Positive m-divisible non-crossing partitions and their cylic sieving

Christian
Krattenthaler and Stump

Universität Wien and Freie Universität Berlin

m-divisible non-crossing partitions associated with reflection groups

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Let W be a finite real reflection group.

The *absolute length* (*reflection length*) $\ell_T(w)$ of an element $w \in W$ is defined by the smallest k such that

$$w = t_1 t_2 \cdots t_k,$$

where all t_i are reflections.

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The *absolute order* (*reflection order*) $\leq_T$ is defined by

$$u \leq_T w \quad \text{if and only if } \ell_T(u) + \ell_T(u^{-1}w) = \ell_T(w).$$

m-divisible non-crossing partitions associated with reflection groups

Definition (Armstrong)

The m-divisible non-crossing partitions for a reflection group W are defined by

$$NC^{(m)}(W) = \big\{(w_0; w_1, \dots, w_m) : w_0 w_1 \cdots w_m = c \text{ and } \ell_T(w_0) + \ell_T(w_1) + \cdots + \ell_T(w_m) = \ell_T(c)\big\},$$

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In particular,

$$NC^{(1)}(W) \cong NC(W),$$

the "ordinary" non-crossing partitions for W.

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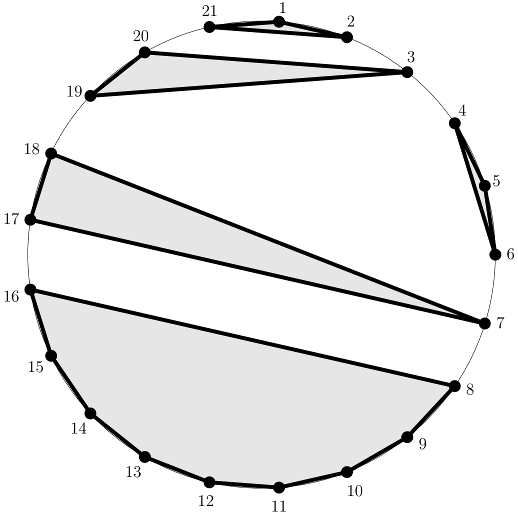
$$(1, 2, \dots, 21)\,(7, 16)^{-1}\,(2, 20)^{-1}\,(3, 6, 18)^{-1} \\ = (1, 2, 21)\,(3, 19, 20)\,(4, 5, 6)\,(7, 17, 18)\,(8, 9, \dots, 16).$$

m-divisible non-crossing partitions associated with reflection groups



A 3-divisible non-crossing partition of type A_6

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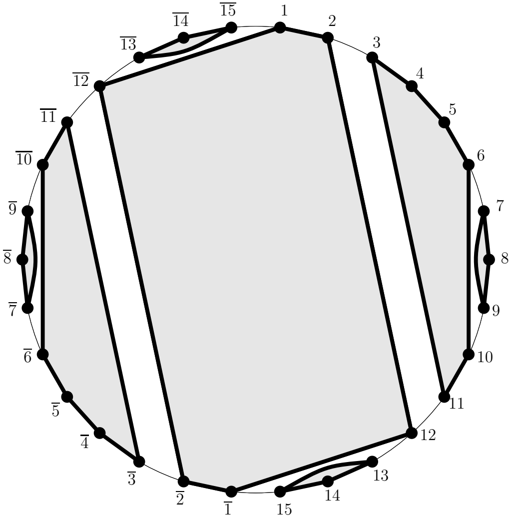

A 3-divisible non-crossing partition of type B_5

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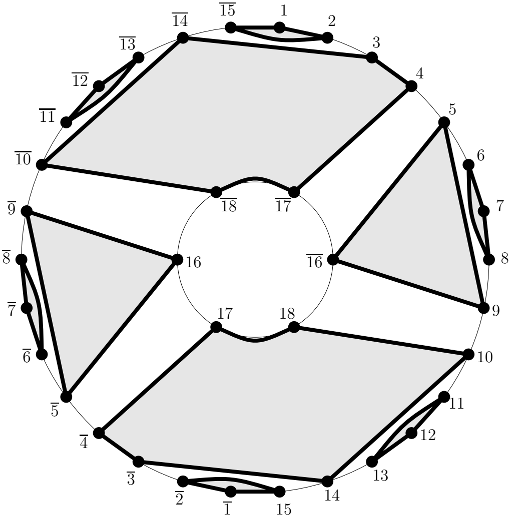

A 3-divisible non-crossing partition of type D_6

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These were defined by Buan, Reiten and Thomas, as an aside in *"m-noncrossing partitions and m-clusters."* There, they constructed a bijection between the facets of the *m*-cluster complex of Fomin and Reading and the *m*-divisible non-crossing partitions of Armstrong.

