

K -theoretic Catalan functions

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CAGE

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- Schubert calculus
- Catalan functions: a new approach to old problems
- K -theoretic Catalan functions

Overview of Schubert Calculus Combinatorics

Geometric problem

Find $c_{\lambda\mu}^\nu = \#$ of points in intersection of subvarieties in a variety X .

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Representatives

Special basis of polynomials $\{f_\lambda\}$ such that $f_\lambda \cdot f_\mu = \sum_\nu c_{\lambda\mu}^\nu f_\nu$

Overview of Schubert Calculus Combinatorics (cont.)

Combinatorial study of $\{f_\lambda\}$ enlightens the geometry (and cohomology).

Goal

Identify $\{f_\lambda\}$ in explicit (simple) terms amenable to calculation and proofs.

Geometric problem

Find $c_{\lambda\mu}^\nu = \#$ of points in intersection of Schubert varieties $\{X_\lambda\}_{\lambda \subseteq (n^m)}$ in variety $X = \text{Gr}(m, n)$.

Classical Schubert Calculus

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Representatives

Special basis of Schur polynomials $\{s_\lambda\}$ such that $s_\lambda \cdot s_\mu = \sum_\nu c_{\lambda\mu}^\nu s_\nu$ for Littlewood-Richardson coefficients $c_{\lambda\mu}^\nu$.

Next Step: Flag Variety

- $X = Fl_n(\mathbb{C}) = \{V_0 \subseteq V_1 \subseteq \cdots \subseteq V_n \mid \dim V_i = i\}$

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Open Problem

Structure constants $\mathfrak{S}_w \mathfrak{S}_u = c_{wu}^v \mathfrak{S}_v$ are combinatorially unknown.

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Schubert Calculus Variations

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Theory	f_λ
(Co)homology of Grassmannian	Schur functions
(Co)homology of flag variety	Schubert polynomials
Quantum cohomology of flag variety	Quantum Schuberts
(Co)homology of Types BCD Grassmannian	Schur- P and Q functions
(Co)homology of affine Grassmannian	(dual) k -Schur functions
K -theory of Grassmannian	Grothendieck polynomials
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And many more!

Peterson Isomorphism

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$$\Phi: QH^*(Fl_{k+1}) \rightarrow H_*(Gr_{SL_{k+1}})_{loc}$$

$$\mathfrak{S}_w^Q \mapsto \frac{s_\lambda^{(k)}}{\prod_{i \in Des(w)} \tau_i}$$

where $s_\lambda^{(k)}$ is a k -Schur function.

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Upshot

Computations for (quantum) Schubert polynomials can be moved into symmetric functions.

k -Schur functions

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- $s_{\lambda}^{(k)} = s_{\lambda}$ as $k \rightarrow \infty$.
- Branching with positive coefficients (Lam et al., 2010):

$$s_{\lambda}^{(2)} = s_{\lambda} + s_{\lambda} + s_{\lambda}$$

The diagram illustrates the branching rule for $k=2$. The left side shows $s_{\lambda}^{(2)}$ with a Young diagram of shape $(2,2)$. The right side shows the sum of three terms, each with a Young diagram of shape $(2,2)$. The first term is $s_{\lambda}^{(3)}$ with a Young diagram of shape $(2,2)$. The second and third terms are grouped by a brace and labeled $s_{\lambda}^{(3)}$ with a Young diagram of shape $(2,2)$.

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$$s_{\lambda}^{(2)} = s_{\lambda}^{(3)} + s_{\lambda}^{(3)}$$

The diagram shows the branching rule for k -Schur functions. On the left, $s_{\lambda}^{(2)}$ is represented by a Young diagram with two rows of two boxes. This is equal to the sum of two $s_{\lambda}^{(3)}$ terms. The first $s_{\lambda}^{(3)}$ is represented by a Young diagram with two rows of two boxes. The second $s_{\lambda}^{(3)}$ is represented by a Young diagram with two rows of three boxes. Brackets below the diagrams indicate the branching rule.

- Has geometric interpretation.

