Introduction to research based coding in SageMath

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June 29, 2016

Why contribute to Sage?

- Benefit to the community

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  - Advertise your work

Why contribute to Sage?

- Benefit to the community
- Benefit to you!
    - Don't lose your code
    - Advertise your work
    - Enable others to build on your code/research, so then you can build on their code/research

Outline

1. Research: Alternating sign matrices
2. Code: Alternating sign matrix methods
3. Implement a new alternating sign matrix method
4. Further alternating sign matrix research/code
5. Research: Posets and rowmotion
6. Code: Posets and rowmotion code

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Alternating sign matrix definition

Definition

Alternating sign matrices (ASMs) are square matrices with the following properties:

- entries $\in \{0, 1, -1\}$
- each row and each column sums to 1
- nonzero entries alternate in sign along a row/column

$$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & -1 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

Examples of alternating sign matrices

- All seven of the 3×3 ASMs.

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 & 0 \\ 1 & -1 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$\begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

- Two of the forty-two 4×4 ASMs.

$$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & -1 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & -1 & 1 & 0 \\ 0 & 1 & -1 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

A large random ASM

$$
\begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & -1 & 1 & -1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & -1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & 1 \\
1 & 0 & -1 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 & 1 & 0 & 0 & -1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 & 1 & -1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & -1 & 0 & 0 & 1 & 0 & -1 & 1 & -1 & 1 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \\
0 & 0 & 1 & -1 & 1 & 0 & -1 & 0 & 0 & 1 & -1 & 1 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
$$

Enumeration

- In 1983, W. Mills, D. Robbins, and H. Rumsey conjectured that $n \times n$ ASMs are counted by:

$$\prod_{j=0}^{n-1} \frac{(3j+1)!}{(n+j)!} = \frac{1!4!7!\cdots(3n-2)!}{n!(n+1)!\cdots(2n-1)!}.$$

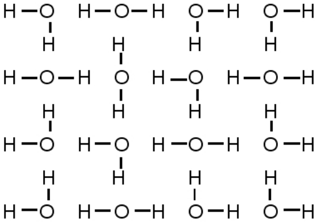
1, 2, 7, 42, 429, 7436, 218348, 10850216, ...

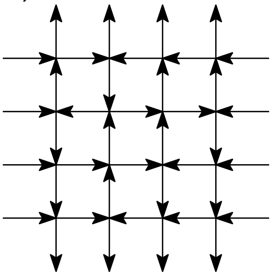
- This was proved in 1996, independently, by D. Zeilberger and G. Kuperberg. Kuperberg's proof introduced the following connection to physics.

Physics connection - Square ice

Alternating sign matrices are in bijection with configurations of the six-vertex model with domain wall boundary conditions.

$$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & -1 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$





Known alternating sign matrix bijections

ASM

$$\begin{pmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & -1 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

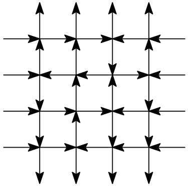
Monotone triangle

$$\begin{array}{ccccccc} & & & 3 & & & \\ & & 1 & & 4 & & \\ & 1 & & 3 & & 4 & \\ 1 & & 2 & & 3 & & 4 \end{array}$$

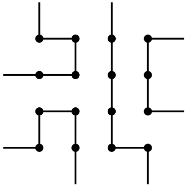
Height function

$$\begin{pmatrix} 0 & 1 & 2 & 3 & 4 \\ 1 & 2 & 3 & 2 & 3 \\ 2 & 1 & 2 & 3 & 2 \\ 3 & 2 & 3 & 2 & 1 \\ 4 & 3 & 2 & 1 & 0 \end{pmatrix}$$

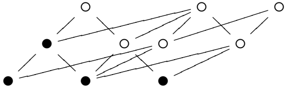
Six-vertex model



Fully-packed loop



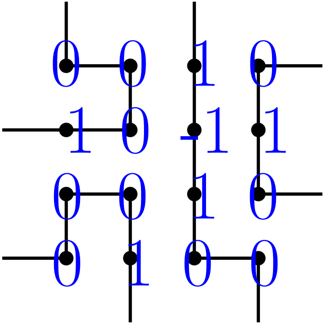
Order ideal



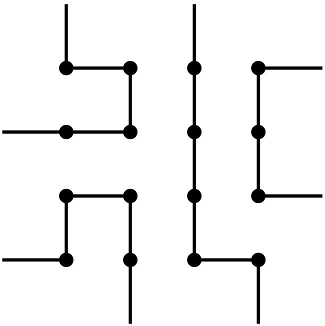
Alternating sign matrices

$$\begin{pmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & -1 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

