Catalanimals, shuffle theorems, and Macdonald polynomials

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SMRI: Modern Perspectives in Representation Theory

22 May 2025

Overview

Algebraic quantity $=$ Combinatorial generating function

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Representation theory

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$$\begin{tikzcd}
\text{Closed form expression} \arrow[d] & = & \text{Infinite symmetric series} \arrow[d] \\
\text{Algebraic quantity} & = & \text{Combinatorial generating function} \\
\text{Representation theory} \arrow[u, dashed] & &
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Outline

1. **Background on symmetric functions and Macdonald polynomials**
2. Shuffle theorems, combinatorics, and LLT polynomials
3. A new formula for Macdonald polynomials

Symmetric polynomials and functions

- Symmetric polynomials $\mathbb{Q}[z_1, \ldots, z_n]^{S_n}$
- Generators

$$e_r(z_1, \ldots, z_n) = \sum_{1 \le i_1 < i_2 < \cdots < i_r \le n} z_{i_1} \cdots z_{i_r}$$

$$\begin{aligned}
e_1(z_1, z_2, z_3) &= z_1 + z_2 + z_3 \\
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- $\Lambda = \mathbb{Q}[e_1, e_2, \ldots]$
- Degree d elements of Λ = $\mathbb{Q}$-vector space of dimension...?
- Integer partitions of d.

Partitions

Definition

$n \in \mathbb{Z}_{>0}$, a *partition of n* is $\lambda = (\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_\ell > 0)$ such that $\lambda_1 + \lambda_2 + \cdots + \lambda_\ell = n$.

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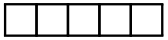
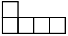
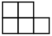
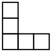
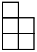
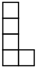
$5 \to$ 

$4 + 1 \to$ 

$3 + 2 \to$ 

$3 + 1 + 1 \to$ 

$2 + 2 + 1 \to$ 

$2 + 1 + 1 + 1 \to$ 

$1 + 1 + 1 + 1 + 1 \to$ 

Young Tableaux

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Filling of partition diagram of λ with numbers such that

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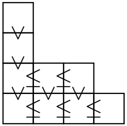

For $\lambda = (2, 1)$,

$$\begin{array}{|c|c} \hline 2 & \multicolumn{1}{c}{} \\ \hline 1 & \multicolumn{1}{c|}{1} \\ \hline \end{array}, \quad \begin{array}{|c|c} \hline 3 & \multicolumn{1}{c}{} \\ \hline 1 & \multicolumn{1}{c|}{1} \\ \hline \end{array}, \quad \begin{array}{|c|c} \hline 3 & \multicolumn{1}{c}{} \\ \hline 2 & \multicolumn{1}{c|}{2} \\ \hline \end{array}, \quad \begin{array}{|c|c} \hline 2 & \multicolumn{1}{c}{} \\ \hline 1 & \multicolumn{1}{c|}{2} \\ \hline \end{array}, \quad \begin{array}{|c|c} \hline 3 & \multicolumn{1}{c}{} \\ \hline 1 & \multicolumn{1}{c|}{3} \\ \hline \end{array}, \quad \begin{array}{|c|c} \hline 3 & \multicolumn{1}{c}{} \\ \hline 2 & \multicolumn{1}{c|}{3} \\ \hline \end{array}, \quad \begin{array}{|c|c} \hline 2 & \multicolumn{1}{c}{} \\ \hline 1 & \multicolumn{1}{c|}{3} \\ \hline \end{array}, \quad \begin{array}{|c|c} \hline 3 & \multicolumn{1}{c}{} \\ \hline 1 & \multicolumn{1}{c|}{2} \\ \hline \end{array}$$

Polynomials from tableaux

Associate a polynomial to SSYT(λ).

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$$\begin{array}{|c|c|}\cline{1-1} 2 & \multicolumn{1}{c}{} \\ \hline 1 & 1 \\ \hline\end{array},\ \begin{array}{|c|c|}\cline{1-1} 3 & \multicolumn{1}{c}{} \\ \hline 1 & 1 \\ \hline\end{array},\ \begin{array}{|c|c|}\cline{1-1} 3 & \multicolumn{1}{c}{} \\ \hline 2 & 2 \\ \hline\end{array},\ \begin{array}{|c|c|}\cline{1-1} 2 & \multicolumn{1}{c}{} \\ \hline 1 & 2 \\ \hline\end{array},\ \begin{array}{|c|c|}\cline{1-1} 3 & \multicolumn{1}{c}{} \\ \hline 1 & 3 \\ \hline\end{array},\ \begin{array}{|c|c|}\cline{1-1} 3 & \multicolumn{1}{c}{} \\ \hline 2 & 3 \\ \hline\end{array},\ \begin{array}{|c|c|}\cline{1-1} 2 & \multicolumn{1}{c}{} \\ \hline 1 & 3 \\ \hline\end{array},\ \begin{array}{|c|c|}\cline{1-1} 3 & \multicolumn{1}{c}{} \\ \hline 1 & 2 \\ \hline\end{array}$$

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- $\mathrm{Frob}(\mathrm{Ind}_{S_1 \times S_1 \times S_1}^{S_3}(\mathbb{C} \times \mathbb{C} \times \mathbb{C})) = (s_{\ydiagram{1}})^3 = s_{\ydiagram{3}} + 2s_{\ydiagram{2,1}} + s_{\ydiagram{1,1,1}}$

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Irreducible representations of S_n are **also** labeled by partitions of n.

$$V_{\ydiagram{3}} = \text{trivial},\ V_{\ydiagram{1,2}} \cong \text{span}\{e_1 - e_2, e_2 - e_3\},\ V_{\ydiagram{1,1,1}} = \text{sign}$$

Frobenius charactersitc, $\mathrm{Frob}\colon Rep(S_n) \to \Lambda$, such that

- Irreducible S_n-representation V_λ has $\mathrm{Frob}(V_\lambda) = s_\lambda$
- $U \cong V \oplus W \implies \mathrm{Frob}(U) = \mathrm{Frob}(V) + \mathrm{Frob}(W)$
- $\mathrm{Ind}_{S_m \times S_n}^{S_{m+n}}(V \times W) \mapsto \mathrm{Frob}(V) \cdot \mathrm{Frob}(W)$
- $\mathrm{Frob}(\mathrm{Ind}_{S_1 \times S_1 \times S_1}^{S_3}(\mathbb{C} \times \mathbb{C} \times \mathbb{C})) = (s_{\ydiagram{1}})^3 = s_{\ydiagram{3}} + 2s_{\ydiagram{1,2}} + s_{\ydiagram{1,1,1}}$

Hidden Guide: Schur Positivity

"Naturally occurring" symmetric functions which are non-negative (coefficients in $\mathbb{N}$) linear combinations in Schur polynomial basis are interesting since they could have representation-theoretic models.