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- Has a tableaux formulation and Pieri rule: $s_1^r s_{\lambda}^{(k)} = \sum_{\mu} a_{\lambda\mu} s_{\mu}^{(k)}$
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$$s_{\lambda}^{(2)} = s_{\lambda}^{(3)} + s_{\mu}^{(3)} + s_{\nu}^{(3)}$$

The diagram shows the branching of the 2-partition $(2,2)$ into 3-partitions. On the left is $s_{(2,2)}^{(2)}$, represented by a 2x2 grid. On the right is the sum of three 3-partitions: $s_{(2,2)}^{(3)}$ (a 2x2 grid), $s_{(3,1)}^{(3)}$ (a 2x2 grid with an extra cell to the right of the bottom row), and $s_{(4)}^{(3)}$ (a single row of 4 cells). Brackets below the three terms on the right group them under $s_{(2,2)}^{(3)}$ and $s_{(3,1)}^{(3)}$ respectively.

- Has geometric interpretation.
- No combinatorial interpretation of branching coefficients.

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$$s_{\lambda}^{(2)} = s_{\begin{array}{|c|c|} \hline \square & \square \\ \hline \square & \square \\ \hline \end{array}} + s_{\begin{array}{|c|c|c|} \hline \square & \square & \square \\ \hline \square & \square & \square \\ \hline \end{array}} + s_{\begin{array}{|c|c|c|c|} \hline \square & \square & \square & \square \\ \hline \square & \square & \square & \square \\ \hline \end{array}}$$

$\underbrace{\hspace{10em}}_{s_{\begin{array}{|c|c|} \hline \square & \square \\ \hline \square & \square \\ \hline \end{array}}^{(3)}} \quad \underbrace{\hspace{10em}}_{s_{\begin{array}{|c|c|} \hline \square & \square \\ \hline \square & \square \\ \hline \end{array}}^{(3)}}$

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- Has geometric interpretation.
- No combinatorial interpretation of branching coefficients.
- Definition with t important for Macdonald polynomials.
- Many definitions. A new one makes proofs easier!

- Schubert calculus
- **Catalan functions: a new approach to old problems**
- K -theoretic Catalan functions

Raising Operators on Symmetric Functions

- Raising operators $R_{i,j}$ act on diagrams

$$R_{1,3} \left(\begin{array}{|c|c|c|} \hline \text{red} & & \\ \hline & & \\ \hline & & \\ \hline \end{array} \right) = \begin{array}{|c|c|c|c|} \hline & & & \\ \hline & & & \text{red} \\ \hline & & & \\ \hline \end{array} \quad R_{2,3} \left(\begin{array}{|c|} \hline \text{red} \\ \hline \\ \hline \\ \hline \end{array} \right) = \begin{array}{|c|c|} \hline & \text{red} \\ \hline & \\ \hline \end{array}$$

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- Extend action to a symmetric function f_λ by $R_{i,j}(f_\lambda) = f_{\lambda + \epsilon_i - \epsilon_j}$.

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$$s_\lambda = \prod_{i < j} (1 - R_{ij}) h_\lambda$$

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$$s_\lambda = \prod_{i < j} (1 - R_{ij}) h_\lambda$$

$$s_{22} = (1 - R_{12}) h_{22} = h_{22} - h_{31}$$

$$s_{211} = (1 - R_{12})(1 - R_{23})(1 - R_{13}) h_{211}$$

$$= h_{211} - h_{301} - h_{220} - \underbrace{h_{310}}_{=0} + \underbrace{h_{310}}_{=0} + \underbrace{h_{32-1}}_{=0} + h_{400} - \underbrace{h_{41-1}}_{=0}$$

some terms cancel

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Gives definition for Schur function indexed by any integer vector $\alpha \in \mathbb{Z}^\ell$.

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For $\langle s_{1^r}^\perp s_\lambda, s_\mu \rangle = \langle s_\lambda, s_{1^r} s_\mu \rangle$,

$$s_{1^r}^\perp s_\lambda = \sum_{S \subseteq [1, \ell], |S|=r} s_{\lambda - \epsilon_S}$$

$$s_{1^2}^\perp s_{333} = s_{322} + s_{232} + s_{223}$$

Root Ideals

A root ideal Ψ of type $A_{\ell-1}$ positive roots: given by Dyck path (lattice path above diagonal).