Alternating sign matrices → fully-packed loops

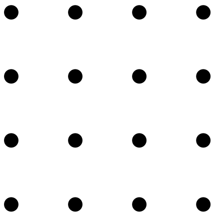


Fully-packed loops



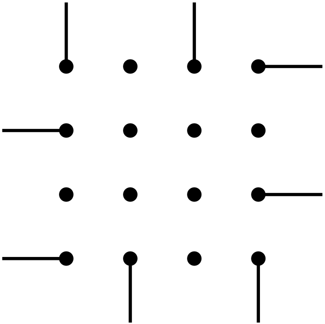
Fully-packed loops

Start with an $n \times n$ grid.



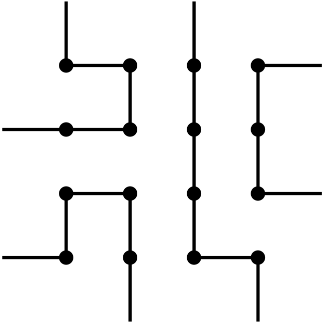
Fully-packed loops

Add boundary conditions.



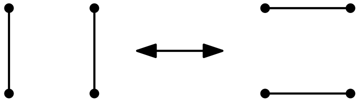
Fully-packed loops

Interior vertices adjacent to 2 edges.

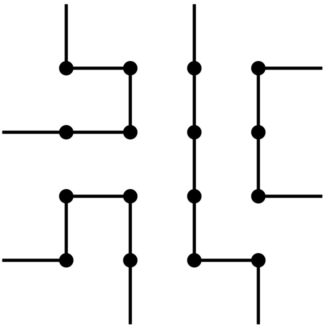


Gyration on fully-packed loops

Given a square in the grid, the *local move* swaps the configurations below and leaves every other edge configuration fixed.

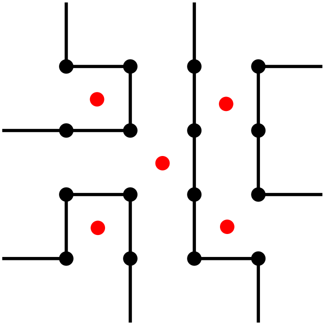


Gyration on fully-packed loops



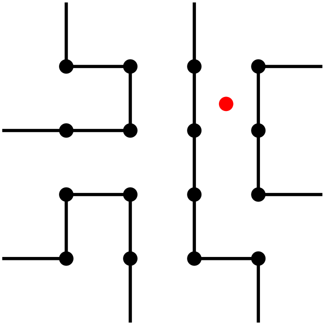
Gyration on fully-packed loops

Start with the even squares.



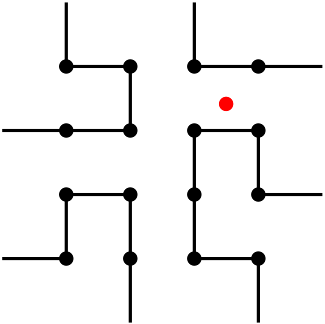
Gyration on fully-packed loops

Apply the local move to all even squares.



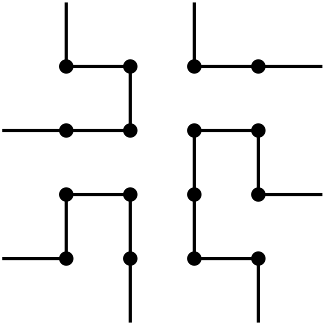
Gyration on fully-packed loops

Apply the local move to all even squares.



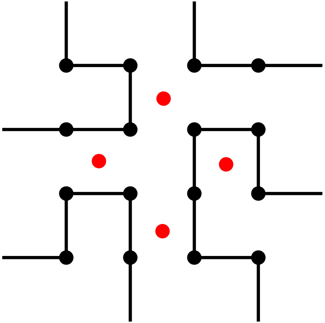
Gyration on fully-packed loops

Apply the local move to all even squares.



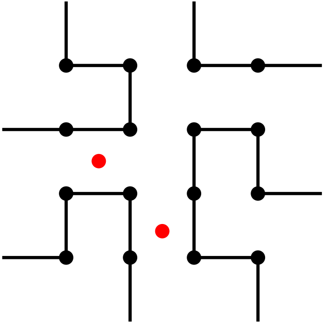
Gyration on fully-packed loops

Now consider the odd squares.



