Tutte polytope

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Combinatorial polytopes

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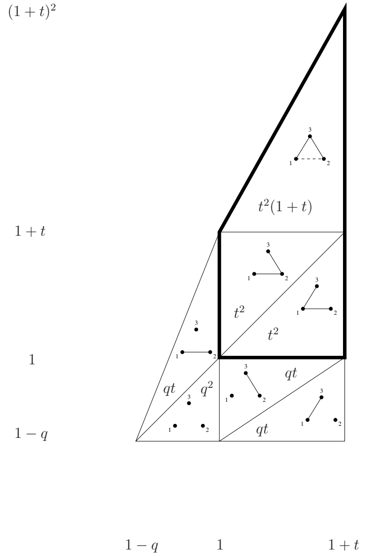
Examples

- permutahedron: vertices are in a bijective correspondence with permutations
- associahedron: vertices are in a bijective correspondence with correct parenthesizations of a string
- Birkhoff polytope: vertices are permutation matrices

Preview of coming attractions



Cayley's theorem and Braun's conjecture

Theorem (Cayley, 1857)

The number of integer sequences $(a_1, \ldots, a_n)$ such that $1 \leq a_1 \leq 2$ and $1 \leq a_i \leq 2a_{i-1}$ for $i = 2, \ldots, n$, is equal to the total number of partitions of integers $N \in \{0, 1, \ldots, 2^n - 1\}$ into parts $1, 2, 4, \ldots, 2^{n-1}$.

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Conjecture (Braun, 2011)

Define the Cayley polytope $\mathbf{C}_n \subseteq \mathbb{R}^n$ by inequalities

$$1 \leq x_1 \leq 2, \quad \text{and} \quad 1 \leq x_i \leq 2x_{i-1} \quad \text{for} \quad i = 2, \ldots, n.$$

Then $n! \operatorname{vol} \mathbf{C}_n$ is equal to the number of connected graphs on $n+1$ nodes.

Main result

Theorem (K-Pak)

Define the Tutte polytope $\mathbf{T}_n(q,t) \subseteq \mathbb{R}^n$ (by inequalities or by vertices), $\mathbf{T}_n(0,1) = \mathbf{C}_n$. Then

$$n! \operatorname{vol} \mathbf{T}_n(q,t) = \sum q^{k(G)-1} t^{|E(G)|},$$

where the sum is over all graphs on $n+1$ nodes, and $k(G)$ is the number of connected components of G.

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In other words, $n!\,\mathrm{vol}\,\mathbf{T}_n(q,t) = t^n T_{K_{n+1}}(1+q/t, 1+t)$, where $T_H(x,y)$ denotes the Tutte polynomial of the graph H.

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We call $n! \operatorname{vol} \mathbf{P}$ the normalized volume of $\mathbf{P} \subseteq \mathbb{R}^n$.

Triangulation of Cayley polytope

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We will define:

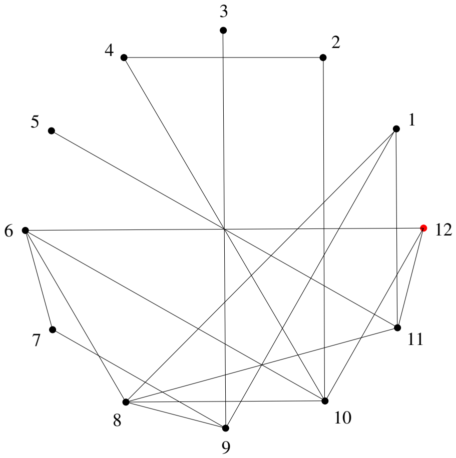
- a map from connected graphs to (labeled) trees
- a map from trees to simplices

so that:

- the simplices triangulate $\mathbf{C}_n$
- the normalized volume of each simplex is equal to the number of graphs that map into the corresponding tree