A Graded Example

$$\Delta = \det \begin{vmatrix} x_1^2 & x_1 & 1 \\ x_2^2 & x_2 & 1 \\ x_3^2 & x_3 & 1 \end{vmatrix} = x_1^2(x_2 - x_3) - x_2^2(x_1 - x_3) + x_3^2(x_1 - x_2)$$

$S_3 \curvearrowright \mathrm{span}\{\Delta\}$ via $\sigma.\Delta = \mathrm{sgn}(\sigma)\Delta$.

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$S_3 \curvearrowright \text{span}\{\Delta\}$ via $\sigma.\Delta = \mathrm{sgn}(\sigma)\Delta$.
Consider $S_3 \curvearrowright M =$ all partial derivatives of Δ.

$$\begin{array}{c} \text{span}\{\Delta\} \\ \Big\downarrow{\scriptstyle \partial_{x_i}} \\ \text{span}\{2x_1(x_2 - x_3) - x_2^2 + x_3^2, 2x_2(x_3 - x_1) - x_3^2 + x_1^2\} \\ \Big\downarrow{\scriptstyle \partial_{x_i}} \\ \text{span}\{x_3 - x_1, x_2 - x_3\} \\ \Big\downarrow{\scriptstyle \partial_{x_i}} \\ \text{span}\{1\} \end{array}$$

A Graded Example

$$
\begin{array}{cr}
\mathrm{span}\{\Delta\} & \cong V_{\ydiagram{1,1,1}} \\
\Big\downarrow \partial_{x_i} & \\
\mathrm{span}\{2x_1(x_2 - x_3) - x_2^2 + x_3^2, 2x_2(x_3 - x_1) - x_3^2 + x_1^2\} & \cong V_{\ydiagram{1,2}} \\
\Big\downarrow \partial_{x_i} & \\
\mathrm{span}\{x_3 - x_1, x_2 - x_3\} & \cong V_{\ydiagram{1,2}} \\
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\end{array}
$$

A Graded Example

$$
\begin{tikzcd}[row sep=large]
\operatorname{span}\{\Delta\} \arrow[d, "\partial_{x_i}"] & \cong V_{\yng(1,1,1)} \\
\operatorname{span}\{2x_1(x_2 - x_3) - x_2^2 + x_3^2, 2x_2(x_3 - x_1) - x_3^2 + x_1^2\} \arrow[d, "\partial_{x_i}"] & \cong V_{\yng(2,1)} \\
\operatorname{span}\{x_3 - x_1, x_2 - x_3\} \arrow[d, "\partial_{x_i}"] & \cong V_{\yng(2,1)} \\
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$$

- $\operatorname{Frob}(M) = s_{\ydiagram{1,1,1}} + 2s_{\ydiagram{1,2}} + s_{\ydiagram{3}}$
- Problem: what about grading?

Getting More Information

$$
\begin{array}{ccc}
\operatorname{span}\{\Delta\} & \cong V_{\ydiagram{1,1,1}} & \deg = 3 \\
\big\downarrow \partial_{x_i} & & \\
\operatorname{span}\{2x_1(x_2 - x_3) - x_2^2 + x_3^2, 2x_2(x_3 - x_1) - x_3^2 + x_1^2\} & \cong V_{\ydiagram{2,1}} & \deg = 2 \\
\big\downarrow \partial_{x_i} & & \\
\operatorname{span}\{x_3 - x_1, x_2 - x_3\} & \cong V_{\ydiagram{2,1}} & \deg = 1 \\
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$$

Getting More Information

$$\begin{array}{ccc}
\mathrm{span}\{\Delta\} & \cong V_{(1,1,1)} & \deg = 3 \\
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\mathrm{span}\{2x_1(x_2 - x_3) - x_2^2 + x_3^2, 2x_2(x_3 - x_1) - x_3^2 + x_1^2\} & \cong V_{(2,1)} & \deg = 2 \\
\big\downarrow \partial_{x_i} & & \\
\mathrm{span}\{x_3 - x_1, x_2 - x_3\} & \cong V_{(2,1)} & \deg = 1 \\
\big\downarrow \partial_{x_i} & & \\
\mathrm{span}\{1\} & \cong V_{(3)} & \deg = 0
\end{array}$$

- $(V_\lambda \text{ in degree } d) \mapsto q^d s_\lambda$

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- Hall-Littlewood polynomial $H_{\ydiagram{1,1,1}}(X; q)$.
- Remark: $M \cong \mathbb{Z}[x_1, x_2, x_3]/\mathrm{Sym}^+ \cong H^*(Fl_3)$ as **graded** S_3-representations.

A Problem

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- $\tilde{H}_\lambda(X;1,1) = s_1^{|\lambda|}$.
- Does there exist a family of S_n-regular representations whose bigraded Frobenius characteristics equal $\tilde{H}_\lambda(X;q,t)$?

Garsia-Haiman modules

- $S_n \curvearrowright \mathbb{Q}[x_1, \ldots, x_n, y_1, \ldots, y_n]$ with $\sigma(x_i) = x_{\sigma(i)}$, $\sigma(y_j) = y_{\sigma(j)}$.

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$$\Delta_{\begin{smallmatrix}\square & \\ \square & \square\end{smallmatrix}} = \det \begin{vmatrix} 1 & y_1 & x_1 \\ 1 & y_2 & x_2 \\ 1 & y_3 & x_3 \end{vmatrix} = x_3 y_2 - y_3 x_2 - y_1 x_3 + y_1 x_2 + y_3 x_1 - y_2 x_1$$

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$$M_{2,1} =$$

$$\underbrace{\mathrm{span}\{\Delta_{2,1}\}}_{\deg=(1,1)} \oplus \underbrace{\mathrm{span}\{y_3 - y_1, y_1 - y_2\}}_{\deg=(0,1)} \oplus \underbrace{\mathrm{span}\{x_3 - x_1, x_1 - x_2\}}_{\deg=(1,0)} \oplus \underbrace{\mathrm{span}\{1\}}_{\deg=(0,0)}$$

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Garsia-Haiman modules

Theorem (Haiman, 2001)

The Garsia-Haiman module M_λ has bigraded Frobenius characteristic given by $\tilde{H}_\lambda(X; q, t)$

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Corollary

$\tilde{H}_\lambda(X; q, t) = \sum_\mu \tilde{K}_{\lambda\mu}(q, t) s_\mu$ *satisfies* $\tilde{K}_{\lambda\mu}(q, t) \in \mathbb{N}[q, t]$.