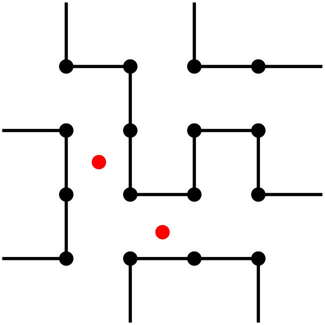
Gyration on fully-packed loops

Apply the local move to all odd squares.



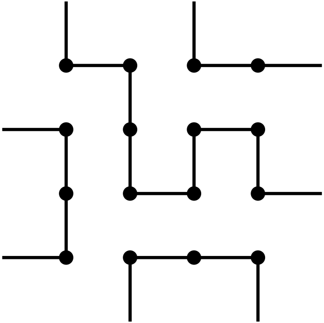
Gyration on fully-packed loops

Apply the local move to all odd squares.

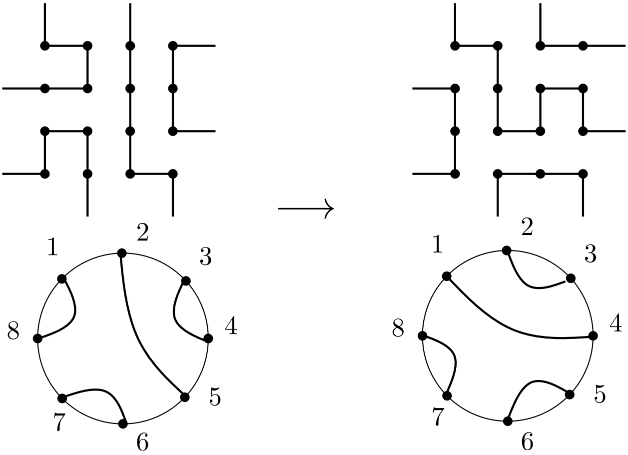


Gyration on fully-packed loops

Apply the local move to all odd squares.



Gyration rotates the link pattern (B. Wieland 2000)



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Writing methods for combinatorial classes

- First, write a function that does what you want it to do.
- Then write some documentation and examples (tests).
- *Add it to your local Sage source code to test (on a new git branch).
- *When everything works, pull a trac ticket and push your code to the trac server.

*Kevin's talk on Friday

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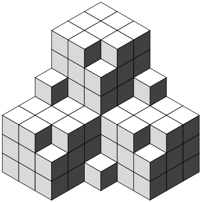
A missing bijection

Definition

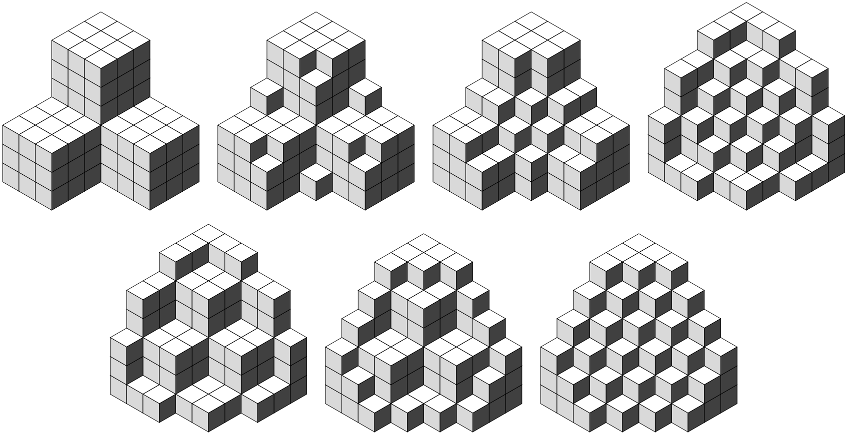
Totally Symmetric Self-Complementary Plane Partitions are:

- Plane Partitions
- Totally Symmetric (invariant under all permutations of the axes)
- Self-Complementary (inside $2n \times 2n \times 2n$ box)



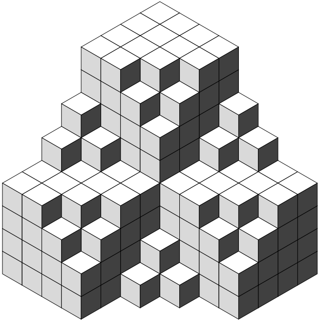
A missing bijection

- All seven of the TSSCPPs inside a $6 \times 6 \times 6$ box.