$\Psi =$ Roots above Dyck path
 $\Delta_{\ell}^{+} \setminus \Psi =$ Non-roots below

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Catalan Function (Chen, 2010; Panyushev, 2010; Blasiak et al., 2019)

For Ψ and $\gamma \in \mathbb{Z}^{\ell}$

$$H(\Psi; \gamma)(x) = \prod_{(i,j) \in \Delta_{\ell}^{+} \setminus \Psi} (1 - R_{ij}) h_{\gamma}(x)$$

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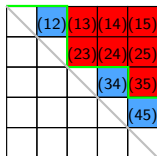
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- $\Psi = \text{all roots} \implies H(\Psi; \gamma) = h_{\gamma}$

k -Schur root ideal for λ

$$\begin{aligned}\psi = \Delta^k(\lambda) &= \{(i, j) : j > k - \lambda_i\} \\ &= \text{root ideal with } k - \lambda_i \text{ non-roots in row } i\end{aligned}$$

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$$\Delta^4(3, 3, 2, 2, 1, 1) =$$

3					
	3				
		2			
			2		
				1	
					1

\leftarrow row i has $4 - \lambda_i$ non-roots

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k -Schur is a Catalan function (Blasiak et al., 2019).

For partition λ with $\lambda_1 \leq k$,

$$s_{\lambda}^{(k)} = H(\Delta^k(\lambda); \lambda).$$

Key ingredient of branching proof

Dual vertical Pieri rule: $s_{1^r}^\perp s_\lambda^{(k)} = \sum_\mu a_{\lambda\mu} s_\mu^{(k)}$ for $\langle s_{1^r}^\perp f, g \rangle = \langle f, s_{1^r} g \rangle$.

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Proof: $k - \lambda_i = (k + 1) - (\lambda_i + 1)$

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3					
	3				
		2			
			2		
				1	
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$$\Delta^5(4, 4, 3, 3, 2, 2) =$$

4					
	4				
		3			
			3		
				2	
					2

Key ingredient of branching proof

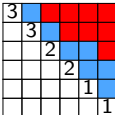
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Pieri:

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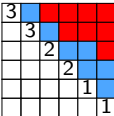
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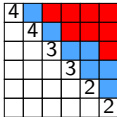
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Branching is a special case of Pieri:

$$s_\lambda^{(k)} = s_{1^\ell}^\perp s_{\lambda+1^\ell}^{(k+1)} = \sum_\mu a_{\lambda+1^\ell, \mu} s_\mu^{(k+1)}$$

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Dual Grothendieck polynomials

- Inhomogeneous basis: $g_\lambda = s_\lambda + \text{lower degree terms}$.

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- $g_\lambda = \prod_{i < j} (1 - R_{ij}) k_\lambda$ for k_λ and inhomogeneous analogue of h_λ .
- Dual to Grothendieck polynomials G_λ : Schubert representatives for $K^*(Gr(m, n))$

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$$g_1 g_{211}^{(2)} = g_{2111}^{(2)} - 2g_{211}^{(2)}$$

2-bounded partitions \leftrightarrow 3-cores

The diagram illustrates the Pieri rule for K - k -Schur functions. It shows the product of a 1-strip (g_1) and a 2-bounded partition ($g_{211}^{(2)}$) resulting in the difference of two 2-bounded partitions ($g_{2111}^{(2)} - 2g_{211}^{(2)}$). The partitions are represented as 5x5 grids of colored dots (red, blue, black) with some cells shaded gray to indicate the addition or subtraction of strips.

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- Conjecture: $g_\lambda^{(k)}$ have positive branching into $g_\mu^{(k+1)}$ (Lam et al., 2010; Morse, 2011).

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Problem

No direct formula for $g_{\lambda}^{(k)}$

An Extra Ingredient: Lowering Operators

Lowering Operators $L_j(f_\lambda) = f_{\lambda - \epsilon_j}$

$$L_3 \left(\begin{array}{|c|c|c|c|} \hline \text{red} & & & \\ \hline & & & \\ \hline & & & \\ \hline \end{array} \right) = \begin{array}{|c|c|c|} \hline & & \\ \hline & & \\ \hline \end{array}, \quad L_1 \left(\begin{array}{|c|c|c|c|} \hline & & & \\ \hline & & & \\ \hline & & & \\ \hline & & \text{red} & \\ \hline \end{array} \right) = \begin{array}{|c|c|} \hline & \\ \hline & \\ \hline & \\ \hline \end{array}$$