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- No combinatorial description of $\tilde{K}_{\lambda\mu}(q,t)$.

Symmetric functions, representation theory, and combinatorics

Symmetric function	Representation theory	Combinatorics
s_λ	Irreducible V_λ	$\mathrm{SSYT}(\lambda)$
$\tilde{H}_\lambda(X; q, t)$	Garsia-Haiman M_λ	Later

Garsia-Haiman modules

Observation

All of these Garsia-Haiman modules are contained in the module of diagonal harmonics:

$$DH_n = \text{span}\{f \in \mathbb{C}[x_1, \ldots, x_n, y_1, \ldots, y_n] \mid \left(\sum_{j=1}^{n} \partial_{x_j}^r \partial_{y_j}^s\right) f = 0, \forall r+s > 0\}$$

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Question

What symmetric function is the bigraded Frobenius characteristic of DH_n?

∇e_n

Frobenius characteristic of DH_3

∇e_n

Frobenius characteristic of DH_3

$$= \frac{t^3\tilde{H}_{1,1,1}}{-qt^2+t^3+q^2-qt} - \frac{(q^2t+qt^2+qt)\tilde{H}_{2,1}}{-q^2t^2+q^3+t^3-qt} - \frac{q^3\tilde{H}_3}{-q^3+q^2t+qt-t^2}$$

∇e_n

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Compare to

$$e_3 = \frac{\tilde{H}_{1,1,1}}{-qt^2+t^3+q^2-qt} - \frac{(q+t+1)\tilde{H}_{2,1}}{-q^2t^2+q^3+t^3-qt} - \frac{\tilde{H}_3}{-q^3+q^2t+qt-t^2}$$

∇e_n

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Operator ∇

$$\nabla \tilde{H}_\lambda(X;q,t) = q^{n(\lambda)} t^{n(\lambda^*)} \tilde{H}_\lambda(X;q,t)\,,$$

where $n(\lambda) = \sum_i (i-1)\lambda_i$ and λ^* is the transpose partition to λ.

∇e_n

Frobenius characteristic of DH_3

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Theorem (Haiman, 2002)

The bigraded Frobenius characteristic of DH_n is given by ∇e_n.

Symmetric functions, representation theory, and combinatorics

Symmetric function	Representation theory	Combinatorics
s_λ	Irreducible V_λ	$\mathrm{SSYT}(\lambda)$
$\tilde{H}_\lambda(X; q, t)$	Garsia-Haiman M_λ	Later
∇e_n	DH_n	Now: Shuffle theorem

Outline

1. Background on symmetric functions and Macdonald polynomials
2. **Shuffle theorems, combinatorics, and LLT polynomials**
3. A new formula for Macdonald polynomials

A Combinatorial Connection: Shuffle Theorem

Theorem (Carlsson-Mellit, 2018)

$$\nabla e_k = \sum_{\lambda} (q, t \ \mathit{monomial})(\mathit{LLT\ polynomial})$$

- Summation over all k-by-k Dyck paths.

A Combinatorial Connection: Shuffle Theorem

Theorem (Carlsson-Mellit, 2018)

$$\nabla e_k = \sum_{\lambda} t^{\mathrm{area}(\lambda)} q^{\mathrm{dinv}(\lambda)} (\mathit{LLT\ polynomial})$$

- Summation over all k-by-k Dyck paths.
- $\mathrm{area}(\lambda)$ and $\mathrm{dinv}(\lambda)$ statistics of Dyck paths.

A Combinatorial Connection: Shuffle Theorem

Theorem (Carlsson-Mellit, 2018)

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- ω a standard involution of symmetric polynomials.

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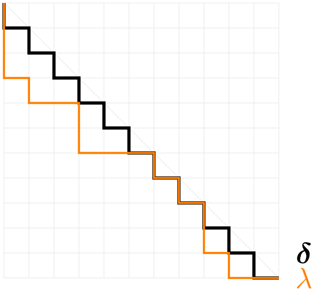
- $\mathrm{area}(\lambda)$ and $\mathrm{dinv}(\lambda)$ statistics of Dyck paths.
- $\mathcal{G}_{\nu(\lambda)}(X; q)$ a symmetric LLT polynomial indexed by a tuple of offset (skew) rows.
- ω a standard involution of symmetric polynomials.
- Conjectured by (Haiman-Haglund-Loehr-Remmel-Ulyanov, 2002).

Dyck paths

Dyck paths

A Dyck path λ is a south-east lattice path lying below the line segment from $(0, k)$ to $(k, 0)$.



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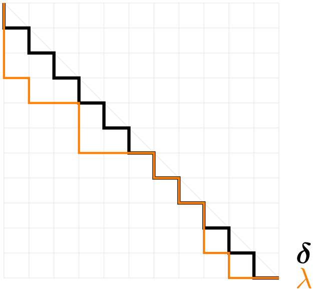

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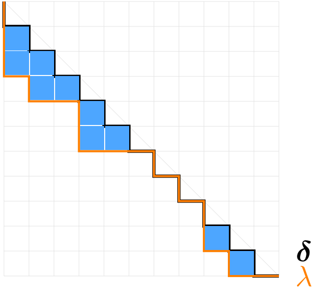

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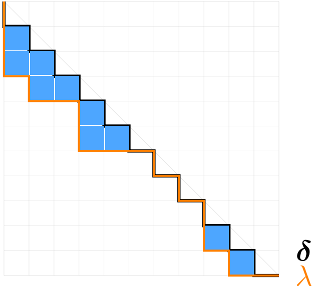

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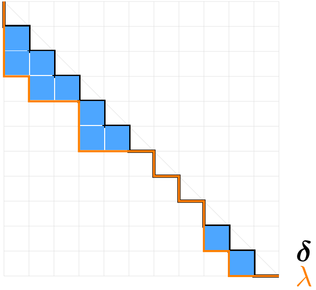

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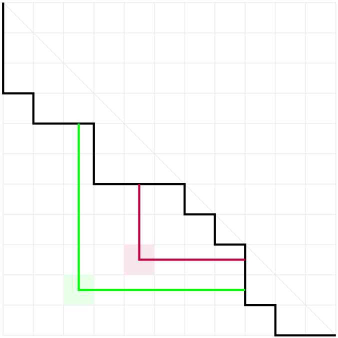
dinv

dinv(λ) $=\#$ of balanced hooks in diagram below λ.