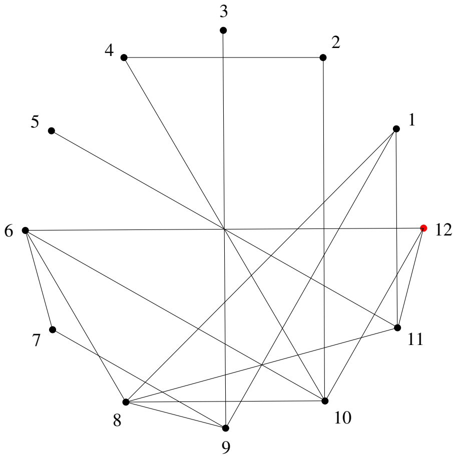
Connected graphs to trees: neighbors first search

- the node with the maximal label is the first active node and the 0-th visited node



Connected graphs to trees: neighbors first search

- visit the unvisited neighbors of the active node in decreasing order of labels; the one with the smallest label becomes active



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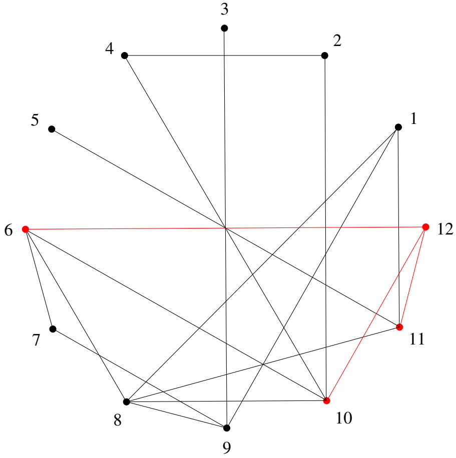

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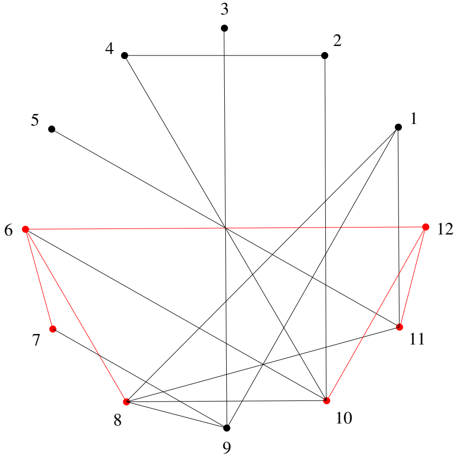

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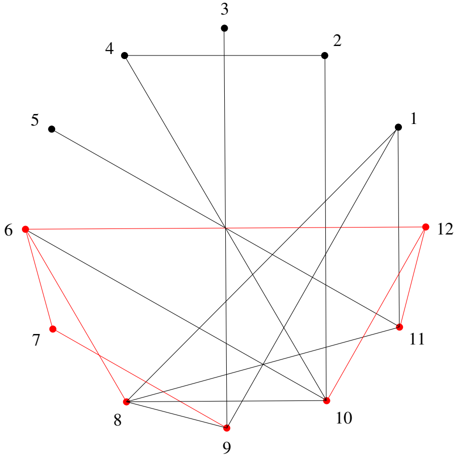

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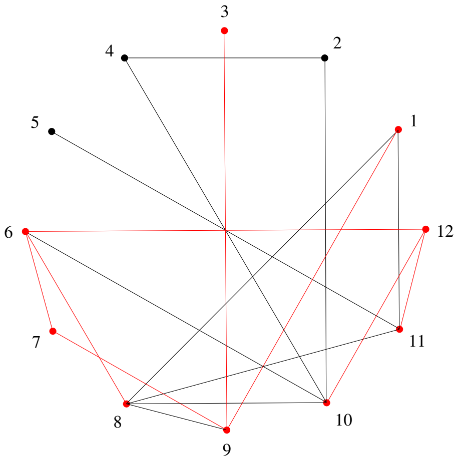

