Combinatorial Actions, Orbit Averages, and Sage Implementation

Tom Roby (University of Connecticut)
Darij Grinberg (MIT)

Describing joint research with Jim Propp

Sage Days 7² Orsay, France

28 June 2013

Slides for this talk are available online (or will be soon) at

http://www.math.uconn.edu/~troby/research.html
Abstract

We consider a variety of combinatorial actions on finite sets, e.g., cyclic rotation of binary strings, promotion of Young tableaux and rowmotion on order ideals of partially ordered sets. We identify a particular phenomenon called “homomesy” appearing in many unrelated combinatorial contexts: namely that the average value of some natural statistic over each orbit is the same as the average over the entire set. Viewing these actions as products of “toggle operations” allows us to see how some of these actions are related and to extend much of this picture more broadly. In particular, we can generalize the operations of rowmotion and promotion (in Striker and Williams’ terminology) on order ideals in a poset to (1) the order polytope of a poset (the continuous piecewise-linear category), and (2) to the collection of maps from a poset $P$ to rational functions in $|P|$ variables (the birational category).

For this latter category, we have developed Sage code that (1) computes the rowmotion operator; (2) checks whether this operator appears to have finite order; (3) helps check for homomesy of particular statistics under the action of the operator. Although we have proofs of homomesy for a number of special cases, much remains to be done even at the combinatorial level of order ideals on posets. For the two other categories most of what we have discovered via computations is still conjectural.
This talk largely discusses recent work with Jim Propp, including ideas and results from Arkady Berenstein, David Einstein, Shahrzad Haddadan, Jessica Striker, and Nathan Williams.

Mike LaCroix wrote fantastic postscript code to generate animations and pictures that illustrate our maps operating on order ideals on products of chains. Jim Propp created many of the other pictures and slides that are used here.

Thanks also to Omer Angel, Drew Armstrong, Anders Björner, Barry Cipra, Karen Edwards, Robert Edwards, Svante Linusson, Vic Reiner, Richard Stanley, Ralf Schiffler, Hugh Thomas, Pete Winkler, and Ben Young.
Overview

- Rotation of bit-strings;
- Unexpected averaging properties: homomesic statistics;
- Suter’s dihedral symmetries in Young’s lattice;
- Rowmotion and Promotion actions on antichains and order ideals of posets;
- Homomesic statistics for actions in \([a] \times [b]\);
- Generalizing to other actions on order polytopes and rational functions;
- Demonstration of Sage code; and
- Wish list for Sage implementation.

Please interrupt with questions!
Example 1: Rotation of bit-strings

Let $S$ denote the set of length $n$ binary strings with exactly $k$ 1’s. and set $\tau := C_R : S \to S$ by $b = b_1b_2\cdots b_n \mapsto b_nb_1b_2\cdots b_{n-1}$ (cyclic shift). Let $\varphi(b) = \#\text{inversions}(b) = \#\{i < j : b_i > b_j\}$.

Then over any $\tau$-orbit $O$ we have:

$$\frac{1}{\#O} \sum_{s \in O} \varphi(s) = \frac{k(n-k)}{2} = \frac{1}{\#S} \sum_{s \in S} \varphi(s).$$
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EG: $n = 4, k = 2$ gives us two orbits:

$$\begin{array}{cc}
0011 & 0101 \\
1001 & 1010 \\
1100 & 0110 \\
0011 & 0101 \\
\end{array}$$
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EG: $n = 6, k = 2$ gives us three orbits:

\begin{align*}
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More rotation

EG: \( n = 6, k = 2 \) gives us three orbits:

\[
\begin{array}{c|c|c}
000011 & 000101 & 001001 \\
100011 & 100100 & 100001 \\
110011 & 010100 & 010010 \\
011101 & 000110 & 000110 \\
001011 & 010001 & 010010 \\
000001 & 000011 & 000011 \\
\end{array}
\]

\[
\begin{array}{c|c|c}
100011 \mapsto 4 & 100010 \mapsto 5 & 100100 \mapsto 6 \\
110000 \mapsto 8 & 010001 \mapsto 3 & 010010 \mapsto 4 \\
011000 \mapsto 6 & 101000 \mapsto 7 & 001001 \mapsto 2 \\
001100 \mapsto 4 & 010100 \mapsto 5 & \\
000110 \mapsto 2 & 001010 \mapsto 3 & \\
000011 \mapsto 0 & 000101 \mapsto 1 & \\
\end{array}
\]

\[
\text{AVG} = \frac{24}{6} = 4 \quad \text{AVG} = \frac{24}{6} = 4 \quad \text{AVG} = \frac{12}{3} = 4
\]
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AVG = \( \frac{24}{6} = 4 \)   AVG = \( \frac{24}{6} = 4 \)   AVG = \( \frac{12}{3} = 4 \)

We know two simple ways to prove this: one can show pictorially that the value of the sum doesn’t change when you mutate \( b \) (replacing a 01 somewhere in \( b \) by 10 or vice versa), or one can write the number of inversions in \( b \) as \( \sum_{i<j} b_i(1 - b_j) \) and then perform algebraic manipulations.
Main definition: Homomesic