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The positive *m*-clusters are those which do not contain any negative roots. They are enumerated by the *positive* Fuß–Catalan numbers

$$\mathrm{Cat}_+^{(m)}(W) := \prod_{i=1}^{n} \frac{mh + d_i - 2}{d_i}.$$

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One can give an intrinsic definition:

Definition

An m-divisible non-crossing partition $(w_0; w_1, \dots, w_n)$ in $NC^{(m)}(W)$ is positive, if and only if $w_0 w_1 \cdots w_{m-1}$ is not contained in any proper standard parabolic subgroup of W.

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Let $NC_+^{(m)}(W)$ denote the set of all positive m-divisible non-crossing partitions for W.

Trivial corollary:

$$|NC_+^{(m)}(W)| = \mathrm{Cat}_+^{(m)}(W).$$

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Buan, Reiten and Thomas then write:

> *"Other than that, there do not seem to be enumerative results known for these families."*

Enumeration of positive m-divisible non-crossing partitions

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For "ordinary" m-divisible non-crossing partitions, closed-form enumeration results are known for:

- total number;
- number of those of given rank;
- number of those with given block sizes (in types A, B, D);
- number of chains;
- number of chains with elements at given ranks;
- number of chains with elements at given ranks and bottom element with given block sizes (in types A, B, D).

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Fact: Under Armstrong's map, the elements of $NC_+^{(m)}(A_{n-1})$ correspond to those m-divisible non-crossing partitions of $\{1, 2, \ldots, mn\}$ in which mn and 1 are in the same block.

Enumeration in $NC_+^{(m)}(A_{n-1})$

Theorem

Let m, n be positive integers, The total number of positive m-divisible non-crossing partitions of $\{1, 2, \dots, mn\}$ is given by

$$\frac{1}{n}\binom{(m+1)n-2}{n-1}.$$

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Theorem

Let m, n, l be positive integers, The number of multi-chains $\pi_1 \leq \pi_2 \leq \cdots \leq \pi_{l-1}$ in the poset of positive m-divisible non-crossing partitions of $\{1, 2, \dots, mn\}$ is given by

$$\frac{1+(l-1)(m-1)}{n-1}\binom{n-1+(l-1)(mn-1)}{n-2}.$$

Theorem

Let m and n be positive integers, For non-negative integers $b_1, b_2, \ldots, b_n$, the number of positive m-divisible non-crossing partitions of $\{1, 2, \ldots, mn\}$ which have exactly b_i blocks of size mi, $i = 1, 2, \ldots, n$, is given by

$$\frac{1}{mn-1}\binom{b_1+b_2+\cdots+b_n}{b_1, b_2, \ldots, b_n}\binom{mn-1}{b_1+b_2+\cdots+b_n}$$

if $b_1 + 2b_2 + \cdots + nb_n = n$, and 0 otherwise.

Enumeration in $NC_+^{(m)}(A_{n-1})$

Theorem

Let m, n, l be positive integers, and let $s_1, s_2, \dots, s_l$ be non-negative integers with $s_1 + s_2 + \cdots + s_l = n - 1$. The number of multi-chains $\pi_1 \le \pi_2 \le \cdots \le \pi_{l-1}$ in the poset of positive m-divisible non-crossing partitions of $\{1, 2, \dots, mn\}$ with the property that $\operatorname{rk}(\pi_i) = s_1 + s_2 + \cdots + s_i$, $i = 1, 2, \dots, l-1$, is given by

$$\frac{mn - s_2 - s_3 - \cdots - s_l - 1}{(mn-1)n} \binom{n}{s_1} \binom{mn-1}{s_2} \cdots \binom{mn-1}{s_l}.$$