A missing bijection

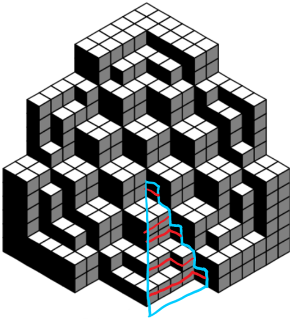
Totally symmetric self-complementary plane partitions inside a $2n \times 2n \times 2n$ box are also counted by $\prod_{j=0}^{n-1} \frac{(3j+1)!}{(n+j)!}$ (Andrews 1994), but **no explicit bijection is known**.



?

$$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & -1 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

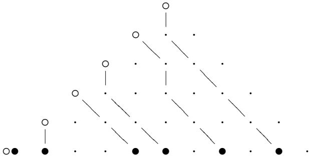
Known TSSCPP bijections



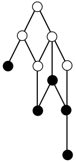
Magog triangle

5
5 6
3 4 5
2 3 4 6
1 2 3 4 5
1 2 3 4 5 6

Lattice paths

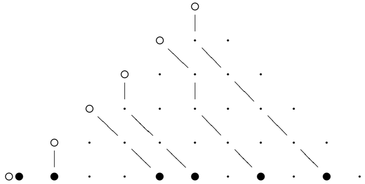


Order ideal



Permutation case progress (S. 2014)

TSSCPP



⇔

Boolean triangle

1

0 0

1 1 0

0 0 0 0

1 0 0 0 0

⇔

Monotone triangle

4

4 6

3 4 6

3 4 5 6

1 3 4 5 6

1 2 3 4 5 6

⇔

Permutation matrix

$$\begin{pmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{pmatrix}$$

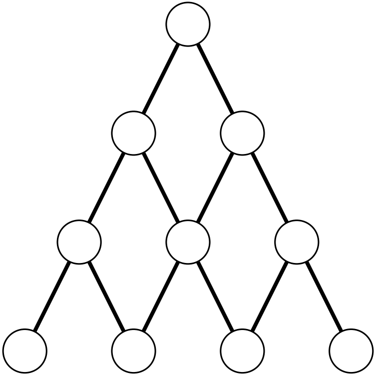
Outline

Posets

A **poset** is a **p**artially **o**rdered **set**.

Definition

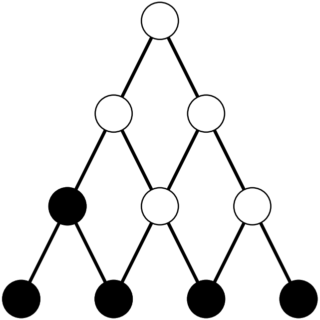
A *poset* is a set with a partial order " $\leq$ " that is reflexive, antisymmetric, and transitive.



Order ideals

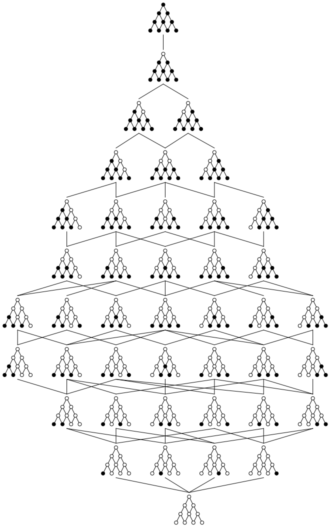
Definition

An *order ideal* of a poset P is a subset $I \subseteq P$ such that if $y \in I$ and $z \leq y$, then $z \in I$.



Ordered by inclusion, order ideals form a *distributive lattice*, denoted $J(\mathcal{P})$.