**Main Def:** Given an (invertible) action $\tau$ on a finite set of objects $S$, call a statistic $\varphi : S \to \mathbb{C}$ **homomesic** with respect to $(S, \tau)$ iff the average of $\varphi$ over each $\tau$-orbit $O$ is the same for all $O$, i.e., $\frac{1}{\#O} \sum_{s \in O} \varphi(s)$ does not depend on the choice of $O$. 
**MAIN DEF:** Given an (invertible) action \( \tau \) on a finite set of objects \( S \), call a statistic \( \varphi : S \to \mathbb{C} \) **homomesic** with respect to \((S, \tau)\) iff the average of \( \varphi \) over each \( \tau \)-orbit \( O \) is the same for all \( O \), i.e., \[
\frac{1}{\#O} \sum_{s \in O} \varphi(s) \text{ does not depend on the choice of } O.
\]
Equivalently: the average of \( \varphi \) over each \( \tau \)-orbit \( O \) is the same as the average over the entire set \( S \):

\[
\frac{1}{\#O} \sum_{s \in O} \varphi(s) = \frac{1}{\#S} \sum_{s \in S} \varphi(s).
\]
So in looking for homomesic statistics we can compute what the average should be before checking whether a statistic is homomesic.
Fix a positive integer $N$. A **semi-standard Young tableau (SSYT) of shape $\lambda$ and ceiling $N$** is a labeling of the cells of the Young diagram of a partition $\lambda$ with numbers from 1, 2, ..., $N$ which increases **weakly** along each row and **strictly** along each column. For example,

$$
\begin{array}{cccc}
1 & 1 & 2 & 4 \\
2 & 3 & 4 \\
4 & 4 \\
\end{array}, \quad
\begin{array}{cccc}
1 & 1 & 1 & 2 & 2 & 5 \\
4 & 4 & 4 & 5 \\
5 & 5 & 6 \\
\end{array}, \quad
\begin{array}{cccc}
1 & 1 & 2 & 2 & 3 & 3 \\
2 & 3 & 4 & 4 \\
3 & 4 & 4 \\
\end{array}
$$

The **weight vector** $\alpha(T) = (\alpha_1, \alpha_2, \ldots, \alpha_N)$ is given by $\alpha_i := \alpha_i(T) = \#\text{occurrences of } i \text{ in } T$. EG, the weight vectors for the two tableaux above are $(2, 2, 1, 4)$ and $(3, 2, 0, 3, 4, 1)$.

We let $SSYT(\lambda, N)$ denote the set of all semi-standard Young tableaux whose entries lie within $[N] = \{1, 2, \ldots, N\}$. 

A standard method for proving combinatorially that Schur functions are symmetric is to use Bender-Knuth involutions. Given $T \in SSYT(\lambda, N)$ and $i \in [N - 1]$, consider all the $i$’s that appear above an $i + 1$ in the same column, and all the $i + 1$’s that appear below an $i$ in the same column to be married and the remainder free. Then in each row with $r$ free $i$’s and $s$ free $i + 1$’s, $\beta_i$ replaces these with $s$ free $i$’s and $r$ free $i + 1$’s.
Define the following operator on $SSYT(\lambda, N)$:

$$\partial := \beta_{N-1} \circ \beta_{N-2} \circ \cdots \circ \beta_2 \circ \beta_1,$$

the composition of all BK involutions in order. By a result of Gansner [Gan80], this operator coincides with Schützenberger’s promotion operator. Then for all $i \in [N]$, the weight vector coordinate $\alpha_i(T)$ is homomesic w.r.t. $\partial$ acting on $SSYT(\lambda, N)$. 

EG: Let $N = 5$ and $T = 1 1 1 2 2 3 3 3 4 2 2 3 3 4 4 5 3 4 4 5$. Then the content vectors $\alpha = [\alpha_1, \alpha_2, \ldots, \alpha_N]$ that arise as we successively apply $\beta_i$’s behave as follows, starting from $[3, 4, 6, 5, 2]$:

\[
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EG: Let $N = 5$ and $T = \begin{pmatrix} 1 & 1 & 1 & 2 & 2 & 3 & 3 & 3 & 4 \\ 2 & 2 & 3 & 3 & 4 & 4 & 5 \\ 3 & 4 & 4 & 5 \end{pmatrix}$

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$$
\begin{array}{ccccccc}
\end{array}
$$
An easy homomesy for Promotion

*From previous slide:* The content vectors $\alpha = [\alpha_1, \alpha_2, \ldots, \alpha_N]$ that arise as we successively apply $\beta_i$'s behave as follows (working down columns), starting from $[3, 4, 6, 5, 2]$:

$$
\begin{align*}
\end{align*}
$$

Note that each iteration of promotion (going down each full column) applies a cyclic shift of the content vector. This is enough to prove that $\alpha_i(T)$ is homomesic, even though we don’t know how long the orbit is. But it must be a multiple of 5 for the content vector to return to where it started. So over any orbit, each content value visits each position equally often.
An easy homomesy for Promotion

