Schröder number [OEIS, A001003] which counts lattice paths from \((0,0)\) to \((2n,0)\) with steps \((1,1), (1,-1), \) and \((2,0)\) that never go below the \( x \)-axis and no steps \((2,0)\) on the \( x \)-axis.

**Theorem 9.1.** We have: \( p(\delta_n+2/\delta_n) = 2^{n+2}s_n \), for all \( n \geq 1 \).

![Figure 10. Each Dyck path \( p \) of size \( n \) with \( m \) excited peaks (denoted in gray) yields \( 2^{2n-m+2} \) pleasant diagrams. For \( n = 3 \), we have \( C_5 = 5 \) and \( s_3 = 11 \). Thus, there are \( |E(\delta_3+2/\delta_3)| = C_3 = 5 \) excited diagrams and \( p(\delta_3+2/\delta_3) = 2^5s_3 = 352 \) pleasant diagrams.](image)

The proof is based on the following corollary which is in turn a direct application of Theorem 4.4. A high peak of a Dyck path \( p \) is a peak of height strictly greater than one. We denote by \( \mathcal{H}P(p) \) the set of high peaks of \( p \), and by \( N\mathcal{P}(p) \) the points of the path that are not high peaks. We use \( 2^S \) denote the set of subsets of \( S \).

**Corollary 9.2.** The pleasant diagrams in \( P(\delta_n+2/\delta_n) \) are in bijection with

\[
\bigcup_{p \in \text{Dyck}(n)} \left( \mathcal{H}P(p) \times 2^{N\mathcal{P}(p)} \right).
\]

**Proof.** By Corollary 8.4 for the zigzag strip \( \delta_n+2/\delta_n \), \( N\mathcal{I}(\delta_n+2/\delta_n) \) is the set of Dyck paths \( \text{Dyck}(n) \). Then by Theorem 4.4 we have:

\[
\mathcal{P}(\delta_n+2/\delta_n) = \bigcup_{p \in \text{Dyck}(n)} \left( \Lambda(p) \times 2^{p \setminus \Lambda(p)} \right).
\]

Lastly, note that the excited peaks of a Dyck path are exactly the high peaks so \( \Lambda(p) = \mathcal{H}P(p) \) and \( p \setminus \Lambda(p) = N\mathcal{P}(p) \). \( \square \)

\(^2\)Jang Soo Kim has a direct proof of Corollary 1.7 using continued fractions and orthogonal polynomials (private communication).
**Proof of Theorem 9.1.** It is known (see [Den]), that the number of Dyck paths of size $n$ with $k-1$ high peaks equals the Narayana number $N(n, k) = \frac{1}{n} \binom{n}{k} \binom{n-1}{k-1}$. On the other hand, Schröder numbers $s_n$ can be written as

$$s_n = \sum_{k=1}^{n} N(n, k) 2^{k-1}$$

(see e.g. [Sul]). By Lemma 9.2 we have:

$$p(\delta_{n+2}/\delta_n) = \sum_{p \in \text{Dyck}(n)} 2^{\text{maj}(p)}.$$  

Suppose Dyck path $\gamma$ has $k-1$ peaks, $1 \leq k \leq n$. Then $|\mathcal{P}(\gamma)| = 2n + 1 - (k-1)$. Therefore, equation (9.2) becomes

$$p(\delta_{n+2}/\delta_n) = 2^{n+2} \sum_{k=1}^{n} N(n, k) 2^{n-k} = 2^{n+2} \sum_{k=1}^{n} N(n, n-k+1) 2^{n-k} = 2^{n+2} s_n,$$

where we use the symmetry $N(n, k) = N(n, n-k+1)$ and (9.1). \qed

In the same way as $|\mathcal{E}(\delta_{n+2k}/\delta_n)|$ is given by a determinant of Catalan numbers, preliminary computations suggest that $p(\delta_{n+2k}/\delta_n)$ is given by a determinant of Schröder numbers.

**Conjecture 9.3.** We have: $p(\delta_{n+4}/\delta_n) = 2^{2n+5} (s_n s_{n+2} - s_{n+1}^2)$. More generally, for all $k \geq 1$, we have:

$$p(\delta_{n+2k}/\delta_n) = 2^{(2k)} \det[s_{n-2i+j}]_{i,j=1}^{k}, \quad \text{where} \quad s_n = 2^{n+2} s_n.$$

Here we use $s_n = p(\delta_{n+2}/\delta_n)$ in place of $s_n$ in the determinant to make the formula more elegant. In fact, the power of 2 can be factored out.