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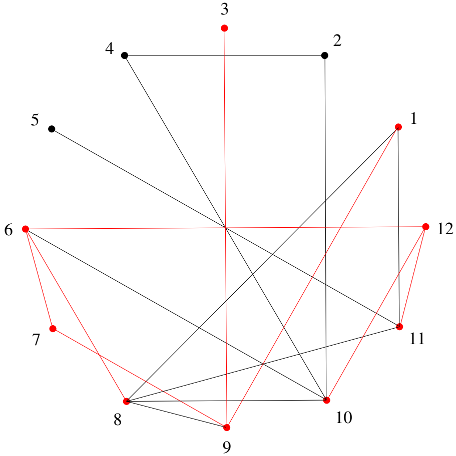

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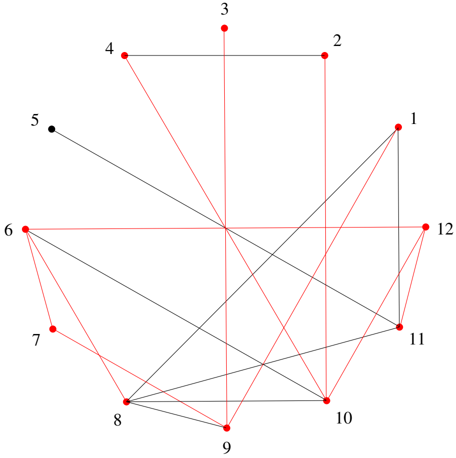

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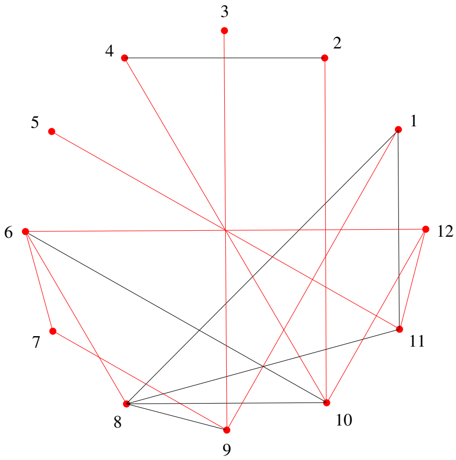
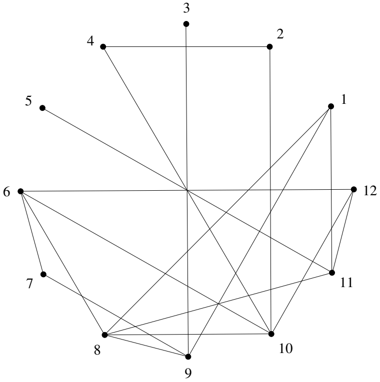
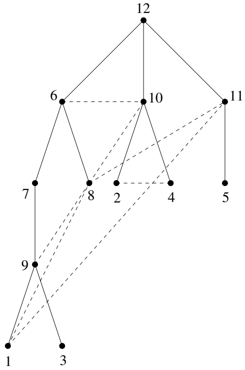


Connected graphs to trees: neighbors first search

- the result is an ordering of the nodes and a search tree





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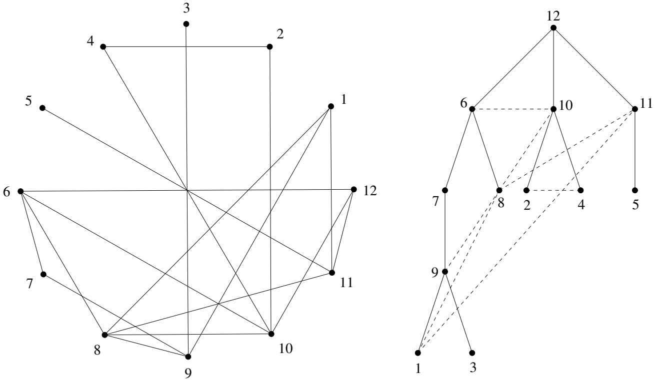
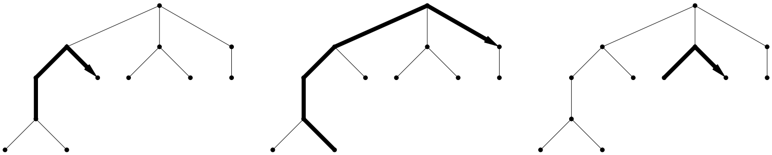


This is a variant of the neighbors first search introduced by Gessel and Sagan (1996).