*From previous slide:* The content vectors \( \alpha = [\alpha_1, \alpha_2, \ldots, \alpha_N] \) that arise as we successively apply \( \beta_i \)'s behave as follows (working down columns), starting from \([3, 4, 6, 5, 2]:\)

\[
\begin{align*}
[4, 3, 6, 5, 2] & \quad [6, 4, 5, 2, 3] & \quad [5, 6, 2, 3, 4] & \quad [2, 5, 3, 4, 6] & \quad [3, 2, 4, 6, 5] \\
[4, 6, 3, 5, 2] & \quad [6, 5, 4, 2, 3] & \quad [5, 2, 6, 3, 4] & \quad [2, 3, 5, 4, 6] & \quad [3, 4, 2, 6, 5] \\
[4, 6, 5, 3, 2] & \quad [6, 5, 2, 4, 3] & \quad [5, 2, 3, 6, 4] & \quad [2, 3, 4, 5, 6] & \quad [3, 4, 6, 2, 5] \\
[4, 6, 5, 2, 3] & \quad [6, 5, 2, 3, 4] & \quad [5, 2, 3, 4, 6] & \quad [2, 3, 4, 6, 5] & \quad [3, 4, 6, 5, 2]
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However, we conjecture more interesting homomesies which we are about to test more thoroughly using Sage.
A small example of promotion


![Diagram](image-url)

*Fig. 5. The two orbits of SYT of shape (3, 3) under promotion, the same two orbits as maximal chains, and the same two orbits as order ideals under Pro.*
A small example of promotion: centrally symmetric sums

Fig. 5. The two orbits of SYT of shape (3, 3) under promotion, the same two orbits as maximal chains, and the same two orbits as order ideals under Pro.

Average within each orbit is 7
Conjecture

Let $S$ be the set of Semi-Standard Young Tableaux of rectangular shape $\lambda$ and ceiling $N$. If $c$ and $c'$ are opposite cells, i.e., $c$ and $c'$ are related by 180-degree rotation about the center (note: the case $c = c'$ is permitted when $\lambda$ is odd-by-odd), and $\varphi(T)$ denotes the sum of the numbers in cells $c$ and $c'$, then $\varphi$ is homomesic with respect to $(S, \partial)$ with average value $N + 1$. 

**Conjecture**

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Rectangular shapes are one of the few shapes where the order of promotion on the set of SYT is small, i.e., $n$ or $2n$. Striker & Williams note that the order of promotion on SYT of shape $(8, 6)$ is $7,554,844,752$. 

\[
\begin{array}{ccccccccc}
\text{cell} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\
\text{cell} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\
\end{array}
\]
A **partially ordered set** (or **poset**) is a set $P$ with a binary relation $\leq$ that satisfies the following properties for every $a, b, c \in P$:

(a) *reflexive* ($a \leq a$),

(b) *antisymmetric* ($a \leq b$ and $b \leq a$ $\implies$ $a = b$), and

(c) *transitive* ($a \leq b$ and $b \leq c$ $\implies$ $a \leq c$). All our posets will be finite and can be represented by directed graphs of minimal covering relations, as I’ll draw on the board.
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An **antichain** $A \subseteq P$ is any set of unrelated elements. The collection of all antichains is denoted $\mathcal{A}(P)$. 

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**Basics of partially ordered sets**
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An **antichain** $A \subseteq P$ is any set of unrelated elements. The collection of all antichains is denoted $\mathcal{A}(P)$.

An **order ideal** or **down-set** $I \subseteq P$ is any set with the property that $z \in I$ and $x \leq z$ in $P \implies x \in I$. The collection of all order ideals is denoted $\mathcal{J}(P)$.

There is an easy bijection between $\mathcal{A}(P)$ and $\mathcal{J}(P)$, given by taking $A \in \mathcal{A}(P)$ to the order ideal generated by $A$, and conversely taking $I \in \mathcal{J}(P)$ to the maximal elements of $I$. 
Rowmotion: an invertible operation on antichains

Given $A \in \mathcal{A}(P)$, let $\tau(A)$ be the set of minimal elements of the complement of the order ideal generated by $A$. 

$\tau$ is invertible since it is a composition of three invertible operations:

$$\text{antichains} \leftrightarrow \text{down-sets} \leftrightarrow \text{up-sets} \leftrightarrow \text{antichains}$$

We can also view this as an invertible action $\bar{\tau}$ on $J(P)$, the set of order ideals of $P$, via the above isomorphism between $\mathcal{A}(P)$ and $J(P)$; in other words, perform the above steps in the order 2,3,1.

This map and its inverse have been considered with varying degrees of generality, by many people more or less independently (using a variety of nomenclatures and notations): Duchet, Brouwer and Schrijver, Cameron and Fon Der Flaass, Fukuda, Panyushev, Rush and Shi, and Striker and Williams [SW12]. Following [SW12], we call this rowmotion.
1. Saturate downward

2. Complement

3. Take minimal element(s)
Example in lattice cell form

Viewing the elements of the poset as **squares**, we would map:

![Diagram with areas 8 and 10]
Let $\Delta$ be a reduced irreducible root system in $\mathbb{R}^n$. (Picture coming soon!)