The distributive lattice of order ideals $J(P)$



ASM height functions

All seven of the height functions of order 3.

$$\begin{pmatrix} 0 & 1 & 2 & 3 \\ 1 & 0 & 1 & 2 \\ 2 & 1 & 0 & 1 \\ 3 & 2 & 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 2 & 3 \\ 1 & 2 & 1 & 2 \\ 2 & 1 & 0 & 1 \\ 3 & 2 & 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 2 & 3 \\ 1 & 0 & 1 & 2 \\ 2 & 1 & 2 & 1 \\ 3 & 2 & 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 2 & 3 \\ 1 & 2 & 1 & 2 \\ 2 & 3 & 2 & 1 \\ 3 & 2 & 1 & 0 \end{pmatrix}$$

$$\begin{pmatrix} 0 & 1 & 2 & 3 \\ 1 & 2 & 3 & 2 \\ 2 & 1 & 2 & 1 \\ 3 & 2 & 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 2 & 3 \\ 1 & 2 & 3 & 2 \\ 2 & 3 & 2 & 1 \\ 3 & 2 & 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 2 & 3 \\ 1 & 2 & 1 & 2 \\ 2 & 1 & 2 & 1 \\ 3 & 2 & 1 & 0 \end{pmatrix}$$

Alternating sign matrix poset (EKLP 1992)

$$\begin{pmatrix} 2 & 3 \\ 3 & 2 \end{pmatrix}$$

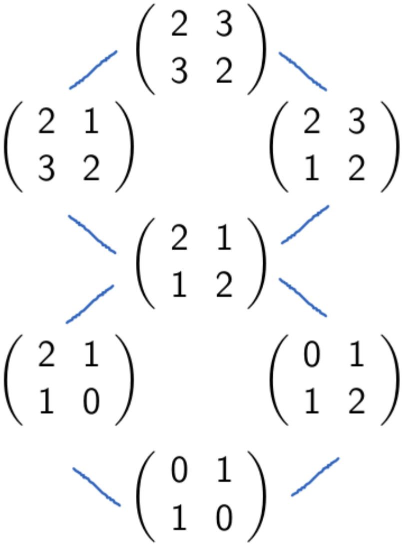
$$\begin{pmatrix} 2 & 1 \\ 3 & 2 \end{pmatrix} \qquad \begin{pmatrix} 2 & 3 \\ 1 & 2 \end{pmatrix}$$

$$\begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix}$$

$$\begin{pmatrix} 2 & 1 \\ 1 & 0 \end{pmatrix} \qquad \begin{pmatrix} 0 & 1 \\ 1 & 2 \end{pmatrix}$$

$$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

Alternating sign matrix poset (EKLP 1992)



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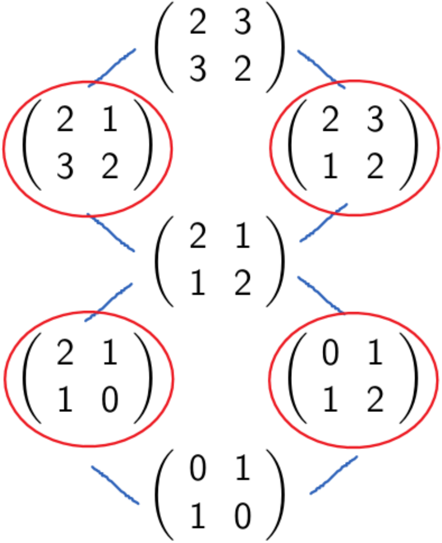

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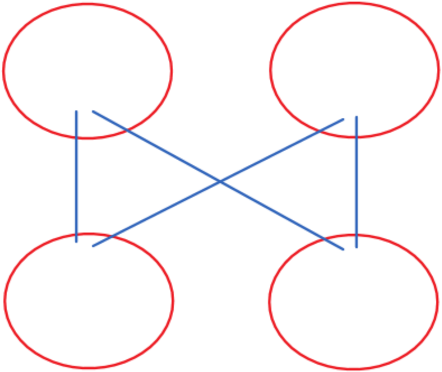

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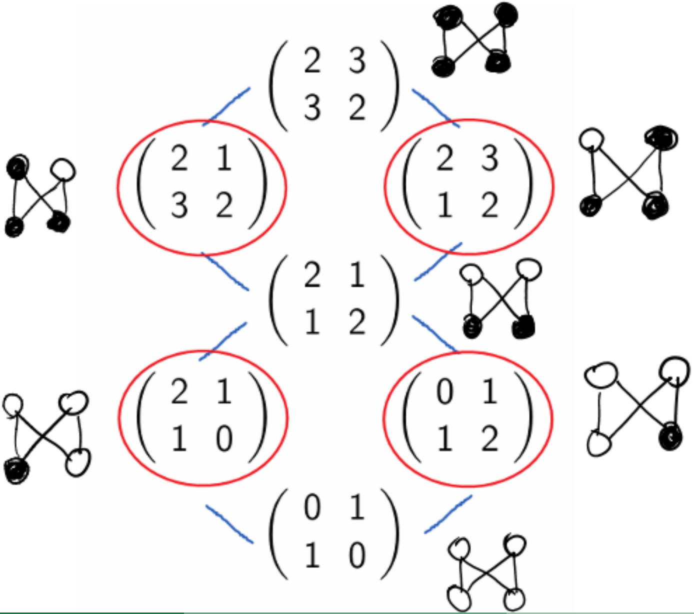