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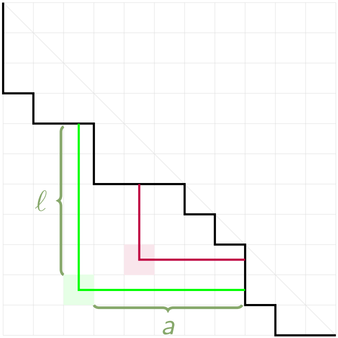

Balanced hook is given by a cell below λ satisfying

$$\frac{\ell}{a+1} < 1 - \epsilon < \frac{\ell + 1}{a}, \quad \epsilon \text{ small.}$$

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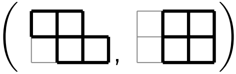
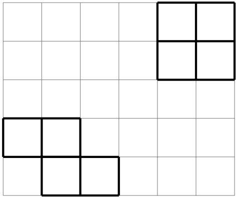
$\boldsymbol{\nu} =$ 



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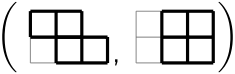
$\boldsymbol{\nu} =$ 

-4	-3	-2	-1	0	1
-3	-2	-1	0	1	2
-2	-1	0	1	2	3
-1	0	1	2	3	4
0	1	2	3	4	5

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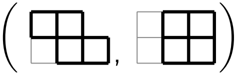
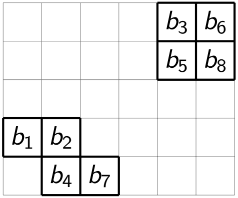
$\boldsymbol{\nu} =$ 



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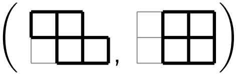
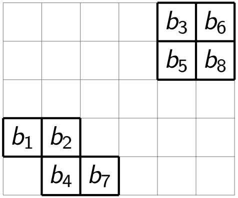
$\boldsymbol{\nu} =$ 



Attacking pairs: $(b_2, b_3), (b_3, b_4), (b_4, b_5), (b_4, b_6), (b_5, b_7), (b_6, b_7), (b_7, b_8)$

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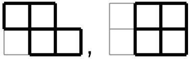
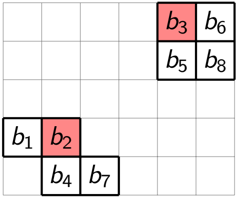
$\boldsymbol{\nu} = \Big($  $\Big)$



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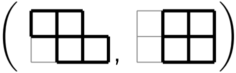
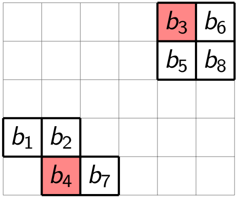
$\boldsymbol{\nu} =$ 



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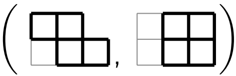
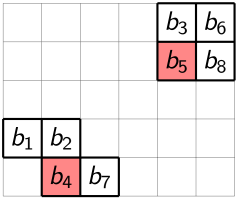
$\boldsymbol{\nu} =$ 



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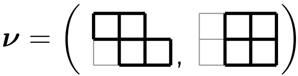

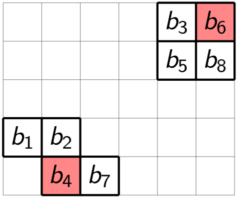

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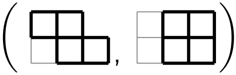
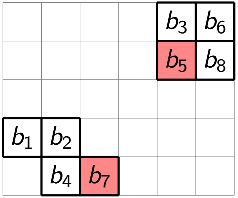
$\boldsymbol{\nu} =$ 



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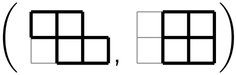
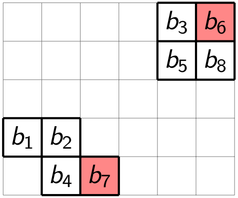
$\boldsymbol{\nu} =$ 



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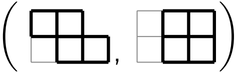
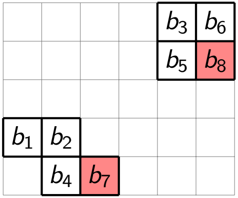
$\boldsymbol{\nu} =$ 



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LLT Polynomials

- A *semistandard tableau* on $\boldsymbol{\nu}$ is a map $T\colon \boldsymbol{\nu} \to \mathbb{Z}_+$ which restricts to a semistandard tableau on each $\nu_{(i)}$.

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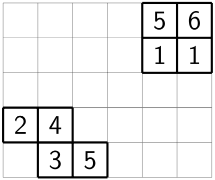
$$\mathcal{G}_{\boldsymbol{\nu}}(\boldsymbol{z};q) = \sum_{T \in \mathrm{SSYT}(\boldsymbol{\nu})} \boldsymbol{z}^T,$$

$\boldsymbol{z}^T = \prod_{a \in \boldsymbol{\nu}} z_{T(a)}$.

