Between weak and Bruhat: the middle order on permutations

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talk based on joint work with
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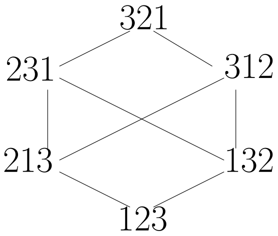
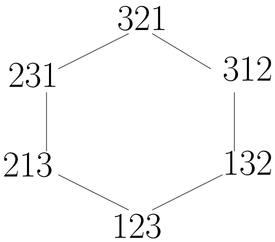
Journées annuelles du GT Combinatoire Algébrique, Lyon, October 2024.

You may know these two



Bruhat order



weak order

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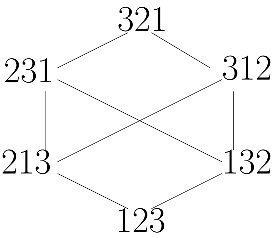
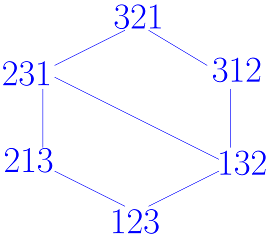
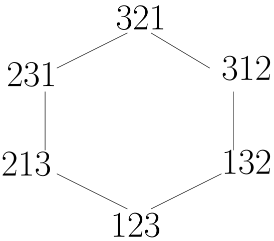


Bruhat order



middle order



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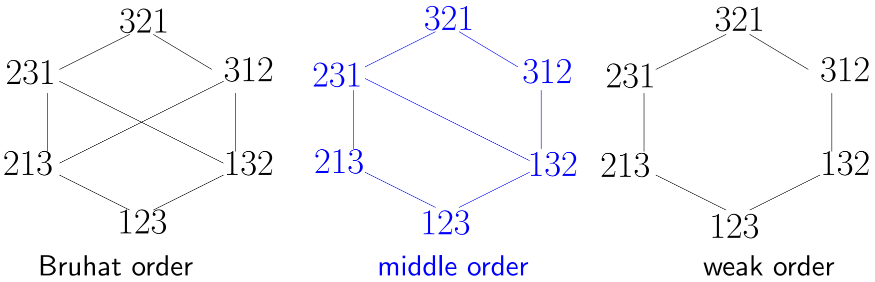


Goals of the talk:

- Define the middle order on S_n
- Give meaning to the property that "it sits between weak and Bruhat"
- Describe some of its properties
- Popularize this new order, hoping to raise new questions about it

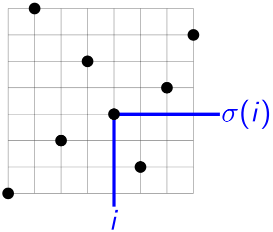
Our 3 orders through “mesh patterns”

Permutation diagrams

Notation:

- S_n = the set of permutations of size n
- $\sigma \in S_n$ is seen as the word $\sigma(1)\sigma(2)\cdots\sigma(n)$
- σ is also seen as its diagram *i.e.* the $n \times n$ grid with points at coordinates $(i, \sigma(i))$

Example: The word 1 8 3 6 4 2 5 7, or equivalently the diagram



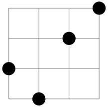
, represents $\sigma = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\ 1 & 8 & 3 & 6 & 4 & 2 & 5 & 7 \end{pmatrix}$

A permutation $\pi \in S_k$ is a pattern of a permutation $\sigma \in S_n$ (written $\pi \preccurlyeq \sigma$) when there exist indices $1 \leq i_1 < i_2 \cdots < i_k \leq n$ such that $\sigma(i_a) < \sigma(i_b)$ if and only if $\pi(a) < \pi(b)$

The subsequence $\sigma(i_1)\sigma(i_2)\cdots\sigma(i_k)$ is an occurrence of π in σ

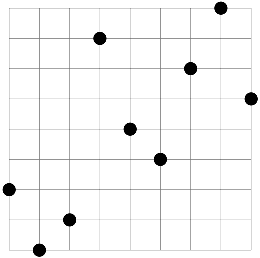
Example: 2134 is a pattern of 3 1 2 8 5 4 7 9 6, one occurrence being 3157

This is also seen on diagrams:



