Valid Orderings of Hyperplane Arrangements

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M.I.T.

Visible facets

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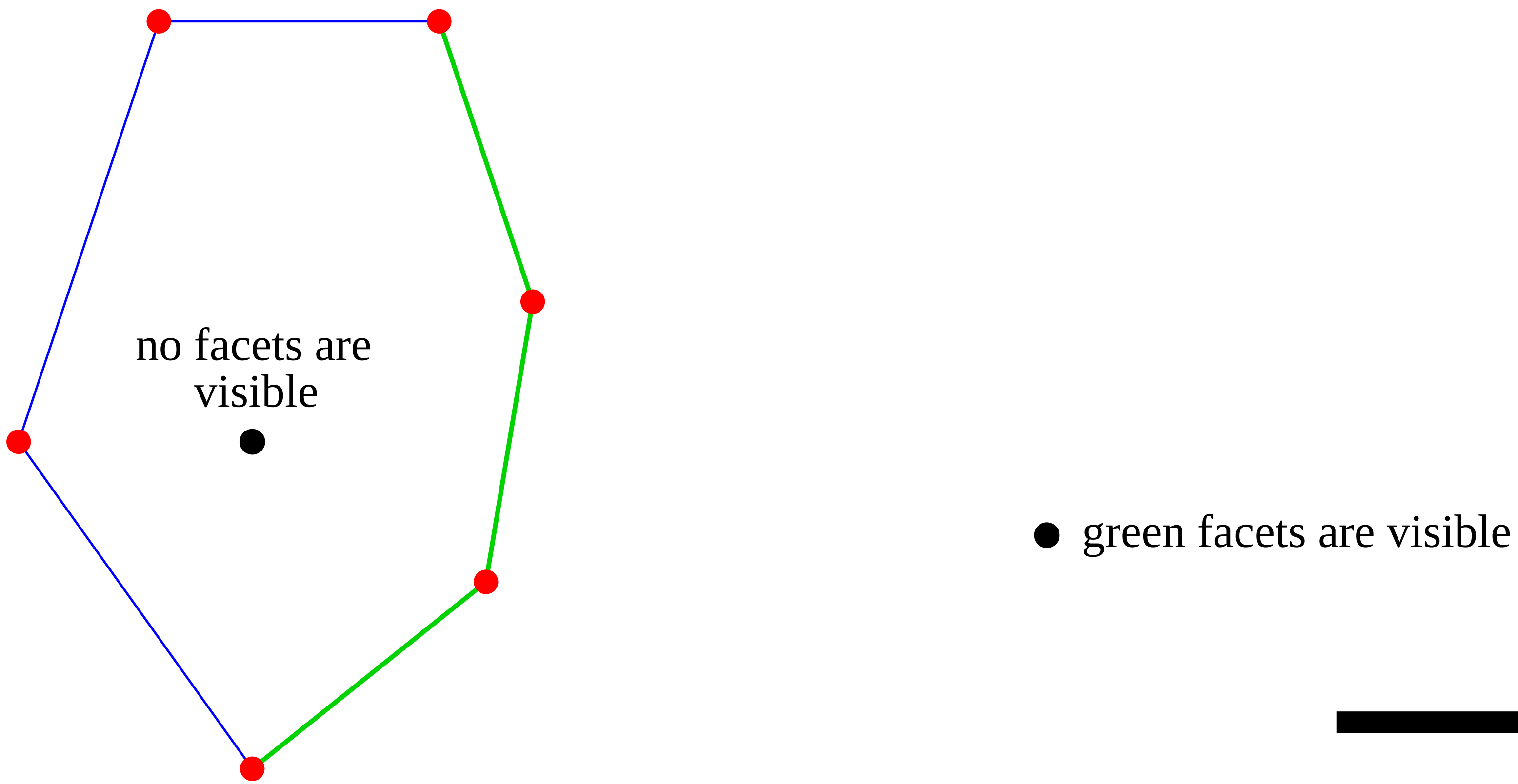

The visibility arrangement

aff(S): the affine span of a subset $S \subset \mathbb{R}^d$

visibility arrangement:

$$\mathbf{vis}(\mathcal{P}) = \{\mathrm{aff}(F) \;:\; F \text{ is a facet of } \mathcal{P}\}$$