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$$\frac{mn - b_1 - b_2 - \cdots - b_n}{(mn-1)(b_1 + b_2 + \cdots + b_n)} \binom{b_1 + b_2 + \cdots + b_n}{b_1, b_2, \dots, b_n} \times \binom{(l-1)(mn-1)}{b_1 + b_2 + \cdots + b_n - 1}$$

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Let m, n, l be positive integers, and let $s_1, s_2, \dots, s_l, b_1, b_2, \dots, b_n$ be non-negative integers with $s_1 + s_2 + \cdots + s_l = n - 1$. The number of multi-chains $\pi_1 \le \pi_2 \le \cdots \le \pi_{l-1}$ in the poset of positive m-divisible non-crossing partitions of $\{1, 2, \dots, mn\}$ with the property that $\mathrm{rk}(\pi_i) = s_1 + s_2 + \cdots + s_i$, $i = 1, 2, \dots, l - 1$, and that the number of blocks of size mi of π_1 is b_i, $i = 1, 2, \dots, n$, is given by

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if $b_1 + 2b_2 + \cdots + nb_n = n$ and $s_1 + b_1 + b_2 + \cdots + b_n = n$, and 0 otherwise.

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Fact: Under Armstrong's map, the elements of $NC_+^{(m)}(B_n)$ correspond to those m-divisible non-crossing partitions of $\{1, 2, \dots, mn, -1, -2, \dots, -mn\}$ which are invariant under rotation by 180°, and in which the block of 1 contains a negative element.

Enumeration in $NC_+^{(m)}(B_n)$

Theorem

Let m, n, l be positive integers such that $r \geq 2$ and $r \mid mn$. Furthermore, let $s_1, s_2, \ldots, s_l$ be non-negative integers with $s_1 + s_2 + \cdots + s_l = n$. The number of multi-chains $\pi_1 \leq \pi_2 \leq \cdots \leq \pi_{l-1}$ in the poset of positive m-divisible non-crossing partitions in $NC^{(m)}(B_n)$ which the property that $\operatorname{rk}(\pi_i) = s_1 + s_2 + \cdots + s_i$, $i = 1, 2, \ldots, l-1$, and that the number of non-zero blocks of size mi of π_1 is rb_i, $i = 1, 2, \ldots, n$, is given by

$$\binom{b_1 + b_2 + \cdots + b_n}{b_1, b_2, \ldots, b_n} \binom{mn-1}{s_2} \cdots \binom{mn-1}{s_l}.$$

Etc.

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Fact: Under CK's map, the elements of $NC_+^{(m)}(D_n)$ correspond to those m-divisible non-crossing partitions on the annulus with $\{1, 2, \dots, m(n-1), -1, -2, \dots, -m(n-1)\}$ on the outer circle and $\{m(n-1)+1, \dots, mn, -m(n-1)-1, \dots, -mn\}$ on the inner circle which are invariant under rotation by 180°, satisfy the earlier mentioned and non-defined technical constraint, and in which the predecessor of 1 in its block is a negative element on the outer circle.

Enumeration in $NC_+^{(m)}(D_n)$

Under construction

A Fundamental Principle of Combinatorial Enumeration (2004ff)

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Every family of combinatorial objects satisfies the

cyclic sieving phenomenon!

Cyclic sieving (Reiner, Stanton, White)

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Ingredients:

— a set M of *combinatorial objects*,

— a *cyclic group* $C = \langle g \rangle$ acting on M,

— a *polynomial* $P(q)$ in q with non-negative integer coefficients.

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Definition

The triple (M, C, P) exhibits the *cyclic sieving phenomenon* if

$$|\operatorname{Fix}_M(g^p)| = P\left(e^{2\pi i p/|C|}\right).$$

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Corollary

The positive m-divisible non-crossing partitions satisfy the cyclic sieving phenomenon.