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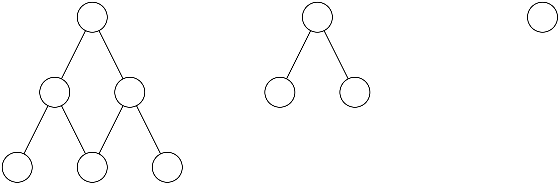

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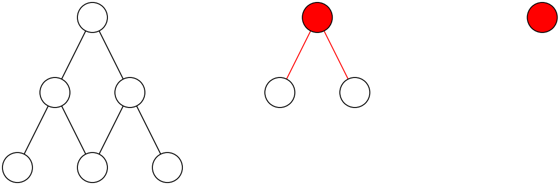

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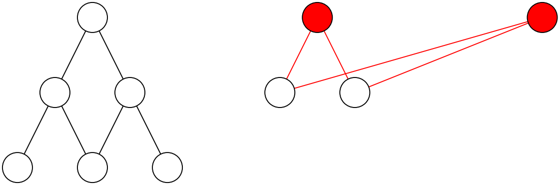

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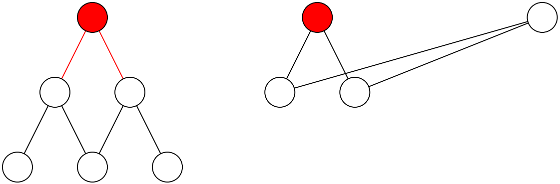

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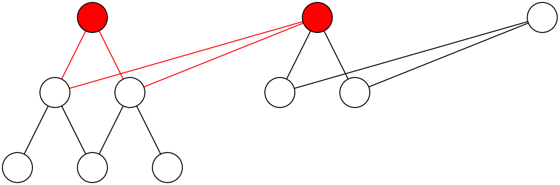
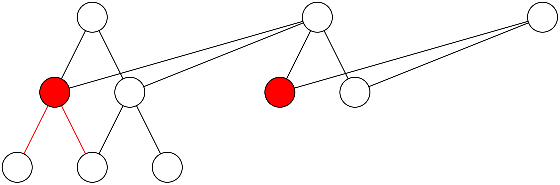
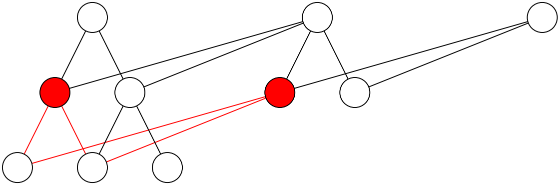