Choose a system of positive roots and make it a poset of rank $n$ by decreeing that $y$ covers $x$ iff $y - x$ is a simple root.

**Conjecture** (Conjecture 2.1(iii) in D.I. Panyushev, *On orbits of antichains of positive roots*, European J. Combin. 30 (2009), 586-594): Let $O$ be an arbitrary $\tau$-orbit. Then

$$\frac{1}{\#O} \sum_{A \in O} \#A = \frac{n}{2}.$$ 

In our language, the cardinality statistic is homomesic with respect to the action of rowmotion on antichains in root posets.

Panyushev’s Conjecture 2.1(iii) (along with much else) was proved by Armstrong, Stump, and Thomas in their article *A uniform bijection between nonnesting and noncrossing partitions*, [http://arxiv.org/abs/1101.1277](http://arxiv.org/abs/1101.1277).
Here are the classes of posets included in Panyushev’s conjecture.

(Graphic courtesy of Striker-Williams.)
Here we have just an orbit of size 2 and an orbit of size 3:

Within each orbit, the average antichain has cardinality $n/2 = 1$. 
Here’s an example orbit taken from [AST] for the $A_3$ root poset:

For $A_3$ this action has three orbits (sized 2, 4, and 8), and the average cardinality of an antichain is

$$\frac{1}{8} (2 + 1 + 1 + 2 + 2 + 1 + 1 + 2) = \frac{3}{2} = \frac{n}{2}$$
A simpler-to-prove phenomenon of this kind concerns the poset $[a] \times [b]$ (where $[k]$ denotes the linear ordering of $\{1, 2, \ldots, k\}$):

**Theorem (Propp, R.)**

Let $\mathcal{O}$ be an arbitrary $\tau$-orbit in $A([a] \times [b])$. Then

$$\frac{1}{\# \mathcal{O}} \sum_{A \in \mathcal{O}} \# A = \frac{ab}{a + b}.$$ 

Antichains in $[a] \times [b]$: the case $a = b = 2$

Here we have an orbit of size 2 and an orbit of size 4:

Within each orbit, the average antichain has cardinality $ab/(a + b) = 1$. 
Within each orbit, the average antichain has $\frac{1}{2}$ a green element and $\frac{1}{2}$ a blue element.
Antichains in \([a] \times [b]\): fiber-cardinality is homomesic

For \((i, j) \in [a] \times [b]\), and \(A\) an antichain in \([a] \times [b]\), let \(1_{i,j}(A)\) be 1 or 0 according to whether or not \(A\) contains \((i, j)\).

Also, let \(f_i(A) = \sum_{j \in [b]} 1_{i,j}(A) \in \{0, 1\}\) (the cardinality of the intersection of \(A\) with the fiber \(\{(i, 1), (i, 2), \ldots, (i, b)\}\) in \([a] \times [b]\)), so that \(#A = \sum_i f_i(A)\). Likewise let \(g_j(A) = \sum_{i \in [a]} 1_{i,j}(A)\), so that \(#A = \sum_j g_j(A)\).

**Theorem (Propp, R.)**

For all \(i, j\),

\[
\frac{1}{\#O} \sum_{A \in O} f_i(A) = \frac{b}{a + b} \quad \text{and} \quad \frac{1}{\#O} \sum_{A \in O} g_j(A) = \frac{a}{a + b}.
\]

The indicator functions \(f_i\) and \(g_j\) are homomesic under \(\tau\), even though the indicator functions \(1_{i,j}\) aren’t.
Antichains in $[a] \times [b]$: centrally symmetric homomesies

Theorem (Propp, R.)

In any orbit, the number of $A$ that contain $(i, j)$ equals the number of $A$ that contain the opposite element $(i', j') = (a + 1 - i, b + 1 - j)$.

That is, the function $1_{i,j} - 1_{i',j'}$ is homomesic under $\tau$, with average value 0 in each orbit.
Useful triviality: every linear combination of homomesies is itself homomesic.

E.g., consider the adjusted major index statistic defined by $\text{amaj}(A) = \sum_{(i,j) \in A} (i - j)$.

Propp and R. proved that $\text{amaj}$ is homomesic under $\tau$ by writing it as a linear combination of the functions $1_{i,j} - 1_{i',j'}$. Haddadan gave a simpler proof, writing $\text{amaj}$ as a linear combination of the functions $f_i$ and $g_j$.

**Question:** Are there other homomesic combinations of the indicator functions $1_{i,j}$ (with $(i,j) \in [a] \times [b]$), linearly independent of the functions $f_i, g_j$, and $1_{i,j} - 1_{i',j'}$?
As we’ve seen, one can view rowmotion as acting either on *antichains* \((\mathcal{A}(P))\) or on *order ideals* \((\mathcal{J}(P))\); we denote the latter map \(\overline{\tau}\). It turns out that the cardinality of the order ideal is also homomesic with respect to rowmotion on \([a] \times [b]\).