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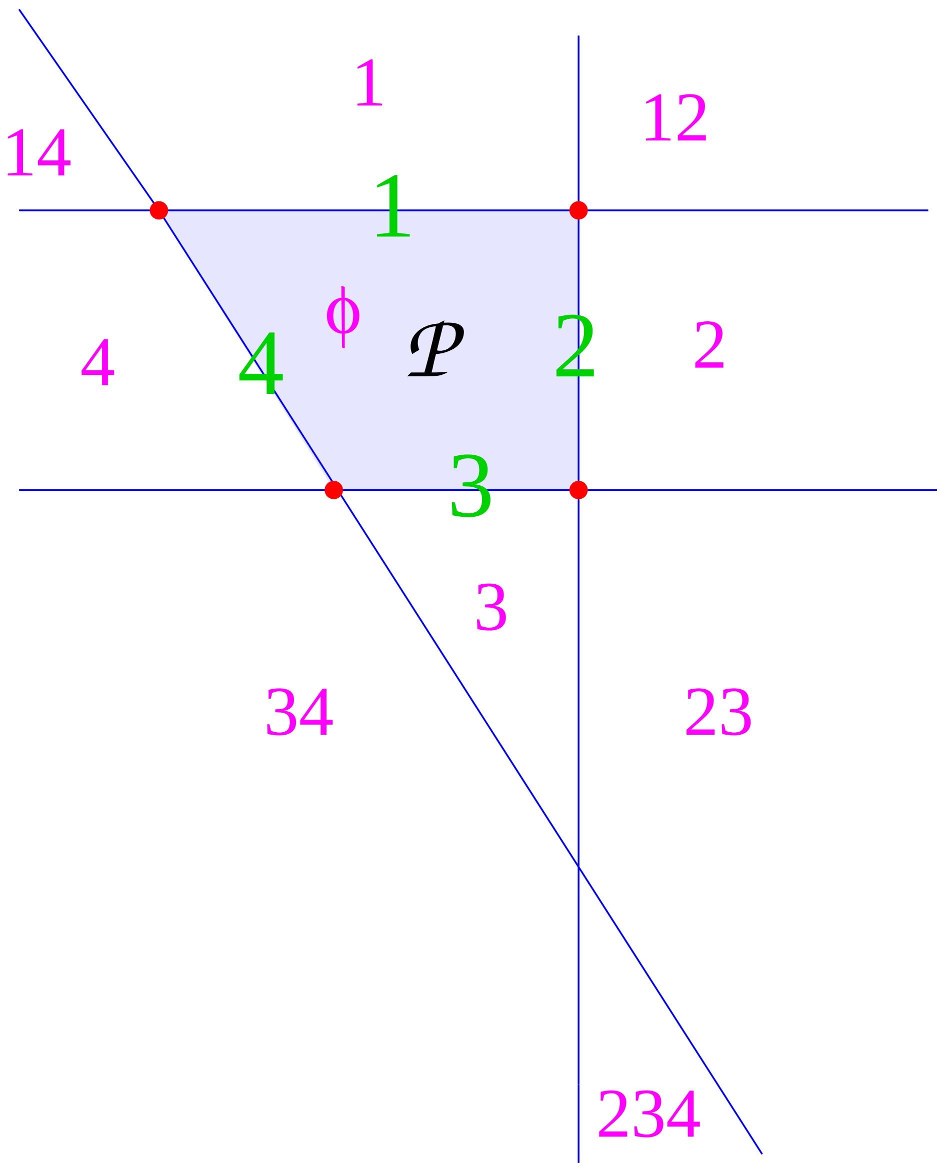
Regions of $\mathrm{vis}(\mathcal{P})$ correspond to sets of facets that are visible from some point $v \in \mathbb{R}^d$.

An example



Number of regions

$\boldsymbol{v}(\mathcal{P})$: number of regions of $\mathrm{vis}(\mathcal{P})$, i.e., the number of visibility sets of $\mathcal{P}$

$\boldsymbol{\chi_{\mathcal{A}}}(q)$: characteristic polynomial of the arrangement $\mathcal{A}$

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In general, $v(\mathcal{P})$ and $\chi_{\mathrm{vis}(\mathcal{P})}(q)$ are hard to compute.

A simple example

$\mathcal{P}_n = n$-cube

$$\chi_{\mathrm{vis}(\mathcal{P}_n)}(q) \;=\; (q-2)^n$$

$$v(\mathcal{P}_n) \;=\; 3^n$$

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$$\chi_{\mathrm{vis}(\mathcal{P}_n)}(q) = (q-2)^n$$