$\pi =$ 2 1 3 4

$\preccurlyeq$



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Permutation patterns

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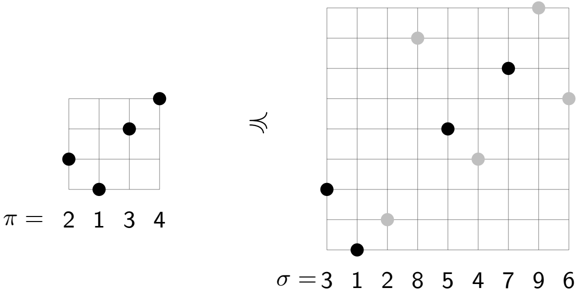

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This is also seen on diagrams:

An inversion is a subsequence $\cdots j \cdots i \cdots$ in a permutation, with $j > i$.

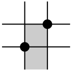
Equivalently, it is an occurrence of the pattern 21 = 

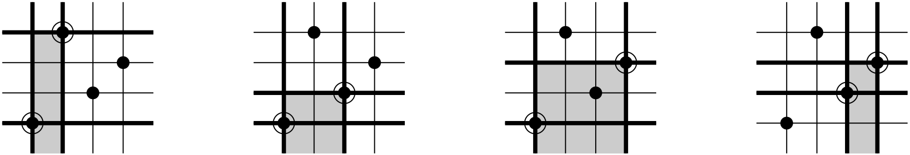
Example: The inversions of 3 1 2 8 5 4 7 9 6 are
31, 32, 85, 84, 87, 86, 54, 76 and 96

Mesh patterns

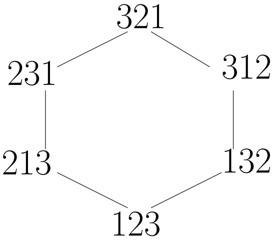
A mesh pattern (π, M) is the data of a pattern π (say, of size k) drawn in the central $k \times k$ square of the grid $[0, k+1]^2$, together with a set M of shaded unit cells in this grid. (M is called the mesh.)

An occurrence of (π, M) in σ is an occurrence of π in σ such that the regions of $[0, n+1]^2$ corresponding to the mesh M contain no points of σ

Example: Consider the mesh pattern $\mu =$ . The permutation 1423 contains four occurrences of 12, but only three of μ.



Weak order, seen through mesh patterns



Covering relations are described by

$$\cdots i\, j \cdots \rightsquigarrow \cdots j\, i \cdots$$

i.e., transforming an ascent[(a)] into a descent[(d)] using the same two values.

(a) occurrence of 12 at consecutive positions

(d) occurrence of 21 at consecutive positions

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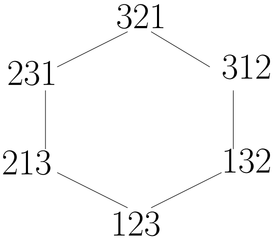

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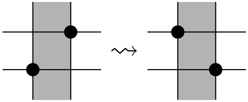
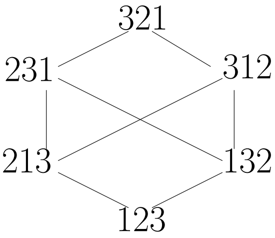


Bruhat order, seen through mesh patterns

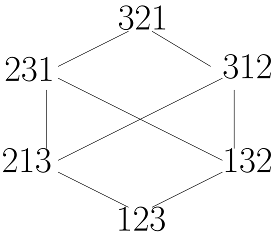


Relations are described by the swaps

$$\cdots i \cdots j \cdots \rightsquigarrow \cdots j \cdots i \cdots$$

i.e., transforming a non-inversion (=occurrence of 12) into an inversion using the same two values.

Covering relations are the relations that do not create additional inversions.