**Theorem (Propp, R.)**

Let \(\mathcal{O}\) be an arbitrary \(\overline{\tau}\)-orbit in \(\mathcal{J}([a] \times [b])\). Then

\[
\frac{1}{\#\mathcal{O}} \sum_{I \in \mathcal{O}} \#I = \frac{ab}{2}.
\]

It’s worth noting even though there’s a strong connection between the rowmotion map on antichains and on order ideals, that the homomesy situation could be quite different.
The map $\overline{\tau}$ is “the same” as $\tau$ in the sense that the standard bijection from $\mathcal{A}(P)$ to $J(P)$ (downward saturation) makes the following diagram commute:

$$
\begin{array}{ccc}
\mathcal{A}(P) & \xrightarrow{\tau} & \mathcal{A}(P) \\
\downarrow & & \downarrow \\
J(P) & \xrightarrow{\overline{\tau}} & J(P)
\end{array}
$$

However, the bijection from $\mathcal{A}(P)$ to $J(P)$ does not carry the vector space generated by the functions $1_{i,j}$ to the vector space generated by the functions $\overline{1}_{i,j}$ in a linear way.

So the homomesy situation for $\overline{\tau} : J(P) \rightarrow J(P)$ could be (and, as we’ll see, is) different from the homomesy situation for $\tau : \mathcal{A}(P) \rightarrow \mathcal{A}(P)$. 

$\frac{0+1+3+5+7+8}{6} = 4$

Rowmotion

\[
\frac{2 + 4 + 6 + 6 + 4 + 2}{6} = 4
\]

\[
(3 + 5 + 4 + 3 + 5 + 4) / 6 = 4
\]
Again we have an orbit of size 2 and an orbit of size 4:

Within each orbit, the average order ideal has cardinality $\frac{ab}{2} = 2$. 
We also have homomesies for more refined statistics than $\#I$.

Within each orbit, the average order ideal has $1/2$ a violet element, 1 red element, and $1/2$ a brown element.
Ideals in $[a] \times [b]$: file-cardinality is homomesic

For $1 - b \leq k \leq a - 1$, define the $k$th file of $[a] \times [b]$ as

$$\{(i, j) : 1 \leq i \leq a, \ 1 \leq j \leq b, \ i - j = k\}.$$ 

For $1 - b \leq k \leq a - 1$, let $h_k(I)$ be the number of elements of $I$ in the $k$th file of $[a] \times [b]$, so that $\# I = \sum_k h_k(I)$.

**Theorem (Propp, R.)**

For every $\overline{\tau}$-orbit $\mathcal{O}$ in $J([a] \times [b])$,

$$\frac{1}{\# \mathcal{O}} \sum_{I \in \mathcal{O}} h_k(I) = \begin{cases} 
\frac{(a-k)b}{a+b} & \text{if } k \geq 0 \\
\frac{a(b+k)}{a+b} & \text{if } k \leq 0.
\end{cases}$$
Given \((i, j) \in [a] \times [b]\), and \(I\) an ideal in \([a] \times [b]\), define the indicator function \(\overline{1}_{i,j}(I)\) to be 1 or 0 according to whether or not \(I\) contains \((i, j)\).

Write \((i', j') = (a + 1 - i, b + 1 - j)\), the point opposite \((i, j)\) in the poset.

**Theorem (Propp, R.)**

\[\overline{1}_{i,j} + \overline{1}_{i',j'} \text{ is homomesic under } \overline{\tau}.\]
The two vector spaces, compared

In the space associated with **antichains**: fiber-cardinalities and centrally symmetric **differences** are homomesic.

In the space associated with **order ideals**: file-cardinalities and centrally symmetric **sums** are homomesic.
The two vector spaces, compared

In the space associated with **antichains:**
- fiber-cardinalities and
- centrally symmetric **differences**
are homomesic.

In the space associated with **order ideals:**
- file-cardinalities and
- centrally symmetric **sums**
are homomesic.

Note that the discovery of these homomesies was driven by calculation, and the project of generalizing these results to other posets will clearly be aided by computer-assisted search. Some work has already been done along these lines in a different computer algebra package...
In their 1995 article *Orbits of antichains revisited*, European J. Combin. 16 (1995), 545–554, Cameron and Fon-der-Flaass give an alternative description of $\tau$.

Given $I \in J(P)$ and $x \in P$, let $\tau_x(I) = I \triangle \{x\}$ (symmetric difference) provided that $I \triangle \{x\}$ is an order ideal of $P$; otherwise, let $\tau_x(I) = I$.

We call the involution $\tau_x$ “toggling at $x$”.

The involutions $\tau_x$ and $\tau_y$ commute unless $x$ covers $y$ or $y$ covers $x$. 
An example

1. Toggle the top element
2. Toggle the left element
3. Toggle the right element
4. Toggle the bottom element
Theorem ([CF95])

Let $x_1, x_2, \ldots, x_n$ be any order-preserving enumeration of the elements of the poset $P$. Then the action on $J(P)$ given by the composition $\tau_{x_1} \circ \tau_{x_2} \circ \cdots \circ \tau_{x_n}$ coincides with the action of $\overline{\tau}$.