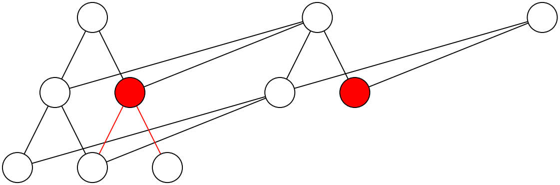
Alternating sign matrix poset



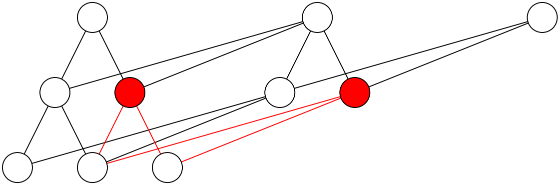
Alternating sign matrix poset



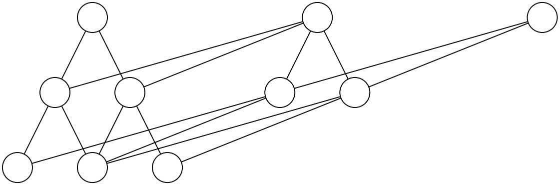
Alternating sign matrix poset



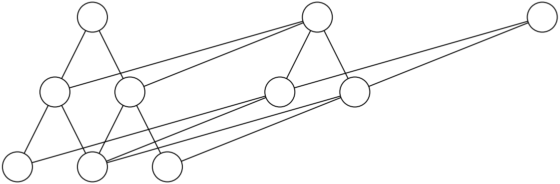
Alternating sign matrix poset



Alternating sign matrix poset



Alternating sign matrix poset

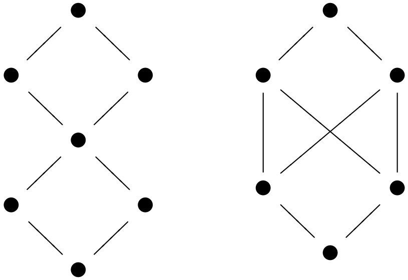


$n \times n$ ASMs are in bijection with order ideals in this poset with $n-1$ layers, as constructed above.

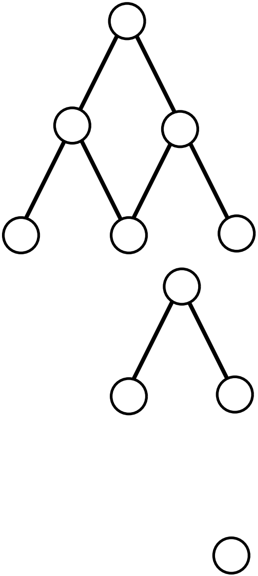
Alternating sign matrix poset

Theorem (Lascoux and Schützenberger 1996)

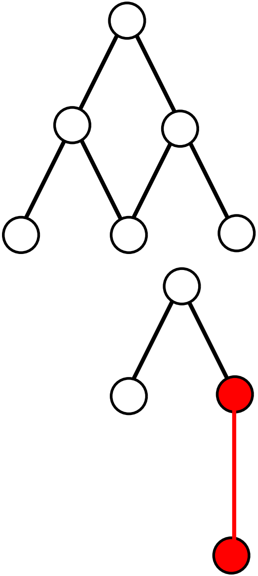
The restriction of the ASM poset to permutations is the Bruhat order. In fact, is the smallest lattice containing the Bruhat order on the symmetric group as a subposet.