$T \quad =$



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$$T \quad = \quad \begin{array}{|c|c|c|c|c|c|} \hline & & & & 5 & 6 \\ \hline & & & & 1 & 1 \\ \hline & & & & & \\ \hline 2 & 4 & & & & \\ \hline & 3 & 5 & & & \\ \hline \end{array}$$

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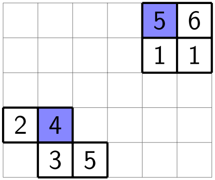

non-inversion

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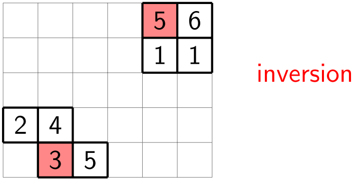

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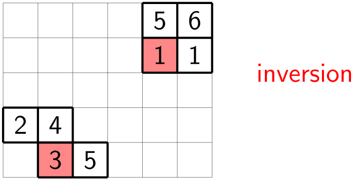

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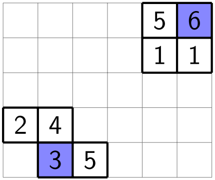

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- A *semistandard tableau* on $\boldsymbol{\nu}$ is a map $T\colon \boldsymbol{\nu} \to \mathbb{Z}_+$ which restricts to a semistandard tableau on each $\nu_{(i)}$.
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$$\mathcal{G}_{\boldsymbol{\nu}}(\boldsymbol{z}; q) = \sum_{T \in \mathrm{SSYT}(\boldsymbol{\nu})} q^{\mathrm{inv}(T)} \boldsymbol{z}^T,$$

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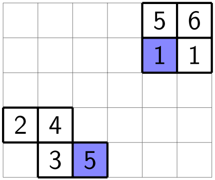

non-inversion

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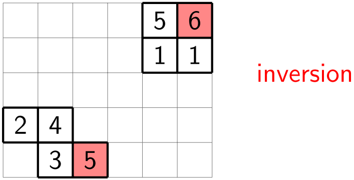

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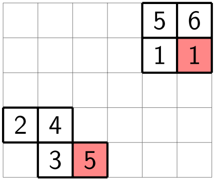

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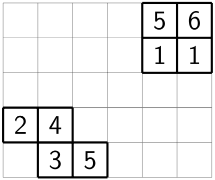

$$\mathrm{inv}(T) = 4, \quad \boldsymbol{z}^T = z_1^2 z_2 z_3 z_4 z_5^2 z_6$$

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- $\mathcal{G}_{\boldsymbol{\nu}}$ is Schur-positive for any tuple of skew shapes $\boldsymbol{\nu}$ [Grojnowski-Haiman, 2007].

Example ∇e_3

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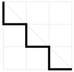		
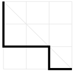		
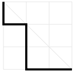		
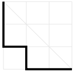		
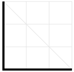		

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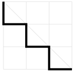
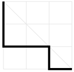
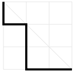
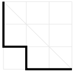
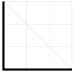
	q^3	
	$q^2 t$	
	qt	
	qt^2	
	t^3	

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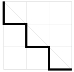
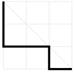
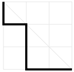
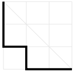
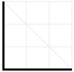
	q^3	$s_3 + q s_{2,1} + q^2 s_{2,1} + q^3 s_{1,1,1}$
	$q^2 t$	$q t s_{2,1} + q^2 t s_{1,1,1}$
	qt	$t s_{2,1} + q t s_{1,1,1}$
	qt^2	$t^2 s_{2,1} + q t^2 s_{1,1,1}$
	t^3	$t^3 s_{1,1,1}$

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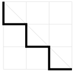
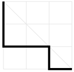
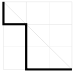
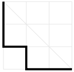
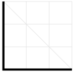
	q^3	$s_3 + qs_{2,1} + q^2 s_{2,1} + q^3 s_{1,1,1}$
	$q^2 t$	$qts_{2,1} + q^2 ts_{1,1,1}$
	qt	$ts_{2,1} + qts_{1,1,1}$
	qt^2	$t^2 s_{2,1} + qt^2 s_{1,1,1}$
	t^3	$t^3 s_{1,1,1}$

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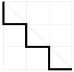
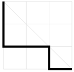
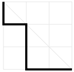
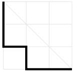
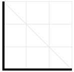
	q^3	$s_3 + qs_{2,1} + q^2 s_{2,1} + q^3 s_{1,1,1}$
	$q^2 t$	$qts_{2,1} + q^2 ts_{1,1,1}$
	qt	$ts_{2,1} + qts_{1,1,1}$
	qt^2	$t^2 s_{2,1} + qt^2 s_{1,1,1}$
	t^3	$t^3 s_{1,1,1}$

- Entire quantity is q, t-symmetric
- Coefficient of $s_{1,1,1}$ in sum is a "(q, t)-Catalan number" $(q^3 + q^2 t + qt + qt^2 + t^3)$.

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What generalizes ∇e_k ?

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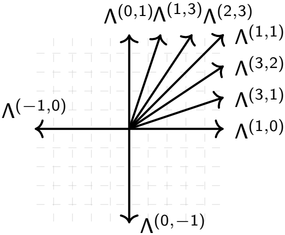

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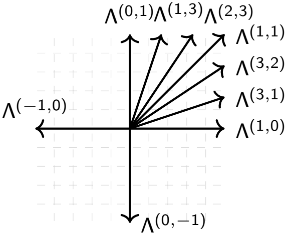

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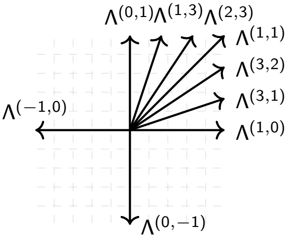

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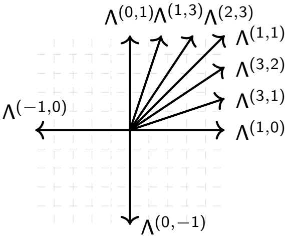

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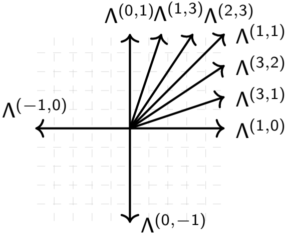

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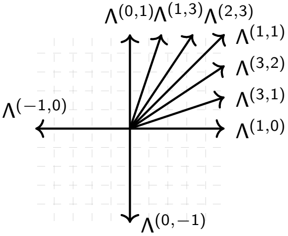

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- $e_k^{(1,1)} \cdot 1 = \nabla e_k^{(0,1)} \nabla^{-1} \cdot 1 = \nabla e_k$.
- Can be difficult to work with in general. Can we make it more explicit?

Root ideals

$R_+ = \{\alpha_{ij} \mid 1 \le i < j \le n\}$ denotes the set of positive roots for GL_n, where $\alpha_{ij} = \epsilon_i - \epsilon_j$.