A cyclic action for m-divisible non-crossing partitions

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Let $K : NC^{(m)}(W) \to NC^{(m)}(W)$ be the map defined by

$$(w_0; w_1, \dots, w_m) \\ \mapsto \big((cw_mc^{-1})w_0(cw_mc^{-1})^{-1}; cw_mc^{-1}, w_1, w_2, \dots, w_{m-1}\big).$$

It generates a cyclic group of order mh.

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Furthermore, let

$$\operatorname{Cat}^{(m)}(W;q) := \prod_{i=1}^{n} \frac{[mh+d_i]_q}{[d_i]_q},$$

where $[\alpha]_q := (1-q^\alpha)/(1-q)$.

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Theorem (with T. W. Müller)

The triple $(NC^{(m)}(W), \langle K \rangle, \mathrm{Cat}^{(m)}(W;q))$ exhibits the cyclic sieving phenomenon.

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where $[\alpha]_q := (1 - q^\alpha)/(1 - q)$.

Theorem (with T. W. Müller)

Let $NC^{(m;0)}(W)$ denote the subset of $NC^{(m)}(W)$ consisting of those elements for which $w_0 = id$. Then the triple $(NC^{(m;0)}(W), \langle K \rangle, \mathrm{Cat}^{(m-1)}(W; q))$ exhibits the cyclic sieving phenomenon.

A cyclic action for positive m-divisible non-crossing partitions?

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Bad news:

The map $K : NC^{(m)}(W) \to NC^{(m)}(W)$ defined by

$$(w_0; w_1, \dots, w_m) \\ \mapsto \left((cw_m c^{-1}) w_0 (cw_m c^{-1})^{-1}; cw_m c^{-1}, w_1, w_2, \dots, w_{m-1}\right)$$

does not necessarily map positive m-divisible non-crossing partitions to positive ones!

A cyclic action for positive m-divisible non-crossing partitions?

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Consequently: we have to modify the above action.

A cyclic action for positive m-divisible non-crossing partitions?

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Let $K_+ : NC^{(m)}(W) \to NC^{(m)}(W)$ be the map defined by

$$
\begin{aligned}
(w_0; w_1, \dots, w_m) \\
&\mapsto \Big((c w_{m-1}^R w_m c^{-1}) w_0 (c w_{m-1}^R w_m c^{-1})^{-1}; \\
&\qquad c w_{m-1}^R w_m c^{-1}, w_1, \dots, w_{m-1}^L \Big),
\end{aligned}
$$

where $w_{m-1} = w_{m-1}^L w_{m-1}^R$ is the factorisation of w_{m-1} into its "good" and its "bad" part.

A cyclic action for positive m-divisible non-crossing partitions?

Factorisation into “good” and “bad” part

A cyclic action for positive m-divisible non-crossing partitions?

Factorisation into "good" and "bad" part

Fix a reduced word $c = c_1 \cdots c_n$ for the Coxeter element c.
Define the *c-sorting word* $\mathrm{w}(c)$ for $w \in W$ to be the lexicographically first reduced word for w when written as a subword of c^∞.
Let $\mathrm{w}_\circ(c) = s_{k_1} \cdots s_{k_N}$ with $N = nh/2$ be the c-sorting word of the longest element $w_\circ \in W$.
The word $\mathrm{w}_\circ(c)$ induces a *reflection ordering* given by

$$T = \{s_{k_1} <_c s_{k_1}s_{k_2}s_{k_1} <_c s_{k_1}s_{k_2}s_{k_3}s_{k_2}s_{k_1} <_c \dots \\ <_c s_{k_1} \dots s_{k_{N-1}}s_{k_N}s_{k_{N-1}} \dots s_{k_1}\}.$$

Associate to every element $w \in NC(W)$ a reduced T-word $\mathcal{T}_c(w)$ given by the lexicographically first subword of T that is a reduced T-word for w.
We decompose w as $w = w^L w^R$ where w^R is the part of $\mathcal{T}_c(w)$ within the last n reflections in T.

Cyclic sieving for positive m-divisible non-crossing partitions

Cyclic sieving for positive m-divisible non-crossing partitions

Let $K_+ : NC^{(m)}(W) \to NC^{(m)}(W)$ be the earlier defined map.