**Remark 9.4.** This conjecture is somewhat unexpected since unlike the number of excited diagrams, there is no known Lascoux–Pragacz-type identity for the number of pleasant diagrams (see Section 4.2).

### 9.2. $q$-analogue of Euler numbers via RPP.

We use our second $q$-analogue of the NHLF (Theorem 1.1) and Lemma 9.2 to obtain identities for the generating function of RPP of shape $\delta_{n+2}/\delta_n$ in terms of Dyck paths. Recall the definition of $E^*_n(q)$ from the introduction:

$$E^*_n(q) = \sum_{\sigma \in \text{Alt}(n)} q^{\text{maj}(\sigma^{-1} \kappa)},$$

where $\kappa = (13254\ldots)$. Note that $\text{maj}(\sigma^{-1} \kappa)$ is the sum of the descents of $\sigma \in S_n$ not involving both $2i+1$ and $2i$.

**Example 9.5.** To complement Example 8.6, we have: $E^*_1(q) = E^*_2(q) = 1$, $E^*_3(q) = q + 1$, $E^*_4(q) = q^4 + q^3 + q^2 + q + 1$, and $E^*_5(q) = q^7 + 2q^6 + 2q^5 + 3q^4 + 3q^3 + 2q^2 + 2q + 1$.

**Proof of Corollary 1.8.** By the theory of $P$-partitions, the generating series of RPP of shape $\delta_{n+2}/\delta_n$ equals

$$\sum_{\pi \in \text{RPP}(\delta_{n+2}/\delta_n)} q^{\text{maj}(\pi)} = \frac{\sum_{u \in \mathcal{L}(P_{\delta_{n+2}/\delta_n})} q^{\text{maj}(u)}}{(1-q)(1-q^2)\cdots(1-q^{2n+1})},$$

where the sum in the numerator is over linear extensions $\mathcal{L}(P_{\delta_{n+2}/\delta_n})$ of the zigzag poset $P_{\delta_{n+2}/\delta_n}$ with the order preserving labeling:

```
1 3 2 0 4 ... 2m + 1 2m
```
These linear extensions are in bijection with alternating permutations of size $2n + 1$ and

$$E^*_n(q) = \sum_{\sigma \in \text{Alt}_{2n+1}} q^{\text{maj}^{-1} \kappa} = \sum_{u \in \mathcal{E}(P_{2n+2}/s_n)} q^{\text{maj}(u)}.$$  

Thus

$$\sum_{\pi \in \text{RPP}(\delta_{n+2}/\delta_n)} q^{\pi} = \frac{E^*_{2n+1}(q)}{(1-q)(1-q^2) \cdots (1-q^{2n+1})}. \tag{9.3}$$

By Theorem 4.4 (see also [MPP1, S6.4]) for the skew shape $\delta_{n+2}/\delta_n$ and (9.3), we have:

$$\sum_{D \in \mathcal{E}(\delta_{n+2}/\delta_n)} q^{a'(D)} \prod_{u \in \Lambda(D)} \frac{1}{1-q^{h(u)}} = \frac{E^*_{2n+1}(q)}{(1-q)(1-q^2) \cdots (1-q^{2n+1})}, \tag{9.4}$$

where $a'(D) = \sum_{u \in \Lambda(D)} h(u)$. By the proof of Lemma 9.2 if $D \in \mathcal{E}(\delta_{n+2}/\delta_n)$ corresponds to the Dyck path $p$ then excited peaks $u \in \Lambda(D)$ correspond to high peaks $(c, d) \in \mathcal{H}(p)$ and $h(u) = 2d + 1$. Using this correspondence, the LHS of (9.4) becomes the LHS of the desired expression. \qed

Finally, preliminary computations suggest the following analogue of Corollary 8.8

**Conjecture 9.6.** We have:

$$\sum_{\pi \in \text{RPP}(\delta_{n+2}/\delta_n)} q^{\pi} = q^{-N} \det \left[ \tilde{E}^*_k(q) \right]_{i,j=1}^k,$$

where $N = k(k-1)(6n+8k-1)/6$ and $\tilde{E}^*_k(q) = E^*_k(q)/(1-q) \cdots (1-q^k)$.