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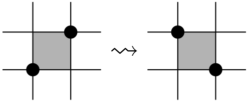

Middle order, defined through mesh patterns

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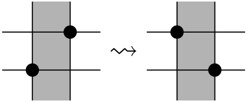
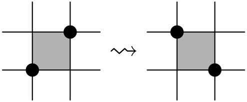


- For the Bruhat order, the covering relations are described by



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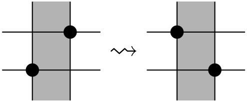

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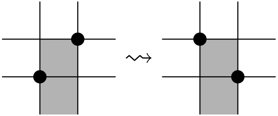

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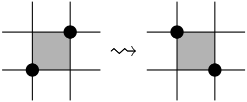
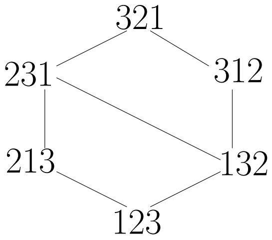
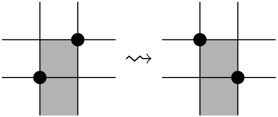


The middle order

- On permutations of size 3:



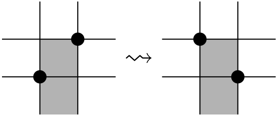
- Covering relations described by



Summary so far, and what's ahead

What we have seen:

- The covering relations of the middle order are described by



- This interpolates between the weak order and the Bruhat order

What comes next:

- Another combinatorial interpretation of the middle order
- Some of its properties as a poset (in particular: distributive lattice)
- Enumeration of its intervals, and of its boolean intervals
- Implication on its Möbius function
- Combinatorial description of its Euler characteristic
- Restriction to the subset of involutions

The middle order and inversion sequences

Inversion sequences, and bijection with permutations

- Reminder: Inversions are occurrences $\cdots j \cdots i \cdots$ of the pattern 21.
- j is called inversion top.

- Given $\sigma \in S_n$, let x_j = number of inversions of σ such that j is the inversion top. Observe that $0 \leq x_j < j$.
- Let $\varphi(\sigma) = (x_1, x_2, \cdots, x_n)$ be the inversion sequence of σ.
- Sometimes called Lehmer code. Several (symmetric) variant exist.

- Example: For $\sigma = 4\,1\,5\,6\,2\,3$, we have $\varphi(\sigma) = (0, 0, 0, 3, 2, 2)$

- This is a bijection between S_n and the set I_n of inversion sequences of size n:

$$I_n = [0, 0] \times [0, 1] \times [0, 2] \times \cdots \times [0, n-1]$$

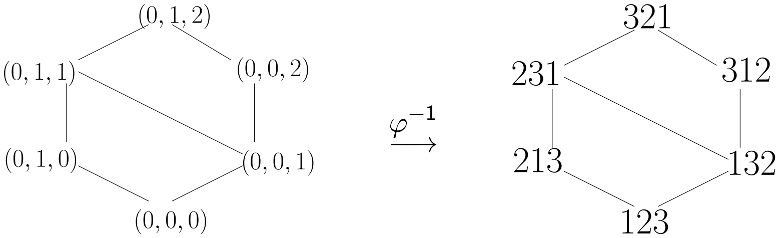
Middle order through inversion sequences

For inversion sequences $\mathbf{x} = (x_1, x_2, \cdots, x_n)$ and $\mathbf{y} = (y_1, y_2, \cdots, y_n)$, define the partial order

$$\mathbf{x} \leq \mathbf{y} \text{ when } x_i \leq y_i \text{ for all } i$$

In particular, covering relations correspond to adding 1 to one component (provided we stay among inversion sequences).

Theorem: The middle order is the image of the above by the bijection φ^{-1}.



Proving this characterization of the middle order

Let $\varphi(\sigma) = (x_1, \dots, x_n)$ and $\varphi(\tau) = (x_1, \dots, x_{j-1}, x_j + 1, x_{j+1}, \dots, x_n)$.

- In particular, $x_j < j - 1$.
- So j is not a LtoR-minimum.
- So, we can define i as the rightmost entry to the left of j in σ such that $i < j$, and (i, j) is an occurrence of .
- We check that τ is the permutation obtained swapping i and j, so that τ covers σ in the middle order.

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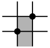
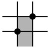
Let τ be obtained from σ by transforming one  into .