	(12)	(13)	(14)	(15)
		(23)	(24)	(25)
			(34)	(35)
				(45)

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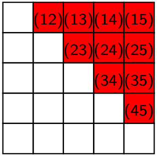
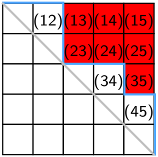


A root ideal $\Psi \subseteq R_+$ is an upper order ideal of positive roots.



$\Psi =$ Roots above Dyck path

Weyl symmetrization

Define the *Weyl symmetrization operator*
$\boldsymbol{\sigma} \colon \mathbb{Q}[z_1^{\pm 1}, \ldots, z_n^{\pm 1}] \to \mathbb{Q}[z_1^{\pm 1}, \ldots, z_n^{\pm 1}]^{S_n}$ by

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$\boldsymbol{\sigma}(\boldsymbol{z}^{111} + \boldsymbol{z}^{201} + \boldsymbol{z}^{210} + \boldsymbol{z}^{3\text{-}11}) = \chi_{111} + 0 + \chi_{210} - \chi_{300}$

Weyl symmetrization

Define the *Weyl symmetrization operator*
$\boldsymbol{\sigma} : \mathbb{Q}[z_1^{\pm 1}, \ldots, z_n^{\pm 1}] \to \mathbb{Q}[z_1^{\pm 1}, \ldots, z_n^{\pm 1}]^{S_n}$ by

$$f(\boldsymbol{z}) \mapsto \sum_{w \in S_n} w \left(\frac{f(\boldsymbol{z})}{\prod_{i<j}(1 - z_j/z_i)} \right) .$$

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- Define $\mathrm{pol}_X\, \chi_\lambda(\boldsymbol{z}) = s_\lambda$ if $\lambda_l \geq 0$, otherwise 0.

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Definition

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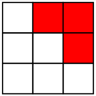
With $n = 3$, $R_+ =$ 

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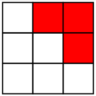
With $n = 3$, $R_+ =$ 

$$\begin{aligned} H(R_+, R_+, \{\alpha_{13}\}, (111)) = {} & \mathrm{pol}_X \, \boldsymbol{\sigma}\left(\frac{\boldsymbol{z}^{111}(1 - qtz_1/z_3)}{\prod_{1 \le i < j \le 3}(1 - qz_i/z_j)(1 - tz_i/z_j)} \right) \\ = {} & s_{111} + (q + t + q^2 + qt + t^2)s_{21} + (qt + q^3 + q^2 t + qt^2 + t^3)s_3 \\ = {} & \omega \nabla e_3. \end{aligned}$$

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Let $R_+ = \{\alpha_{ij} \mid 1 \leq i < j \leq l\}$ and $R_+^0 = \{\alpha_{ij} \in R_+ \mid i+1 < j\}$.

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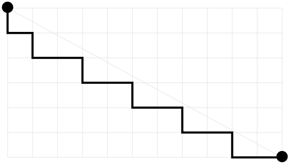
for $\mathbf{b} = (b_0, \ldots, b_{km-1})$ satisfying $b_i =$ the number of south steps on vertical line $x = i$ of highest lattice path under line $y + \frac{n}{m}x = n$.

$\delta =$ highest Dyck path.



δ

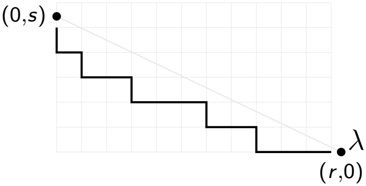
$\mathbf{b} = (1,1,0,1,0,1,0,1,0,1,0)$

Results

Manipulating Catalanimal $\implies$ a proof of the Rational Shuffle Theorem + a generalization.

Theorem (Blasiak-Haiman-Morse-Pun-S., 2023)

Given $r, s \in \mathbb{R}_{>0}$ such that $p = s/r$ irrational, take $\mathbf{b} = (b_1, \ldots, b_l) \in \mathbb{Z}^l$ to be the south step sequence of highest path δ under the line $y + px = s$.



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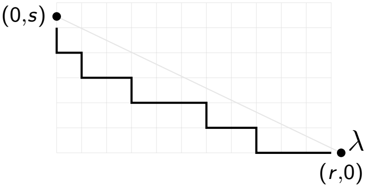
$$H(R_+, R_+, R^0_+, \mathbf{b})$$



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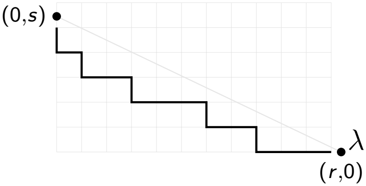

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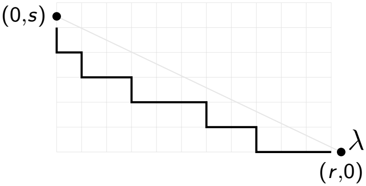
where summation is over all lattice paths under the line $y + px = s$,



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$$H(R_+, R_+, R_+^0, \mathbf{b}) = \sum_{\lambda} t^{\mathrm{area}(\lambda)} q^{\mathrm{dinv}_p(\lambda)} \omega \mathcal{G}_{\nu(\lambda)}(X; q^{-1})$$

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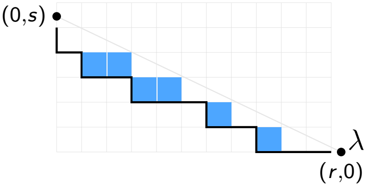

area(λ) as before

$\mathrm{dinv}_p(\lambda) = \#p$-balanced hooks

$\frac{\ell}{a+1} < p < \frac{\ell+1}{a}$

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Special case: $\mathcal{G}_{\boldsymbol{\nu}}^{(1,1)} \cdot 1 = \nabla \mathcal{G}_{\boldsymbol{\nu}}(X;q)$.

LLT Catalanimals

For a tuple of skew shapes $\boldsymbol{\nu}$, the *LLT Catalanimal* $H_{\boldsymbol{\nu}} = H(R_q, R_t, R_{qt}, \lambda)$ is determined by

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  Listing this filling in reading order gives λ.