In the particular case $P = [a] \times [b]$, we can enumerate $P$ rank-by-rank; that is, we can list the $(i, j)$'s in order of increasing $i + j$.

Note that all the involutions coming from a given rank of $P$ commute with one another, since no two of them are in a covering relation.

Striker and Williams refer to $\overline{\tau}$ (and $\tau$) as rowmotion, since for them, “row” means “rank”.
Recall that a **file** in $P = [a] \times [b]$ is the set of all $(i, j) \in P$ with $i - j$ equal to some fixed value $k$.

Note that all the involutions coming from a given file commute with one another, since no two of them are in a covering relation.

It follows that for any enumeration $x_1, x_2, \ldots, x_n$ of the elements of the poset $[a] \times [b]$ arranged in order of increasing $i - j$, the action on $J(P)$ given by $\tau_{x_1} \circ \tau_{x_2} \circ \cdots \circ \tau_{x_n}$ doesn’t depend on which enumeration was used.

Striker and Williams call this well-defined composition **promotion**, and denote it by $\partial$, since for two-rowed tableaux it can be related to Schützenberger’s promotion on SYT, described earlier.
Again we have an orbit of size 2 and an orbit of size 4:
Theorem (Propp, R.)

Let $\mathcal{O}$ be an arbitrary orbit in $J([a] \times [b])$ under the action of promotion $\partial$. Then

$$\frac{1}{\# \mathcal{O}} \sum_{l \in \mathcal{O}} \# l = \frac{ab}{2}.$$ 

The result about cyclic rotation of binary words discussed earlier turns out to be a special case of this.
For $1 - b \leq k \leq a - 1$, let $f_k(I)$ be the number of elements of $I$ in the $k$th file of $[a] \times [b]$, so that $\#I = \sum_k f_k(I)$.

**Theorem**

If $\mathcal{O}$ is any $\partial$-orbit in $J([a] \times [b])$, then

$$\frac{1}{\#\mathcal{O}} \sum_{I \in \mathcal{O}} f_k(I) = \begin{cases} \frac{(a-k)b}{a+b} & \text{if } k \geq 0 \\ \frac{a(b+k)}{a+b} & \text{if } k \leq 0. \end{cases}$$
Cardinality of antichains is not homomesic under promotion. although the antipodal functions $1_{i,j} - 1_{i',j'}$ are.
Recall that, by the Armstrong-Stump-Thomas theorem, the cardinality of antichains is homomesic under the action of rowmotion, where the poset $P$ is a root poset of type $A_n$. E.g., for $n = 2$:

Antichain-cardinality is homomesic: in each orbit, its average is 1.
Root posets of type $A$: order ideals

What if instead of antichains we take order ideals?

E.g., $n = 2$:

What is homomesic here?
Root posets of type $A$: rank-signed cardinality

\[
\begin{array}{c}
\begin{array}{ccc}
& + & 1 \\
0 & & \\
\end{array}
& \begin{array}{c}
& + & 1 \\
1 & & \\
\end{array}

& \begin{array}{c}
& + & 1 \\
2 & & \\
\end{array}
& \begin{array}{c}
& + \\
1 & &
\end{array}
\end{array}
\end{array}
\]
Let $P$ be the root poset of type $A_n$. If we assign an element $x \in P$ weight $wt(x) = (-1)^{\text{rank}(x)}$, and assign an order ideal $I \in J(P)$ weight $\varphi(I) = \sum_{x \in I} wt(x)$, then $\varphi$ is homomesic under rowmotion and promotion, with average $n/2$. 

**Theorem (Haddadan)**
Let $P$ be a poset, with an extra minimal element $\hat{0}$ and an extra maximal element $\hat{1}$ adjoined.

The **order polytope** $\mathcal{O}(P)$ (introduced by R. Stanley) is the set of functions $f : P \to [0, 1]$ with $f(\hat{0}) = 0$, $f(\hat{1}) = 1$, and $f(x) \leq f(y)$ whenever $x \leq_P y$.

We can generalize our entire setup of toggle operators and “rowmotion” to operate on these functions (the “continuous piecewise-linear (CPL) category”).
For each $x \in P$, define the flip-map $\sigma_x : \mathcal{O}(P) \to \mathcal{O}(P)$ sending $f$ to the unique $f'$ satisfying

$$f'(y) = \begin{cases} f(y) & \text{if } y \neq x, \\ \min_{z \cdot > x} f(z) + \max_{w < \cdot x} f(w) - f(x) & \text{if } y = x, \end{cases}$$

where $z \cdot > x$ means $z$ covers $x$ and $w < \cdot x$ means $x$ covers $w$.