- Let j be the largest of the two elements involved in 
- $\varphi(\sigma)$ and $\varphi(\tau)$ differ only at their j-th coordinate
- and the difference is $+1$
- meaning that $\varphi(\tau)$ covers $\varphi(\sigma)$ in the defined order on inversion sequences

First properties of the middle order

A product of chains

We have seen that the middle order $\mathcal{P}_n$ is isomorphic (with explicit bijection φ) to the product of chains

$$[0,0] \times [0,1] \times [0,2] \times \cdots \times [0,n-1]$$

Consequences:

- $\mathcal{P}_n$ is a lattice: any σ and τ have a least upper bound $\sigma \vee \tau$ (called join) and a greatest lower bound, denoted $\sigma \wedge \tau$ (called meet).
  The join (resp. meet) is obtained taking component-wise maximum (resp. minimum) on corresponding inversion sequences.
- In addition, $\mathcal{P}_n$ is a distributive lattice.
  (meaning that $\vee$ is distributive over $\wedge$ and vice-versa).
- $\mathcal{P}_n$ is graded, *i.e.* has a rank function r, meaning that, for any σ, we can define $r(\sigma)$ as the length of any maximal chain from $12 \cdots n$ to σ.
  In $\mathcal{P}_n$, we have $r(\sigma) =$ number of inversions of σ.

Intervals in the middle order

Characterizing and counting all intervals in $\mathcal{P}_n$

Intervals of the j-element chain $[0, j-1]$:

- Such intervals are
  - of the form $\{a\}$ for $0 \leq a \leq j-1$,
  - or of the form $[a, b]$ for $0 \leq a < b \leq j-1$.
- Therefore, there are $j + \binom{j}{2} = \binom{j+1}{2}$ such intervals.

Intervals of $\mathcal{P}_n$ (up to isomorphism φ):

- Such intervals correspond to intervals $[(x_1, \dots, x_n), (y_1, \dots, y_n)]$ where each $[x_j, y_j]$ is an interval of $[0, j-1]$.
- Therefore, there are $\prod_{j=1}^{n} \binom{j+1}{2} = \frac{n!(n+1)!}{2^n}$ intervals in $\mathcal{P}_n$.

Counting intervals by rank

Fact: An interval of rank k in $\mathcal{P}_n$ corresponds to an interval $[(x_1, \ldots, x_n), (y_1, \ldots, y_n)]$ with $\sum x_j + k = \sum y_j$.

Theorem: Denote by $f(n, k)$ the number of intervals in $\mathcal{P}_n$ having rank k, with $n \geq 1$ and $k \geq 0$.

It holds that $f(1, 0) = 1$ and for $n \geq 2$ and $k \in [0, \binom{n}{2}]$,

$$f(n, k) = \sum_{h=0}^{n-1} (n-h) \cdot f(n-1, k-h),$$

(with the convention that $f(n, j) = 0$ when $j < 0$).

Proof: By induction, decomposing an interval of rank k of $[0, 0] \times [0, 1] \times \cdots \times [0, n-2] \times [0, n-1]$ into an interval of rank h of $[0, n-1]$ and an interval of rank $k-h$ of $[0, 0] \times [0, 1] \times \cdots \times [0, n-2]$

Table of $f(n,k)$, which is A139769 on the OEIS

n \ k	**0**	1	2	3	4	5	6	7	8	9	10
1	**1**										
2	**2**	1									
3	**6**	7	4	1							
4	**24**	46	49	36	18	6	1				
5	**120**	326	501	562	497	354	204	94	33	8	1

- $\mathbf{k=0}$: $f(n,0)=n!$ since it counts elements in $\mathcal{P}_n$
- $k=1$: $f(n,1)$ counts the covering relations in $\mathcal{P}_n$. From the previous theorem, we have $f(n,1)=n!(n-H_n)$, where $H_n=\sum_{i=1}^{n}\frac{1}{i}$.

  This is sequence A067318 in the OEIS.

  Another interpretation of this sequence is as the sum of reflection lengths of all elements of S_n. Is there a bijective explanation?

Boolean intervals in the middle order

Characterizing and counting boolean intervals in $\mathcal{P}_n$

Dfn: An interval is boolean if it is isomorphic to a boolean algebra.

Characterization and enumeration:

- Boolean intervals of $\mathcal{P}_n$ correspond to pairs $(x_1, \ldots, x_n), (y_1, \ldots, y_n)$ of inversion sequences with $y_j \in \{x_j, x_j + 1\}$ for all j.
- The number of boolean intervals in $\mathcal{P}_n$ is $(2n-1)!!$.
  - Indeed, each pair (x_j, y_j) has j possibilities if $y_j = x_j$, and $j-1$ possibilities if $y_j = x_j + 1$, hence $2j-1$ possibilities.