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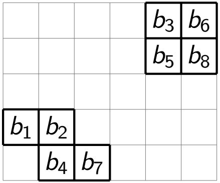
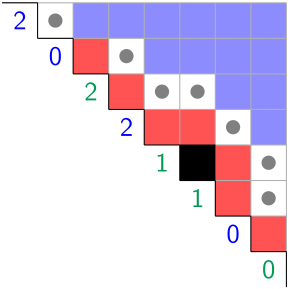


$\boldsymbol{\nu}$



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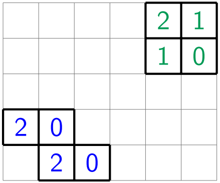
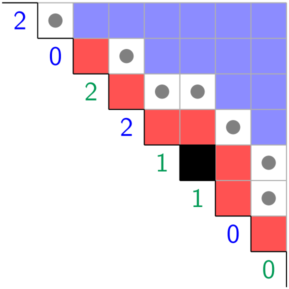


λ, as a filling of $\boldsymbol{\nu}$



LLT Catalanimals

Theorem (Blasiak-Haiman-Morse-Pun-S., 2024)

Let $\boldsymbol{\nu}$ be a tuple of skew shapes and let $H_{\boldsymbol{\nu}} = H(R_q, R_t, R_{qt}, \lambda)$ be the associated LLT Catalanimal. Then

$$\begin{aligned}\nabla \mathcal{G}_{\boldsymbol{\nu}}(X; q) &= c_{\boldsymbol{\nu}}\, \omega H_{\boldsymbol{\nu}} \\ &= c_{\boldsymbol{\nu}}\, \omega \boldsymbol{\sigma} \left(\frac{\boldsymbol{z}^{\lambda} \prod_{\alpha \in R_{qt}} (1 - qt\, \boldsymbol{z}^{\alpha})}{\prod_{\alpha \in R_q} (1 - q\, \boldsymbol{z}^{\alpha}) \prod_{\alpha \in R_t} (1 - t\, \boldsymbol{z}^{\alpha})} \right)\end{aligned}$$

for some $c_{\boldsymbol{\nu}} \in \pm q^{\mathbb{Z}} t^{\mathbb{Z}}$.

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Outline

1. Background on symmetric functions and Macdonald polynomials
2. Shuffle theorems, combinatorics, and LLT polynomials
3. **A new formula for Macdonald polynomials**

Haglund-Haiman-Loehr formula example

$\tilde{H}_\mu(X;q,t) = \sum_D \left(\prod_{u\in D} q^{-\mathrm{arm}(u)} t^{\mathrm{leg}(u)+1}\right) \mathcal{G}_{\boldsymbol{\nu}(\mu,D)}(X;q)$

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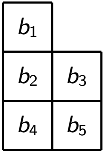
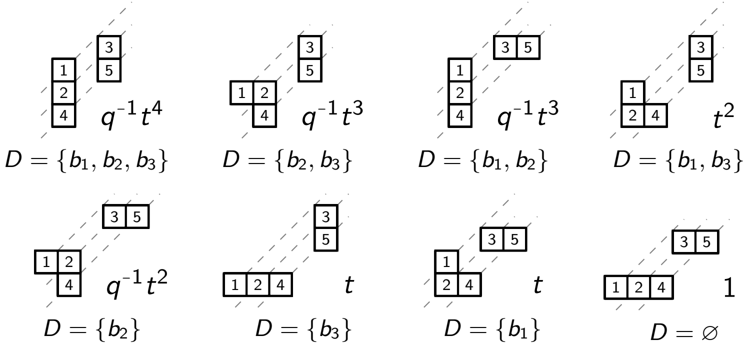


μ



Putting it all together

- Take HHL formula $\tilde{H}_\mu = \sum_D a_{\mu,D} \mathcal{G}_{\boldsymbol{\nu}(\mu,D)}$ and apply $\omega\nabla$.

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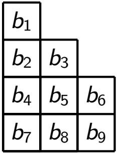
- By construction, all the LLT Catalanimals $H_{\boldsymbol{\nu}(\mu,D)}$ appearing on the RHS will have the same root ideal data (R_q, R_t, R_{qt}).
- Collect terms to get $\prod_{(b_i,b_j)\in V(\mu)}(1 - q^{\mathrm{arm}(b_i)+1} t^{-\mathrm{leg}(b_i)} z_i/z_j)$ factor for $V(\mu)$ the set of vertical dominoes (b_i, b_j) in μ.

$$\tilde{H}_\mu = \omega \,\mathrm{pol}_X\, \boldsymbol{\sigma}\left(z_1 \cdots z_n \frac{\prod\limits_{\alpha_{ij}\in V(\mu)} \left(1 - q^{\mathrm{arm}(b_i)+1} t^{-\mathrm{leg}(b_i)} z_i/z_j\right) \prod\limits_{\alpha\in \widehat{R}_\mu} \left(1 - qt\boldsymbol{z}^\alpha\right)}{\prod_{\alpha\in R_+} \left(1 - q\boldsymbol{z}^\alpha\right) \prod_{\alpha\in R_\mu} \left(1 - t\boldsymbol{z}^\alpha\right)} \right).$$

The root ideal R_μ



row reading order

$b_1 \prec b_2 \prec \cdots \prec b_n$

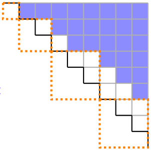
$$R_\mu := \{\alpha_{ij} \in R_+ \mid \mathrm{south}(b_i) \preceq b_j\},$$

$$\widehat{R}_\mu := \{\alpha_{ij} \in R_+ \mid \mathrm{south}(b_i) \prec b_j\},$$

$$R_\mu \setminus \widehat{R}_\mu \leftrightarrow V(\mu) = \text{vertical dominoes in } \mu$$

Example:

$R_{3321} =$



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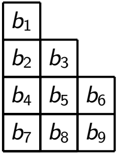

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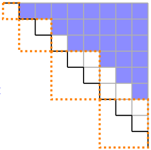
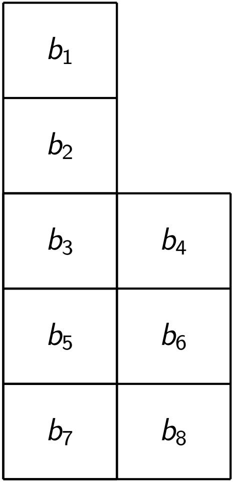
$R_{3321} =$ 