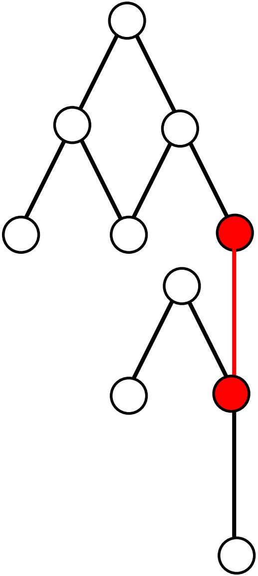
TSSCPP poset



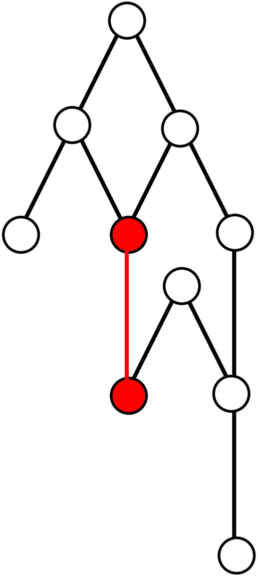
TSSCPP poset



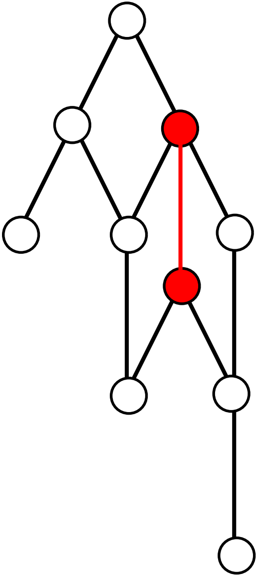
TSSCPP poset



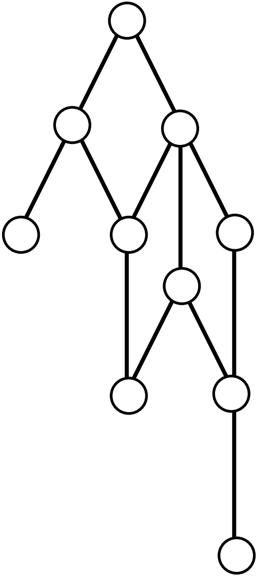
TSSCPP poset



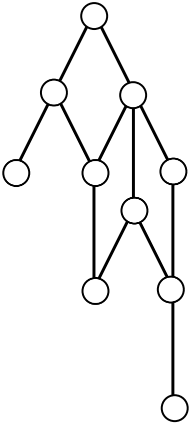
TSSCPP poset



TSSCPP poset

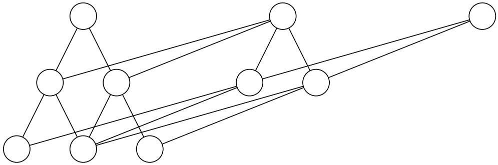


TSSCPP poset

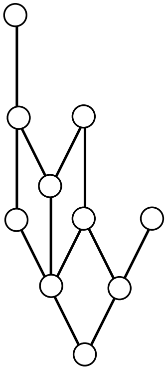


TSSCPPs inside a $2n \times 2n \times 2n$ box are in bijection with order ideals in this poset with $n-1$ layers, as constructed above.

ASM and TSSCPP posets (S. 2011)



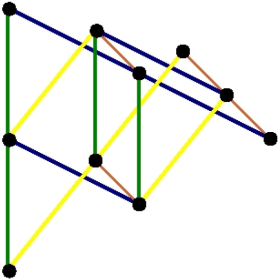
ASM



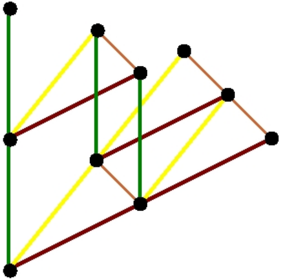
TSSCPP

ASM and TSSCPP posets (S. 2011)

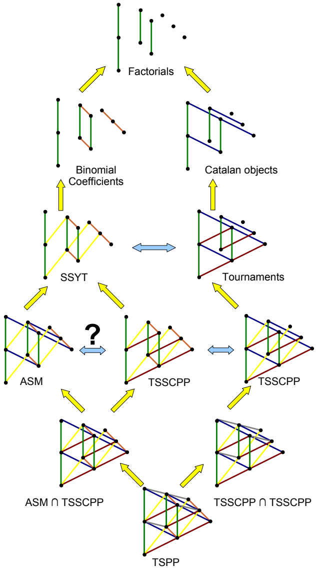
ASM



TSSCPP



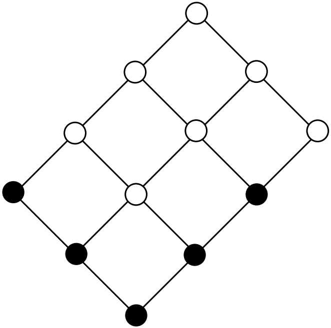
Tetrahedral poset family (S. 2011)



Rowmotion

Definition

Let P be a poset, and let $I \in J(P)$. Then **rowmotion**, $\mathrm{Row}(I)$, is the order ideal generated by the minimal elements of P not in I.

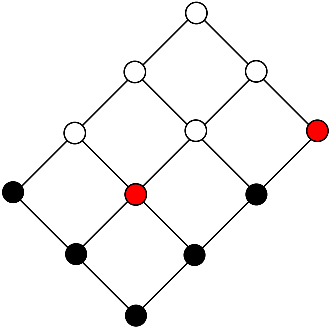


An order ideal I

Rowmotion

Definition

Let P be a poset, and let $I \in J(P)$. Then **rowmotion**, $\text{Row}(I)$, is the order ideal generated by the minimal elements of P not in I.

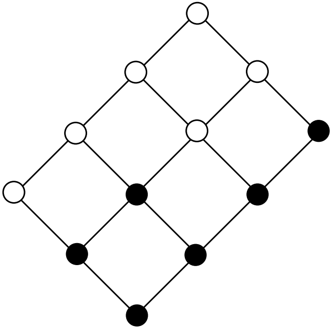


Find the **minimal** elements of P not in I

Rowmotion

Definition

Let P be a poset, and let $I \in J(P)$. Then **rowmotion**, $\mathrm{Row}(I)$, is the order ideal generated by the minimal elements of P not in I.



Use them to generate a new order ideal **Row**(**I**)

Outline

Promotion, rowmotion, and gyration

Theorem (N. Williams and S. 2012)

In any ranked poset, there is an equivariant bijection between the order ideals under rowmotion and promotion.

Corollary

Gyration on fully-packed loops and rowmotion on the ASM poset have the same orbit structure!