K -theoretic Catalan function

Let $\Psi, \mathcal{L} \subseteq \Delta_\ell^+$ be order ideals of positive roots and $\gamma \in \mathbb{Z}^\ell$, then

$$K(\Psi; \mathcal{L}; \gamma) := \prod_{(i,j) \in \mathcal{L}} (1 - L_j) \prod_{(i,j) \in \Delta_\ell^+ \setminus \Psi} (1 - R_{ij}) k_\gamma$$

Affine K -Theory Representatives with Raising Operators

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Example

non-roots of Ψ , roots of \mathcal{L}

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

$$K(\Psi; \mathcal{L}; 54332)$$

$$= (1 - L_4)^2 (1 - L_5)^2 (1 - R_{12}) (1 - R_{34}) (1 - R_{45}) k_{54332}$$

Answer (Blasiak-Morse-S., 2020)

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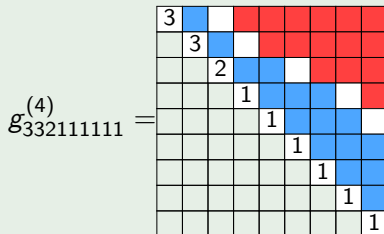
For K -homology of affine Grassmannian, $g_{\lambda}^{(k)} = K(\Delta^k(\lambda); \Delta^{k+1}(\lambda); \lambda)$ since this family satisfies the Pieri rule.

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Example



$$\Delta_9^+ / \Delta^4(332111111), \Delta^5(332111111)$$

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Theorem (Blasiak-Morse-S., 2020)

The branching coefficients in

$$g_\lambda^{(k)} = \sum_{\mu} a_{\lambda\mu} g_\mu^{(k+1)}$$

satisfy $(-1)^{|\lambda|-|\mu|} a_{\lambda\mu} \in \mathbb{Z}_{\geq 0}$.

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$$G_{1^r}^\perp g_\lambda^{(k)} = \sum_\mu ?? g_\mu^{(k)} \iff G_{1^r} G_\mu^{(k)} = \sum_\lambda ?? G_\lambda^{(k)}, \quad 1 \leq r \leq k.$$

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- 3 Combinatorially describe $g_\lambda^{(k)} = \sum_\mu ?? s_\mu^{(k)}$.

Thank you!

- Anderson, David, Linda Chen, and Hsian-Hua Tseng. 2017. *On the quantum K -ring of the flag manifold*, preprint. arXiv: 1711.08414.
- Blasiak, Jonah, Jennifer Morse, Anna Pun, and Daniel Summers. 2019. *Catalan Functions and k -Schur Positivity*, J. Amer. Math. Soc. **32**, no. 4, 921–963.
- Chen, Li-Chung. 2010. *Skew-linked partitions and a representation theoretic model for k -Schur functions*, Ph.D. thesis.
- Ikedai, Takeshi, Shinsuke Iwao, and Toshiaki Maeno. 2018. *Peterson Isomorphism in K -theory and Relativistic Toda Lattice*, preprint. arXiv: 1703.08664.
- Lam, Thomas. 2008. *Schubert polynomials for the affine Grassmannian*, J. Amer. Math. Soc. **21**, no. 1, 259–281.
- Lam, Thomas, Luc Lapointe, Jennifer Morse, and Mark Shimozono. 2010. *Affine insertion and Pieri rules for the affine Grassmannian*, Mem. Amer. Math. Soc. **208**, no. 977.
- Lam, Thomas, Anne Schilling, and Mark Shimozono. 2010. *K -theory Schubert calculus of the affine Grassmannian*, Compositio Math. **146**, 811–852.
- Lapointe, Luc, Alain Lascoux, and Jennifer Morse. 2003. *Tableau atoms and a new Macdonald positivity conjecture*, Duke Mathematical Journal **116**, no. 1, 103–146.
- Morse, Jennifer. 2011. *Combinatorics of the K -theory of affine Grassmannians*, Advances in Mathematics.
- Panyushev, Dmitri I. 2010. *Generalised Kostka-Foulkes polynomials and cohomology of line bundles on homogeneous vector bundles*, Selecta Math. (N.S.) **16**, no. 2, 315–342.