Properties about rank of boolean intervals:

- The rank is the number of j's such that $y_j = x_j + 1$.
- The maximal rank is $n-1$ (as $x_1 = y_1 = 0$).

Counting boolean intervals in $\mathcal{P}_n$ by rank

For $n > k \geq 0$, let $b(n,k)$ be the number of rank-k boolean intervals in $\mathcal{P}_n$.

- For $n \geq j \geq 0$, let $c(n,j)$ be the number of permutations of size n having j cycles.
- Equivalently (using a variant of Foata's bijection), $c(n,j)$ is the number of permutations of size n having j RtoL-minima.

Theorem: $b(n,k) = \sum_{i=0}^{n} \binom{i}{k} c(n, n-i)$.

Proof:

- $x_i = 0$ if and only if i is a RtoL-minimum. So $c(n, n-i)$ is the number of inversion sequences of size n with i non-zero entries.
- A boolean interval of rank k in $\mathcal{P}_n$ is characterized by an inversion sequence $(y_1, \ldots, y_n)$ with k non-zero entries marked (those such that $x_j = y_j - 1$; we take $x_j = y_j$ for non-marked entries).

Möbius function

Dfn: The Möbius function μ on any poset $\mathcal{P}$ is defined recursively by

$$\mu(s,u) = \begin{cases} 0 & \text{if } s \not\leq u, \\ 1 & \text{if } s = u, \text{ and} \\ -\sum_{s \leq t < u} \mu(s,t) & \text{for all } s < u. \end{cases}$$

Prop: In finite distributive lattices, for any v, w, it holds that

- $\mu(v,w)$ is equal to 0 if the interval $[v,w]$ is not boolean
- and otherwise $\mu(v,w) = (-1)^t$, where t is the rank of $[v,w]$.

This holds in $\mathcal{P}_n$. In particular, for $\sigma \in S_n$,

- $\mu(12\cdots n, \sigma) = 0$ if and only if $\varphi(\sigma)$ contains ≥ 1 entry ≥ 2. This is equivalent to σ containing a 312- or 321-pattern.
- Otherwise, $\mu(12\cdots n, \sigma) = (-1)^t$, where t is the number of 1's in $\varphi(\sigma)$ (here, also the number of inversions of σ).

Euler characteristic

Euler characteristic of a finite distributive lattice

Let $\mathcal{P}$ be a finite distributive lattice. (Recall that $\mathcal{P}_n$ has this property.)

- Dfn: An element of $\mathcal{P}$ is join-irreducible if it covers exactly one element of $\mathcal{P}$.
- Dfn: A valuation on $\mathcal{P}$ is a function ν that satisfies $\nu(\min(\mathcal{P})) = 0$ and for all x, y,

$$\nu(x) + \nu(y) = \nu(x \wedge y) + \nu(x \vee y).$$

- Prop.: A valuation is determined by its values on the join-irreducibles.
- Dfn: The Euler characteristic is the unique valuation χ such that $\chi(a) = 1$ for every join-irreducible a.

Join-irreducibles and Euler characteristic in $\mathcal{P}_n$

Prop.: The join-irreducible elements of $\mathcal{P}_n$ are the permutations

$$1\ 2\ \cdots\ i\ j\ (i+1)\ (i+2)\ \cdots\ (j-1)\ (j+1)\ \cdots\ n,$$

for $i \in [0, n-2]$ and $j \in [i+2, n]$.

Proof: Similar to previous ones, using inversion sequences.

Theorem: The Euler characteristic χ on $\mathcal{P}_n$ is

$$\chi(\sigma) = \text{ number of RtoL-non-minima of } \sigma.$$

Proof:

- χ is indeed 0 on $12 \cdots n$, and 1 on join-irreducibles.
- We can easily check that $\chi(x) + \chi(y) = \chi(x \wedge y) + \chi(x \vee y)$.