Cane paths

A cane path is an up-up-. . .-up-down right path.



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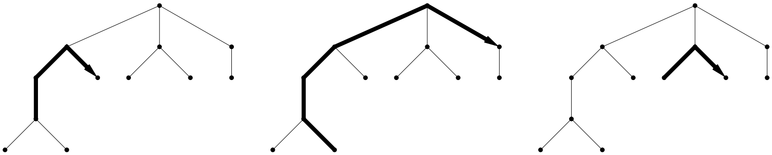
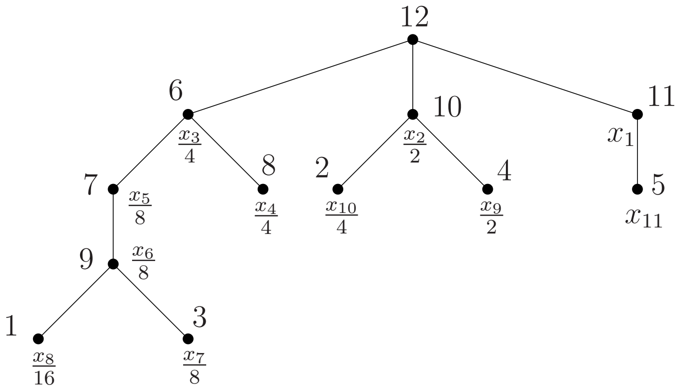


Fact

Number of graphs with neighbors-first search tree T is $2^{\alpha(T)}$, where $\alpha(T)$ is the number of cane paths in T.

Coordinates of nodes in a tree



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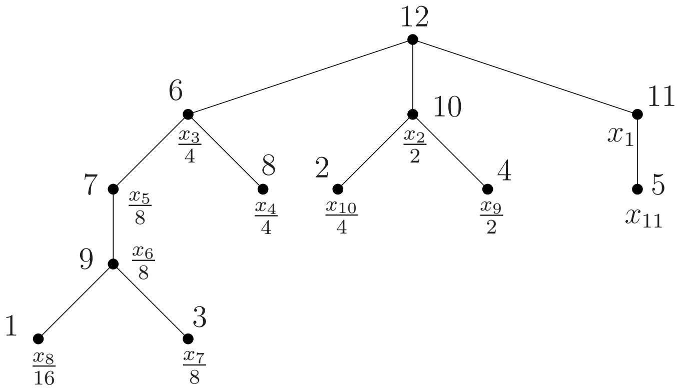
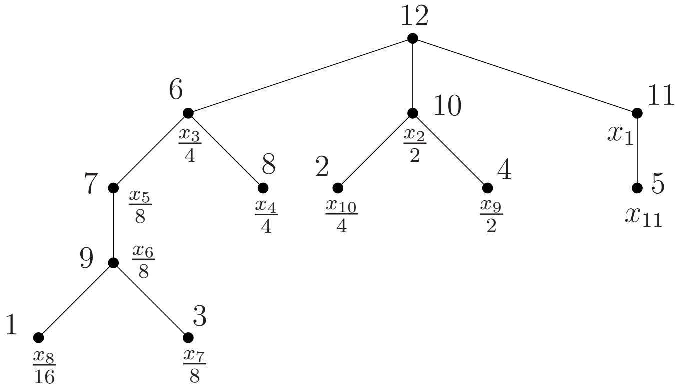


Fact

If the node v is visited i-th in the neighbors first search and j is the number of cane paths starting in v, then the coordinate of v is $x_i/2^j$.