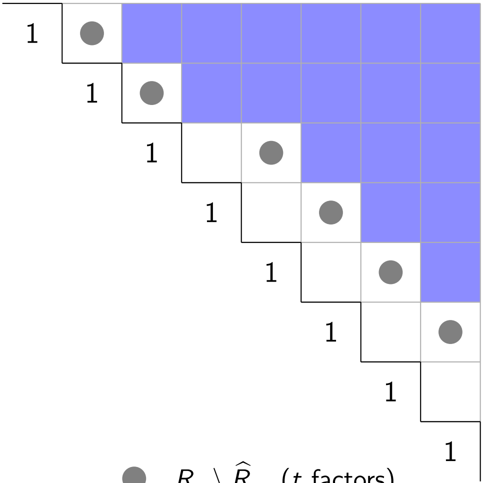
Remark

$$\tilde{H}_\mu(X;0,t) = \omega \,\mathrm{pol}_X\, \boldsymbol{\sigma}\left(\frac{z_1 \cdots z_n}{\prod_{\alpha \in R_\mu}(1 - t\boldsymbol{z}^\alpha)}\right)$$

Example



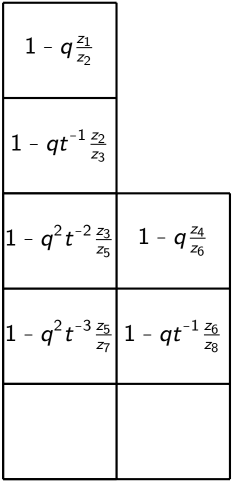
partition $\mu = 22211$



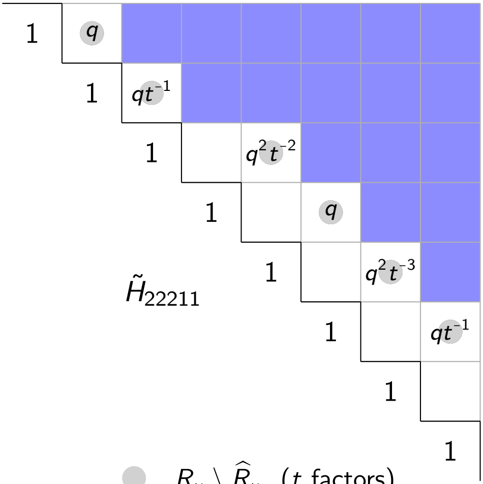
$R_\mu \setminus \widehat{R}_\mu$ (t factors)

$\widehat{R}_\mu$ (t and qt factors)

Example



numerator factors $1 - q^{\mathrm{arm}+1}t^{-\mathrm{leg}}z_i/z_j$



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A positivity conjecture

What can this formula tell us that other formulas for Macdonald polynomials do not?

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$$\tilde{H}_\mu^{(s)} = \omega \,\mathrm{pol}_X\, \boldsymbol{\sigma}\left((z_1 \cdots z_n)^s \frac{\prod_{\alpha_{ij} \in R_\mu \setminus \widehat{R}_\mu} \left(1 - q^{\mathrm{arm}(b_i)+1} t^{-\mathrm{leg}(b_i)} z_i/z_j\right) \prod_{\alpha \in \widehat{R}_\mu} \left(1 - qt\boldsymbol{z}^\alpha\right)}{\prod_{\alpha \in R_+} \left(1 - q\boldsymbol{z}^\alpha\right) \prod_{\alpha \in R_\mu} \left(1 - t\boldsymbol{z}^\alpha\right)} \right)$$

Conjecture (Blasiak-Haiman-Morse-Pun-S., 2025)

For any partition μ and positive integer s, the symmetric function $\tilde{H}_\mu^{(s)}$ is Schur positive. That is, the coefficients in

$$\tilde{H}_\mu^{(s)} = \sum_\nu K_{\nu,\mu}^{(s)}(q,t)\, s_\nu$$

satisfy $K_{\nu,\mu}^{(s)}(q,t) \in \mathbb{N}[q,t]$.

Symmetric functions, representation theory, and combinatorics

Symmetric function	Representation theory	Combinatorics
s_λ	Irreducible V_λ	SSYT(λ)
$\tilde{H}_\lambda(X; q, t)$	Garsia-Haiman M_λ	HHL
∇e_n	DH_n	Shuffle theorem
$H(R_+, R_+, R_+^0, \mathbf{b})$	??	Generalized shuffle theorem
$\tilde{H}_\lambda^{(s)}(X; q, t)$	??	??

Thank you!

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Schiffmann to Shuffle

- Shuffle algebra S given by the image of Laurent polynomials $\phi \in \mathbb{Q}(q,t)[x_1^{\pm 1}, \dots, x_l^{\pm 1}]$ via map

$$H_{q,t} \colon \phi \mapsto \sum_{w \in S_l} w \left(\frac{\phi \prod_{i<j}(1 - qtx_i/x_j)}{\prod_{i<j}((1 - x_j/x_i)(1 - qx_i/x_j)(1 - tx_i/x_j))} \right)$$

- (Schiffmann-Vasserot, 2013) There exists isomorphism $\psi \colon S \to \mathcal{E}^+$.
- (Negut, 2014) gives well-defined

$$D_{b_1,\dots,b_l} = \psi \left(H_{q,t} \left(\frac{x_1^{b_1} \cdots x_l^{b_l}}{\prod_{i=1}^{l-1}(1 - qtx_i/x_{i+1})} \right) \right)$$

Key Relationship (BHMPS, 2023)

For $\zeta = \psi(\phi) \in \mathcal{E}^+$,

$$\omega(\zeta \cdot 1) = \omega \operatorname{pol}_X H_{q,t}(\phi)\,.$$

Cauchy Identity

- (Twisted) non-symmetric Hall-Littlewood polynomials $E^\sigma_\lambda(x;q)$ defined via Demazure-Lusztig operators.

$$T_i = qs_i + (1-q)\frac{s_i - 1}{1 - x_{i+1}/x_i}$$

- Dual basis F^σ_λ.

Cauchy identity

$$\frac{\prod_{i<j}(1-q\,t\,x_i\,y_j)}{\prod_{i\leq j}(1-t\,x_i\,y_j)} = \sum_{\mathbf{a}\geq 0} t^{|\mathbf{a}|}\,E^\sigma_{\mathbf{a}}(x_1,\ldots,x_l;q^{-1})\,F^\sigma_{\mathbf{a}}(y_1,\ldots,y_l;q),$$

- $\mathcal{L}_{\beta/\alpha} = H_q(w_0(F^{\sigma^{-1}}_\beta(x;q)\overline{E^{\sigma^{-1}}_\alpha(x;q)}))$