Furthermore, let

$$\mathrm{Cat}_+^{(m)}(W;q) := \prod_{i=1}^{n} \frac{[mh+d_i-2]_q}{[d_i]_q},$$

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Conjecture

The triple $(NC_+^{(m)}(W), \langle K_+ \rangle, \mathrm{Cat}_+^{(m)}(W;q))$ exhibits the cyclic sieving phenomenon.

Conjecture

Let $NC_+^{(m;0)}(W)$ denote the subset of $NC_+^{(m)}(W)$ consisting of those elements for which $w_0 = id$. Then the triple $(NC_+^{(m;0)}(W), \langle K_+ \rangle, \mathrm{Cat}_+^{(m-1)}(W;q))$ exhibits the cyclic sieving phenomenon.

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State of affairs: This is proved for all types except for type D_n.

Cyclic sieving for positive m-divisible non-crossing partitions for type A_{n-1}

Realisation of the cyclic action in type A_{n-1}

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"In principle," under Armstrong's combinatorial realisation, the map K_+ becomes rotation by one unit, unless this would produce a non-positive m-divisible partition.

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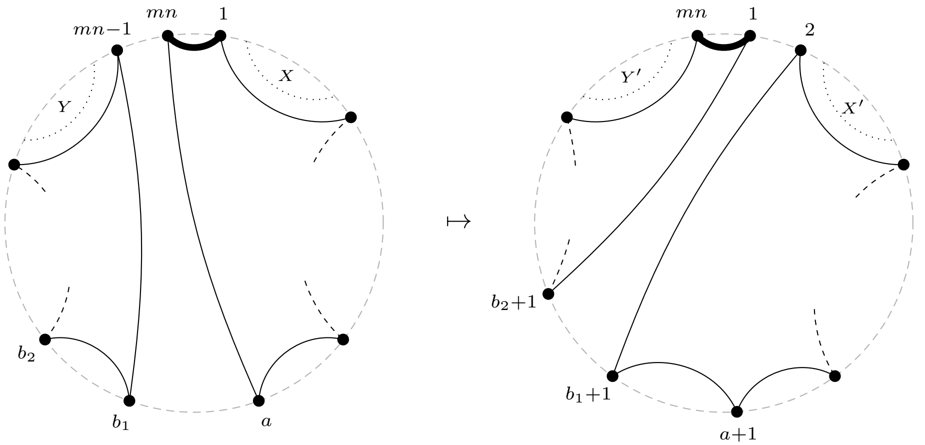

Cyclic sieving for positive m-divisible non-crossing partitions for type A_{n-1}

How do "pseudo-rotationally" invariant elements look like?

Cyclic sieving for positive m-divisible non-crossing partitions for type A_{n-1}

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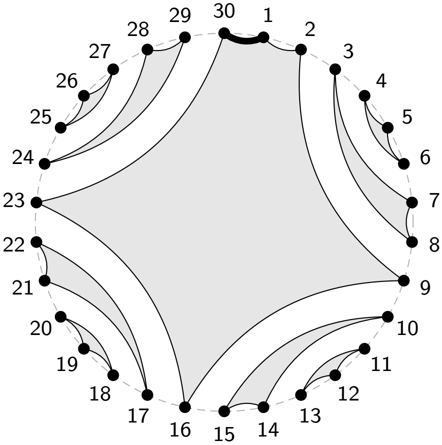

Cyclic sieving for positive m-divisible non-crossing partitions for type A_{n-1}

Theorem

Let m, n, r be positive integers with $r \geq 2$ and $r \mid (mn-2)$. Furthermore, let $b_1, b_2, \dots, b_n$ be non-negative integers. The number of positive m-divisible non-crossing partitions of $\{1, 2, \dots, mn\}$ which are invariant under the r-pseudo-rotation $\widetilde{\phi}^{(mn-2)/r}$, the number of non-zero blocks of size mi being rb_i, $i = 1, 2, \dots, n$, the zero block having size $ma = mn - mr\sum_{j=1}^{n} jb_j$, is given by

$$\binom{b_1 + b_2 + \cdots + b_n}{b_1, b_2, \dots, b_n}\binom{(mn-2)/r}{b_1 + b_2 + \cdots + b_n}$$

if $b_1 + 2b_2 + \cdots + nb_n < n/r$, or if $r = 2$ and $b_1 + 2b_2 + \cdots + nb_n = n/2$, and 0 otherwise.