Trees to simplices



$$1 \leq \frac{x_8}{16} \leq \frac{x_{10}}{4} \leq \frac{x_7}{8} \leq \frac{x_9}{2} \leq x_{11} \leq \frac{x_3}{4} \leq \frac{x_5}{8} \leq \frac{x_4}{4} \leq \frac{x_6}{8} \leq \frac{x_2}{2} \leq x_1 \leq 2.$$

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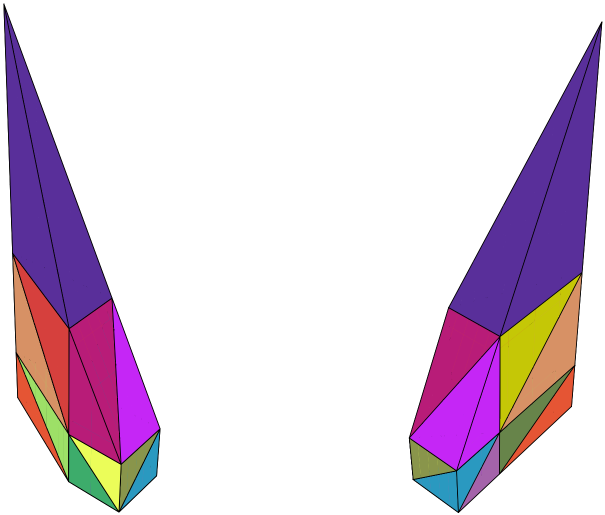
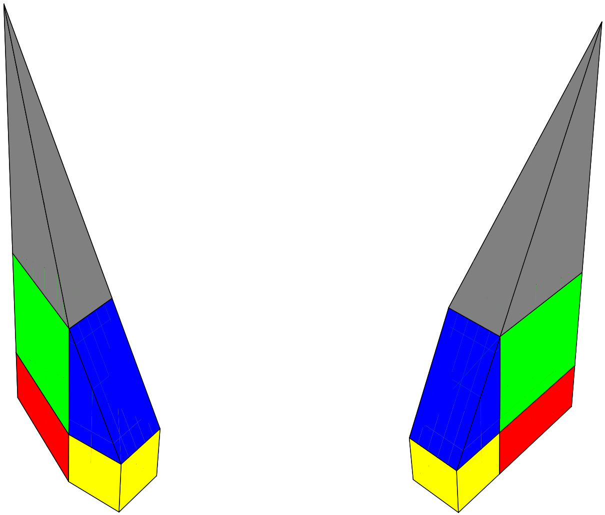
The resulting simplices triangulate Cayley's polytope. So this proves Braun's conjecture.

Triangulation of $\mathbf{C}_3$



Another subdivision of $\mathbf{C}_3$



Sketch of proof

The Cayley polytope consists of all points $(x_1, \ldots, x_n)$ for which $1 \leq x_1 \leq 2$ and $1 \leq x_i \leq 2x_{i-1}$ for $i = 2, \ldots, n$. The main idea of the proof is to divide these inequalities into "narrower" inequalities.

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If $1 \leq x_2 \leq 2$, then either $1 \leq x_3 \leq 2$ or $2 \leq x_3 \leq 2x_2$.

On the other hand, if $2 \leq x_2 \leq 2x_1$, then $2x_2 \geq 4$, so we have $1 \leq x_3 \leq 2$, $2 \leq x_3 \leq 4$ or $4 \leq x_3 \leq 2x_2$.

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<table>
<tr><td rowspan="14">$1 \leq x_1 \leq 2$</td><td rowspan="5">$1 \leq x_2 \leq 2$</td><td rowspan="2">$1 \leq x_3 \leq 2$</td><td>$1 \leq x_4 \leq 2$</td></tr>
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$$C_n = \frac{1}{n+1}\binom{2n}{n},$$

which enumerate many important combinatorial objects: parenthesizations, triangulations of polygons, Dyck paths, plane trees etc.