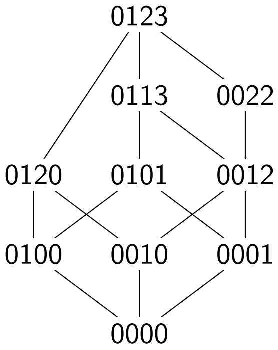
Cor.: The number of σ with Euler characteristic k in $\mathcal{P}_n$ is $c(n, n-k)$.

Proof: As $c(n, n-k) =$ number of σ of size n with k RtoL-non-minima

Restriction to involutions

Finding something not-so-nice in something too-beautiful

$\mathcal{P}_n$ is extremely well behaved. What about its restriction to involutions?



The subsequent poset $\mathcal{I}_n$ is not a lattice, not graded, and not an interval-closed subposet of $\mathcal{P}_n$.

But ... we can still compute the Möbius function in $\mathcal{I}_n$.

Characterizing inversion sequences of involutions

Recall that the number $i(n)$ of involutions of size n satisfies

$$i(n) = i(n-1) + (n-1) \cdot i(n-2) \text{ for } n \geq 2.$$

The decomposition used to prove this recurrence also proves that:

Prop.: Let σ be a permutation and $(x_1, \dots, x_n) = \varphi(\sigma)$ be its inversion sequence.
Then σ is an involution if and only if

(i) $x_n = 0$ and $(x_1, \dots x_{n-1})$ is the inversion sequence of an involution of size $n-1$, or

(ii) $x_n = k > 0$, $x_{n-k} = 0$ and $(x_1, \dots, x_{n-k-1}, x_{n-k+1} - 1, \dots, x_{n-1} - 1)$ is the inversion sequence of an involution of size $n-2$.

Möbius function on $\mathcal{I}_n$

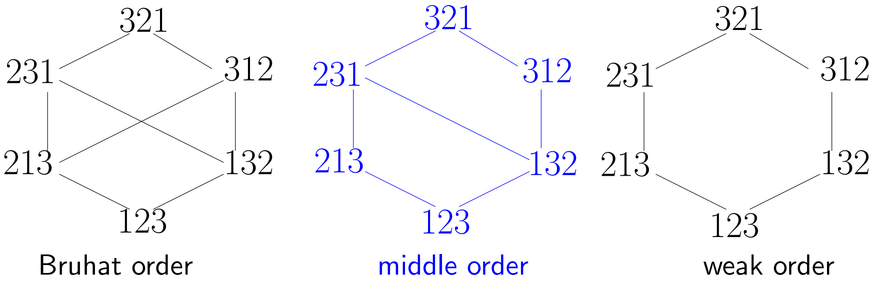
- We say that $(x_1, \dots, x_n)$ is slow-climbing when it does not contain large ascents, defined as factors (x_i, x_{i+1}) with $x_{i+1} > x_i + 1$.
- Lemma: The inversion sequence of an involution is slow-climbing if and only if it is the concatenation of factors $(0, 1, \cdots, h)$ for some (possibly different) $h \geq 0$.

Theorem: For any involution $\sigma \in \mathcal{I}_n$, let α be the number of non-zero entries in $\varphi(\sigma)$. The Möbius function in $\mathcal{I}_n$ is given by

$$\mu(12 \dots n, \sigma) = \begin{cases} (-1)^\alpha & \text{if } \sigma \text{ is slow-climbing, and} \\ 0 & \text{otherwise.} \end{cases}$$

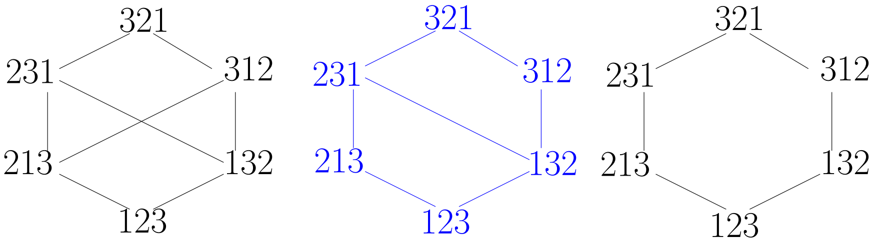
Wrapping up

Recap



My goals were:

- Define the middle order on S_n
- Give meaning to the property that "it sits between weak and Bruhat"
- Describe some of its properties
- Popularize this new order, hoping to raise new questions about it



Bruhat order middle order weak order

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Thank you!