### 10. Final remarks

10.1. Other known formulas for $f^\lambda/\mu$ are the Jacobi–Trudi identity, the Littlewood–Richardson rule, and the Okounkov–Olshanski formula [OO]. We discuss these and other less-known formulas for $f^\lambda/\mu$ coming from equivariant Schubert structure constants in [MPP1, §9].

The Jacobi–Trudi identity is one of the first nontrivial formulas to count $f^\lambda/\mu$. In this paper we have unveiled a strong relation between the Lascoux–Pragacz identity for Schur functions and the NHLF for $f^\lambda/\mu$. As mentioned in Section 7.5, Hamel and Goulden [HaG] unified these two identities into an exponential family of determinantal identities of Schur functions. Chen–Yan–Yang [CYY] gave a method to transform among these identities. It would be of interest if other formulas for $f^\lambda/\mu$, like the ones mentioned above, are related to special cases of Hamel–Goulden identities.

10.2. In [Kon], Konvalinka gives a new proof of the NHLF. Specifically, he presents a bumping algorithm on bicolored flagged tableaux of shape $\mu$ to prove the Pieri–Chevalley formula for general skew shapes (see [IN, §8.4] and [MPP2]). For the border strips this approach is different from our proof of Lemma 6.1. In fact, our proof uses the underlying single path in the excited diagrams of a border strip to perform cancelations. While Konvalinka’s proof is substraction-free, it involves an insertion on the inner partition $\mu$ that could be arbitrary even for a border strip.

It is worth noting that both proofs of Lemma 5.1 are quite technical. Initially, this came as a surprise to us, and our effort to understand the underlying multivariate algebraic identities led to [MPP2]. Let us also mention that in [IN], the authors use the Pieri–Chevalley formula for Billey’s $[B1]$ Kostant polynomials to prove the analogue of Lemma 6.1 for all skew shapes.
10.3. There is a very large literature on alternating permutations, Euler numbers, Dyck paths, Catalan and Schröder numbers, which are some of the classical combinatorial objects and sequences. We refer to [SS] for the survey on the first two, to [S5] for a thorough treatment of the last three, and to [GJ, OEIS, S4] for various generalizations, background and further references.

Finally, the first \( q \)-analogue \( E_n(q) \) of Euler numbers we consider is standard in the literature and satisfies a number of natural properties, including a \( q \)-version of equation (1.1) (see e.g. [GJ, §4.2]). However, the second \( q \)-analogue \( E^*_n(q) \) appears to be new. It would be interesting to see how it fits with the existing literature of multivariate Euler polynomials and statistics on alternating permutations.

10.4. The curious Catalan determinant in Corollary 8.3 appeared in the first arXiv version of [MPP1]. However, the proof here is more self contained as a direct application of Theorem 3.4. This Catalan determinant is both similar and related\(^3\) to another Catalan determinant in [AL, proof of Lemma 1.1]. In fact, both determinants are special cases of more general counting results, and both can be proved by the Lindström–Gessel–Viennot lemma.

10.5. The connection between alternating permutations and symmetric functions of border strips goes back to Foulkes [Fou], and has been repeatedly generalized and explored ever since (see [SS]). It is perhaps surprising that Corollary 1.4 is so simple, since the other two positive formulas in Section 10.1 become quite involved. For the LR-coefficients, let partition \( \nu \vdash 2n+1 \) be such that \( \nu_1, \ell(\nu) \leq n+1 \). It is easy to see that in this case the corresponding LR-coefficient is nonzero:\( c_{\delta,\nu}^{\delta,\nu} > 0 \), suggesting that summation over all such \( \nu \) would be hard to compute.

10.6. The proof in [MPP1] of the skew RPP \( q \)-analogue of Naruse (Theorem 1.4) is already bijective using the Hillman–Grassl correspondence. It would be interesting to see if for RPP the case for border strips implies the case for all connected skew shapes. Note that we do not know of a Lascoux–Pragacz analogue of [5,7] for skew RPP. Relatedly, we also do not know of such an analogue for the number of pleasant diagrams (the supports of arrays obtained from Hillman–Grassl applied to skew RPP) as discussed in Section 4.2. On the other hand, Conjectures 9.6 and 9.3 suggest that there might be such formulas in some cases.

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