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which enumerate many important combinatorial objects: parenthesizations, triangulations of polygons, Dyck paths, plane trees etc.

It turns out that each subpolytope corresponds to a unique plane tree (unlabelled rooted tree).

Example

$$\mathbf{P} = \left\{ \begin{array}{lll} (x_1, \ldots, x_{11}) : & 1 \le x_1 \le 2, & 2 \le x_2 \le 2\,x_1, \\ 4 \le x_3 \le 2\,x_2, & 4 \le x_4 \le 8, & 8 \le x_5 \le 2\,x_4, \\ 8 \le x_6 \le 16, & 8 \le x_7 \le 16, & 16 \le x_8 \le 2\,x_7, \\ 2 \le x_9 \le 4, & 4 \le x_{10} \le 2\,x_9, & 1 \le x_{11} \le 2 \end{array} \right\}$$

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There exist unique integers $a_1, a_2, \ldots, a_k \ge 0$ so that among the inequalities for $x_{k+1}, \ldots, x_n$, the first a_1 inequalities have at least 2^{k-1} on the left, the next a_2 inequalities have at least 2^{k-2} on the left, etc. In our case, $a_1 = 5$, $a_2 = 2$, $a_3 = 1$.

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These inequalities determine polytopes $2^{k-1}\mathbf{P}_1, 2^{k-2}\mathbf{P}_2$, and $\mathbf{P}_1, \mathbf{P}_2, \ldots$ give plane trees by induction. Attach these trees to a new root.

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$$\mathbf{P} = \left\{ \begin{array}{lll} (x_1,\ldots,x_{11}): & 1 \le x_1 \le 2, & 2 \le x_2 \le 2\,x_1, \\ 4 \le x_3 \le 2\,x_2, & 4 \le x_4 \le 8, & 8 \le x_5 \le 2\,x_4, \\ 8 \le x_6 \le 16, & 8 \le x_7 \le 16, & 16 \le x_8 \le 2\,x_7, \\ 2 \le x_9 \le 4, & 4 \le x_{10} \le 2\,x_9, & 1 \le x_{11} \le 2 \end{array} \right\}$$

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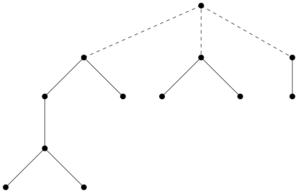

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This corresponds to a labeling of the plane tree.

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Cayley polytope $\mathbf{C}_n$:

$$1 \leq x_1 \leq 2, \quad \text{and} \quad 1 \leq x_i \leq 2x_{i-1} \quad \text{for} \quad i = 2, \ldots, n$$

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Charles Mills Gayley (1858 – 1932), professor of English and Classics at UC Berkeley

Triangulation of Gayley polytope

Neighbors first search on a general graph: arrange connected components so that their maximal labels are decreasing from left to right, perform neighbors first search on each tree from left to right.

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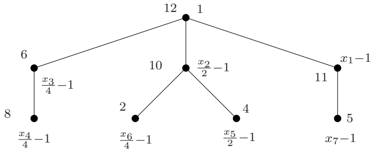

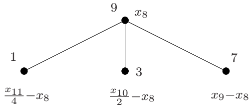

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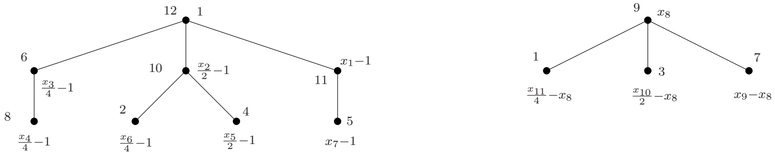

$$0 \leq \frac{x_{11}}{4} - x_8 \leq \frac{x_6}{4} - 1 \leq \frac{x_{10}}{2} - x_8 \leq \frac{x_5}{2} - 1 \leq x_7 - 1 \leq$$

$$\leq \frac{x_3}{4} - 1 \leq x_9 - x_8 \leq \frac{x_4}{4} - 1 \leq x_8 \leq \frac{x_2}{2} - 1 \leq x_1 - 1 \leq 1.$$

t-Cayley and t-Gayley polytope

Replace powers of 2 by powers of $1+t$, $t>0$:

- t-Cayley polytope $\mathbf{C}_n(t)$:

$$1 \le x_1 \le 1+t, \quad \text{and} \quad 1 \le x_i \le (1+t)x_{i-1} \quad \text{for} \quad i = 2, \ldots, n$$

- t-Gayley polytope $\mathbf{G}_n(t)$:

$$0 \le x_1 \le 1+t, \quad \text{and} \quad 0 \le x_i \le (1+t)x_{i-1} \quad \text{for} \quad i = 2, \ldots, n$$

- coordinates of the form $x_i/2^j - x_l$ become $x_i/(1+t)^j - x_l$
- coordinates of the form x_l (for roots) become tx_l

Normalized volumes

Theorem

The normalized volume of $\mathbf{C}_n(t)$ is

$$\sum t^{|E(G)|},$$

where the sum is over all connected graphs G on $n+1$ nodes.
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Tutte polytope: hyperplanes

Take $0 < q \leq 1$ and $t > 0$. Define the Tutte polytope $\mathbf{T}_n(q, t)$ by

$$x_n \geq 1 - q,$$

$$qx_i \leq q(1 + t)x_{i-1} - t(1 - q)(1 - x_{j-1}),$$

where $1 \leq j \leq i \leq n$ and $x_0 = 1$.

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Theorem

The normalized volume of the Tutte polytope is

$$\sum q^{k(G)-1} t^{|E(G)|},$$

where the sum is over all graphs on $n+1$ nodes.

t-Cayley polytope: vertices

Define $V_n(t)$ as the set of points with properties $x_1 \in \{1, 1+t\}$, $x_i \in \{1, (1+t)x_{i-1}\}$ for $i = 2, \ldots, n$.

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1+t & (1+t)^2 & (1+t)^3 \\
1+t & (1+t)^2 & 1 \\
1+t & 1 & 1+t \\
1+t & 1 & 1 \\
1 & 1+t & (1+t)^2 \\
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1 & 1 & 1+t \\
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\end{array}$$

It is easy to see that $V_n(t)$ is the set of vertices of $\mathbf{C}_n(t)$.

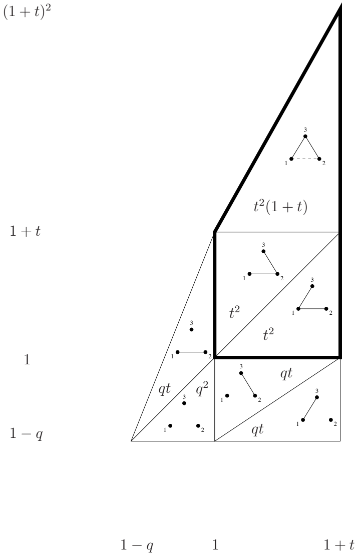
Tutte polytope: vertices

Replace the trailing 1's of each point in $V_n(t)$ by $1-q$, denote the resulting set $V_n(q,t)$.

$$\begin{array}{ccc} 1+t & (1+t)^2 & (1+t)^3 \\ 1+t & (1+t)^2 & 1-q \\ 1+t & 1 & 1+t \\ 1+t & 1-q & 1-q \\ 1 & 1+t & (1+t)^2 \\ 1 & 1+t & 1-q \\ 1 & 1 & 1+t \\ 1-q & 1-q & 1-q \end{array}$$

Then $V_n(q,t)$ is the set of vertices of $\mathbf{T}_n(q,t)$.

Triangulation of $\mathbf{T}_2(q, t)$



Future work

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- What is the f-vector of the Tutte polytope?
- Can we find a nice shelling?
- Can anything similar be done for other graphs (instead of the complete graph)? For some families of graphs?