Note that the interval $[\min_{z \cdot > x} f(z), \max_{w < \cdot x} f(w)]$ is precisely the set of values that $f'(x)$ could have so as to satisfy the order-preserving condition, if $f'(y) = f(y)$ for all $y \neq x$; the map that sends $f(x)$ to $\min_{z \cdot > x} f(z) + \max_{w < \cdot x} f(w) - f(x)$ is just the affine involution that swaps the endpoints.
Example of flipping at a node

\[
\begin{align*}
\min_{z \cdot \succ x} f(z) + \max_{w \prec x} f(w) &= .7 + .2 = .9 \\
\Rightarrow f(x) + f'(x) &= .4 + .5 = .9
\end{align*}
\]
If we associate each order-ideal $I$ with the indicator function $f$ of $P \setminus I$ (that is, the function that takes the value 0 on $I$ and the value 1 everywhere else), then toggling $I$ at $x$ is tantamount to flipping $f$ at $x$.

That is, we can identify $J(P)$ with the vertices of the polytope $\mathcal{O}(P)$ in such a way that toggling can be seen to be a special case of flipping.

This may be clearer if you think of $J(P)$ as being in bijection with the set of monotone 0,1-valued functions on $P$. 
Flipping (at least in special cases) is not new, though it is not well-studied; the most worked-out example we’ve seen is Berenstein and Kirillov’s article *Groups generated by involutions, Gelfand-Tsetlin patterns and combinatorics of Young tableaux* (St. Petersburg Math. J. 7 (1996), 77–127); see http://pages.uoregon.edu/arkadiy/bk1.pdf.
Composing flips

Just as we can apply toggle-maps from top to bottom, we can apply flip-maps from top to bottom (successively at the North, West, East, and South.):
Two Examples of CPL rowmotion orbits

The average at each node across the respective orbits is shown at right, along with the file sums.
It appears that all of the aforementioned results on homomesy for rowmotion and promotion on $J([a] \times [b])$ lift to corresponding results in the order polytope, where instead of composing toggle-maps to obtain rowmotion and promotion we compose the corresponding flip-maps to obtain continuous piecewise-linear maps from $\mathcal{O}([a] \times [b])$ to itself.

News Flash: By lifting an argument from Propp-R. in the combinatorial category, Propp has very recently shown that promotion, and hence rowmotion, must be homomesic (in a slightly generalized sense). But we still don’t have a proof that these maps have finite order.
In the combinatorial category, where \( \mathcal{A}(P) \) and \( \mathcal{J}(P) \) are finite, it’s clear that any map defined as a product of toggles has finite order. But we can no longer take this for granted in the CPL category. Let \( P = [2] \times [2] \). As we’ll soon see, one can show by brute force that the CPL maps

\[
\sigma_{(1,1)} \circ \sigma_{(1,2)} \circ \sigma_{(2,1)} \circ \sigma_{(2,2)} \quad \text{ (“lifted rowmotion”)} \quad \text{and} \\
\sigma_{(2,1)} \circ \sigma_{(1,1)} \circ \sigma_{(2,2)} \circ \sigma_{(1,2)} \quad \text{ (“lifted promotion”)}
\]

are of order 4. However, not every composition of flips has finite order.

**Proposition (Einstein)**

The map \( \sigma_{(1,1)} \circ \sigma_{(1,2)} \circ \sigma_{(2,2)} \circ \sigma_{(2,1)} \) (flipping values in clockwise order, as opposed to going by rows or columns of \( P \)) is of infinite order.
In the so-called *tropical semiring*, one replaces the standard binary ring operations \((+, \cdot)\) with the tropical operations \((\max, +)\). In the continuous piecewise-linear (CPL) category of the order polytope studied above, our flipping-map at \(x\) replaced the value of a function \(f : P \rightarrow [0, 1]\) at a point \(x \in P\) with \(f'\), where

\[
f'(x) := \min_{z \cdot > x} f(z) + \max_{w < \cdot x} f(w) - f(x)
\]

We can “detropicalize” this flip map and apply it to an assignment \(f : P \rightarrow \mathbb{R}(\xi_1, \xi_2, \ldots)\) of *rational functions* to the nodes of the poset (using that \(\min_i (z_i) = -\max_i (-z_i)\)) to get

\[
f'(x) = \frac{\sum_{w < \cdot x} f(w)}{f(x) \sum_{z \cdot > x} \frac{1}{f(z)}}
\]
In our running example, $P = [2] \times [2]$, applying these new flip operators from top to bottom creates a new rowmotion operator. (Here we assign $f(\hat{0}) = f(\hat{1}) = 1$.)

\[
\begin{align*}
\begin{array}{cccc}
  z & \frac{x+y}{z} & \frac{x+y}{z} \\
  x & \rightarrow & x & \rightarrow \\
  y & \rightarrow & \frac{w(x+y)}{xz} & \rightarrow \\
  w & \rightarrow & w & \rightarrow \\
  \frac{x+y}{z} & \rightarrow & \frac{w(x+y)}{xz} & \rightarrow \\
  \frac{w(x+y)}{xz} & \rightarrow & \frac{w(x+y)}{y} & \rightarrow \\
  w & \rightarrow & 1 & \rightarrow \\
  \frac{x+y}{z} & \rightarrow & \frac{w(x+y)}{y} & \rightarrow \\
  w & \rightarrow & \frac{1}{z} & \rightarrow \\
\end{array}
\end{align*}
\]
Example of birational rowmotion orbit