Cyclic sieving for positive m-divisible non-crossing partitions for type A_{n-1}

Theorem

Let C be the cyclic group of pseudo-rotations of an mn-gon generated by K_+. Then the triple (M, P, C) exhibits the cyclic sieving phenomenon for the following choices of sets M and polynomials P:

1. $M = \widetilde{NC}_+^{(m)}(n)$, *and* $P(q) = \frac{1}{[n]_q} \begin{bmatrix} (m+1)n-2 \\ n-1 \end{bmatrix}_q$;
2. *M consists of all elements of $\widetilde{NC}_+^{(m)}(n)$ the block sizes of which are all equal to m, and* $P(q) = \frac{1}{[n]_q} \begin{bmatrix} mn-2 \\ n-1 \end{bmatrix}_q$;
3. *M consists of all elements of $\widetilde{NC}_+^{(m)}(n)$ which have rank s (or, equivalently, their number of blocks is $n-s$), and*

$$P(q) = \frac{1}{[n]_q} \begin{bmatrix} n \\ s \end{bmatrix}_q \begin{bmatrix} mn-2 \\ n-s-1 \end{bmatrix}_q ;$$

Cyclic sieving for positive m-divisible non-crossing partitions for type A_{n-1}

1. *M consists of all elements of $\widetilde{NC}_+^{(m)}(n)$ whose number of blocks of size mi is b_i, $i = 1, 2, \dots, n$, and*

$$P(q) = \frac{1}{[b_1 + b_2 + \cdots + b_n]_q} \begin{bmatrix} b_1 + b_2 + \cdots + b_n \\ b_1, b_2, \dots, b_n \end{bmatrix}_q \times \begin{bmatrix} mn - 2 \\ b_1 + b_2 + \cdots + b_n - 1 \end{bmatrix}_q .$$

Cyclic sieving for positive m-divisible non-crossing partitions for type B_n

Realisation of the cyclic action in type B_n

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Realisation of the cyclic action in type B_n

"In principle," under Armstrong's combinatorial realisation, the map K_+ becomes rotation by one unit, unless this would produce a non-positive m-divisible partition.

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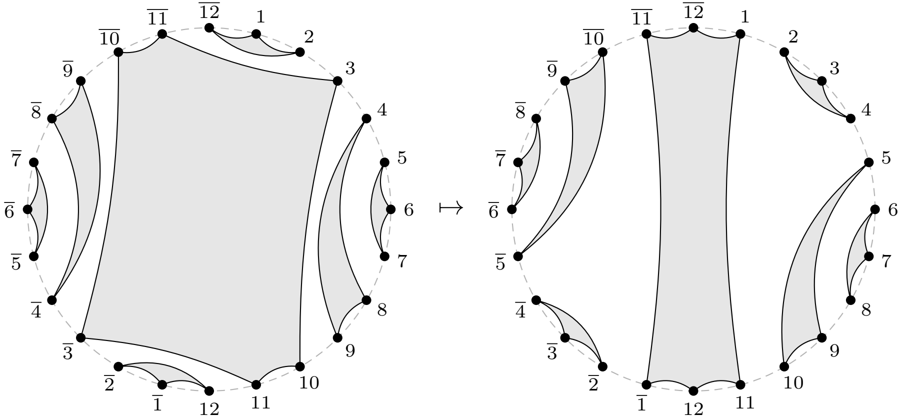

Cyclic sieving for positive m-divisible non-crossing partitions for type B_n

There are results for the positive m-divisible non-crossing partitions for type B_n which are similar to those for type A_{n-1}.

Cyclic sieving for positive m-divisible non-crossing partitions for the exceptional types

The (positive) m-divisible non-crossing partitions

$$(w_0; w_1, \dots, w_m)$$

for the exceptional types become "sparse" for large m.
This allows one to reduce the occurring enumeration problems to finite problems.

"Other than that, there do not seem to be enumerative results known for these families."