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The cardinality of a set is a combinatorial statistic on $\mathcal{S}$.

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Combinatorial statistics provide a *refinement* of counting.

less information *more information*

$\longleftarrow \qquad \longrightarrow$

counting **statistics** **complete enumeration**

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counting

8

statistics

0	1	2	3
1	3	3	1

complete enumeration

$\emptyset$ $\{1\}$ $\{2\}$ $\{3\}$
$\{1,2\}$ $\{1,3\}$ $\{2,3\}$ $\{1,2,3\}$

Statistics and Permutations

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A especially rich playground involves *permutation statistics*.

Representations of permutations

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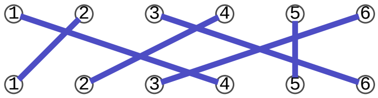
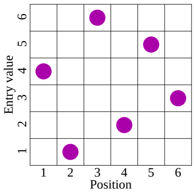
String diagram:



(only two crossings at a time)

Matrix-like diagram:



Descent statistic

Definition: Let $\pi = \pi_1 \pi_2 \cdots \pi_n$ be a permutation.

A **descent** is a position i such that $\pi_i > \pi_{i+1}$.

Define $\mathrm{des}(\pi)$ to be the **number of descents** in π.

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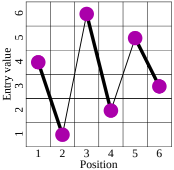

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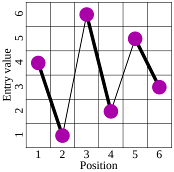

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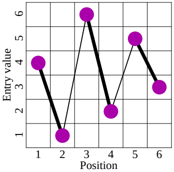

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1	1				
2	1	1			
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4	1	11	11	1	
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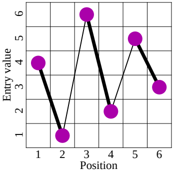

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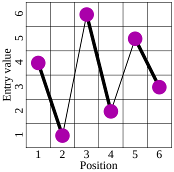

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These are the **Eulerian numbers**.

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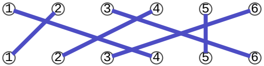

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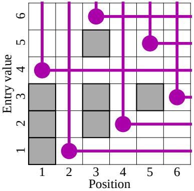

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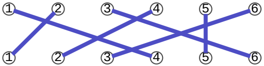

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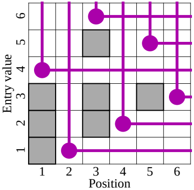

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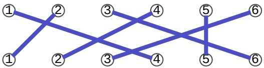

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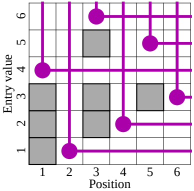

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The inversion number is a good way to count how "far away" a permutation is from the identity.

Major index

Definition: Let $\pi = \pi_1\pi_2\cdots\pi_n$ be a permutation.

Define $\mathrm{maj}(\pi)$, the **major index** of π, to be sum of the descents of π.

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A statistic that has the same distribution as inv is called **Mahonian**.

q-analogs

Definition: A q-**analog** of a number c is an expression $f(q)$ such that $\lim_{q\to 1} f(q) = c$.

Example. $\dfrac{1-q^n}{1-q} = \left(1+q+q^2+\cdots+q^{n-2}+q^{n-1}\right)$ is a q-analog of n because $\lim_{q\to 1} \frac{1-q^n}{1-q} = n$.

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$$\lim_{q\to 1}\sum_{s\in S} q^{\mathrm{stat}(s)} = \sum_{s\in S} 1^{\mathrm{stat}(s)} = \sum_{s\in S} 1 = |S|$$

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2	$1q^0 + 1q^1$	$= (1+q)$
3	$1q^0 + 2q^1 + 2q^2 + 1q^3$	$= (1+q+q^2)(1+q)$
4	$1q^0 + 3q^1 + 5q^2 + 6q^3 + 5q^4 + 3q^5 + 1q^6$	$=$

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Claim: This equation makes sense when $q = 1$.

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Theorem: $\sum_{\pi \in S_n} q^{\mathrm{inv}(\pi)} = [n]_q!$

Proof. There exists a bijection

$$\left\{ \begin{array}{c} \text{permutations} \\ \pi \in S_n \end{array} \right\} \longleftrightarrow \left\{ \begin{array}{c} \text{lists } (a_1, \ldots, a_n) \\ \text{where } 0 \le a_i \le n - i \end{array} \right\}.$$

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Given a permutation π, create its **inversion table**. Define a_i to be the number of entries j to the left of i that are smaller than i.

Then $\mathrm{inv}(\pi) = a_1 + a_2 + \cdots + a_n$.

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Given a permutation π, create its **inversion table**. Define a_i to be the number of entries j to the left of i that are smaller than i. Then $\mathrm{inv}(\pi) = a_1 + a_2 + \cdots + a_n$.

Example. The inversion table of $\pi = 4\,3\,1\,5\,2$ is $(3, 2, 0, 1, 0)$.

Inversion Statistics

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$$\begin{aligned} \sum_{\pi \in S_n} q^{\text{inv}(\pi)} &= \sum_{a_1=0}^{n-1} \sum_{a_2=0}^{n-2} \cdots \sum_{a_n=0}^{0} q^{a_1+a_2+\cdots+a_n} \\ &= \left(\sum_{a_1=0}^{n-1} q^{a_1} \right) \left(\sum_{a_2=0}^{n-2} q^{a_2} \right) \cdots \left(\sum_{a_n=0}^{0} q^{a_n} \right) \\ &= \quad [n]_q \quad [n-1]_q \quad \cdots \quad [1]_q \quad = \quad [n]_q! \end{aligned}$$

Notes

We said that inv and maj are equidistributed. Two possible proofs:

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Define $\mathrm{inv}(\pi) = |\{i < j \colon \pi(i) > \pi(j)\}|$.

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This can also be used to give a q-analog of the Catalan numbers.

There's always more to learn!!!

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