Here’s an orbit of rowmotion in this category:

\[
\begin{align*}
&z \\
x &\mapsto \quad \frac{x+y}{z} \\
x &\mapsto \quad \frac{w(x+y)}{xz} \\
y &\mapsto \quad \frac{w(x+y)}{yz} \\
w &\mapsto \quad \frac{1}{z} \\
x &\mapsto \quad \frac{1}{y} \\
y &\mapsto \quad \frac{1}{x} \\
&w \\
\frac{1}{w} &\mapsto \quad \frac{1}{w} \\
\frac{yz}{w(x+y)} &\mapsto \quad \frac{1}{w} \\
\frac{xz}{w(x+y)} &\mapsto \quad \frac{1}{w} \\
\frac{xy}{w(x+y)} &\mapsto \quad \frac{1}{w} \\
&x \\
&y \\
\end{align*}
\]
In this category, geometric means replace arithmetic means, so let’s compute the product of the function values at each node.

\[
\begin{align*}
\frac{x+y}{z} & \quad \frac{w(x+y)}{xz} & \quad \frac{w(x+y)}{yz} \\
\frac{1}{z} & \quad \frac{1}{y} & \quad \frac{1}{x} \\
\frac{yz}{w(x+y)} & \quad \frac{xz}{w(x+y)} & \quad \frac{xy}{w(x+y)} \\
\frac{(x+y)^2}{xy} & \quad \frac{xy}{w(x+y)} & \quad \frac{xy}{(x+y)^2}
\end{align*}
\]

PROD = 1 1 1
If we instead generically assign variables \( f(\hat{0}) = \alpha \) and \( f(\hat{1}) = \omega \):

\[
\begin{align*}
\omega & \quad \frac{(x+y)\omega}{z} & \quad \frac{w(x+y)\omega}{xy} \\
 z & \quad \frac{w(x+y)\omega}{xz} & \quad \frac{w(x+y)\omega}{yz} & \quad \frac{\alpha\omega}{y} & \quad \frac{\alpha\omega}{x} \\
 x & \quad \frac{\alpha\omega}{z} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} \\
y & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} \\
 w & \quad \frac{\alpha\omega}{z} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} \\
\alpha & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} & \quad \frac{\alpha\omega}{w(x+y)} \\
\end{align*}
\]

So the statistic “multiply opposite nodes” has geometric mean \( \alpha\omega \) across the orbit.
It’s not hard to see that if a map such as rowmotion is homomesic with respect to some statistics in the birational category, then this implies homomesy at the CPL level, which in turn implies it in the combinatorial category.

We believe that multiplicative versions of homomesy in the birational category holds for a large class of posets, often ones that come up in representation theory. There are also simple examples of posets, e.g., the Boolean algebra $B_3$ for which nothing we have tried appears to hold. For example, it appears (conjecturally) that birational rowmotion has infinite order on $B_3$. 
Sage implementation & Wish List

Broader Goals:

- A way to define an action $\tau$ on a finite set $S$ of $n$ objects and have Sage give the permutation $\pi \in S_n$ that it represents in various forms (1-line notation, cycle notation).
- Tools to compute arithmetic and multiplicative averages of statistics defined on $S$ in the above category.

Specific actions to implement

- **Bender-Knuth involutions for SSYT**: Done and merged by Travis Scrimshaw & DG.
- **promotion of SSYT**: Ticket #7983 needs to be reviewed.
- **Suter dihedral map on Young’s Lattice**: Ticket #14763 needs to be reviewed.
- **toggles & rowmotion in a general poset**: Need to discuss implementation of $I \in J(P)$: what data type would work? Can Yan Zhang’s code be put on the Trac server?
birational rowmotion in a general poset: Some code has been written DG, but probably still not in shareable form.

promotion in an arbitrary RC poset? Need input from others on how to implement RC posets. Probably DG and Jessica Striker (and anyone else interested) should discuss.

Unordered trees: It appears that trees currently implemented in Sage are planar/ordered? We need unordered as well.

Semi-fields: The CPL case is just the birational case over the tropical semiring. As a stopgap measure, we could use the recently implemented Tropical Semiring and pretend it’s a field, since Python won’t bother to check types.
A recently identified phenomenon called *homomesy* appears to be lurking in a wide range of combinatorial situations.

We are just beginning to develop tools for studying this, so there are many interesting open problems.

There are intriguing conjectured generalizations to continuous piecewise-linear maps on order polytopes and to birational maps on \( \{ f : P \to \mathbb{R}(\xi_1, \xi_2, \ldots) \} \).

Useful programs exist in Sage for doing computations, and more are currently under development...


Slides for this talk are available online (or will be soon) at

http://www.math.uconn.edu/~troby/research.html

For more information, see:

http://jamespropp.org/mathfest12a.pdf
http://jamespropp.org/mitcomb13a.pdf
http://www.math.uconn.edu/~troby/ceFPSAC.pdf

Thanks for your attention!