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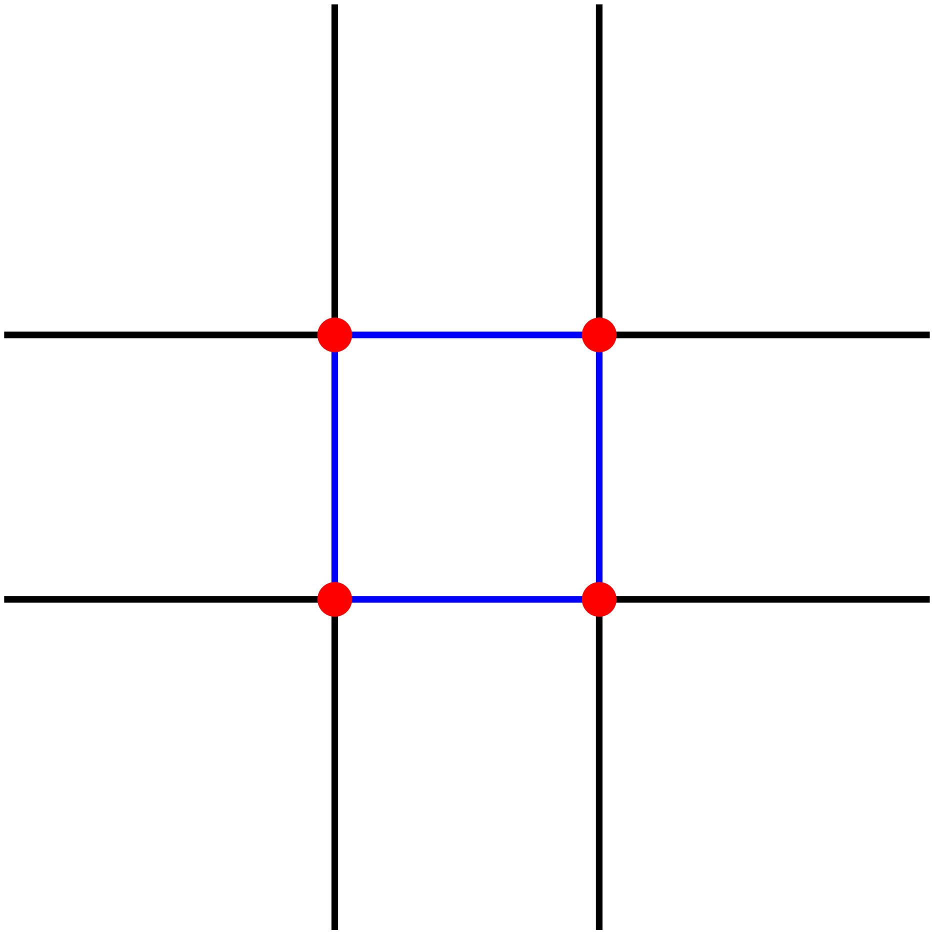
For any facet F, can see either F, $-F$, or neither.

The 2-cube



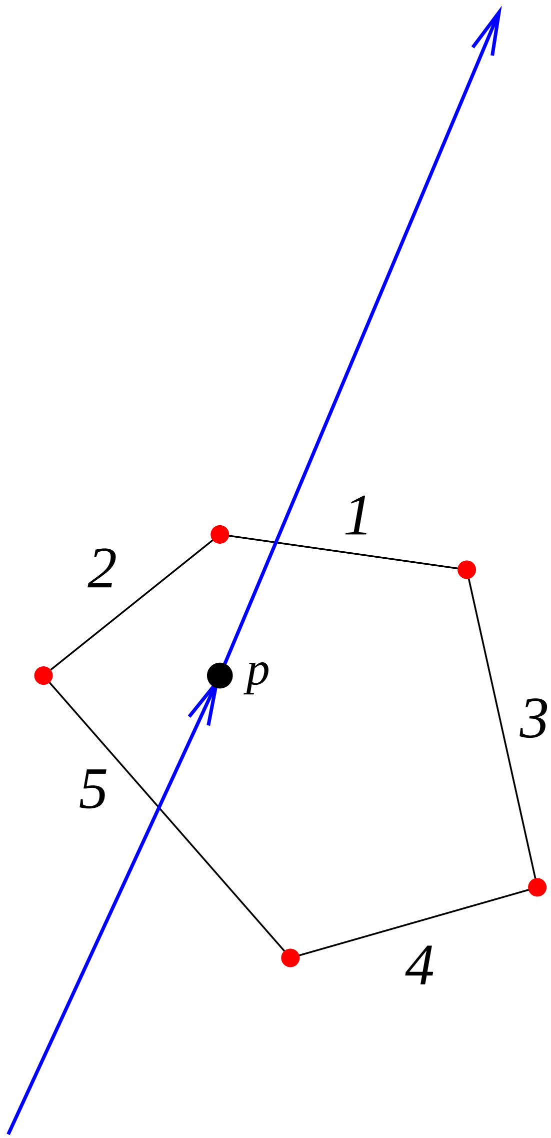
Line shellings

Let $\boldsymbol{p} \in \mathbf{int}(\mathcal{P})$ (interior of $\mathcal{P}$)

Line shelling based at p: let L be a directed line from p. Let $F_1, F_2, \ldots, F_k$ be the order in which facets become visible along L, followed by the order in which they become invisible from ∞ along the other half of L.

Assume L is sufficiently generic so that no two facets become visible or invisible at the same time.

Example of a line shelling



The line shelling arrangment

$\mathrm{ls}(\mathcal{P}, p)$: hyperplanes are

- affine span of p with aff$(F_1) \cap \mathrm{aff}(F_2) \neq \emptyset$, where F_1, F_2 are distinct facets
- if aff$(F_1) \cap \mathrm{aff}(F_2) = \emptyset$, then the hyperplane through p parallel to F_1, F_2

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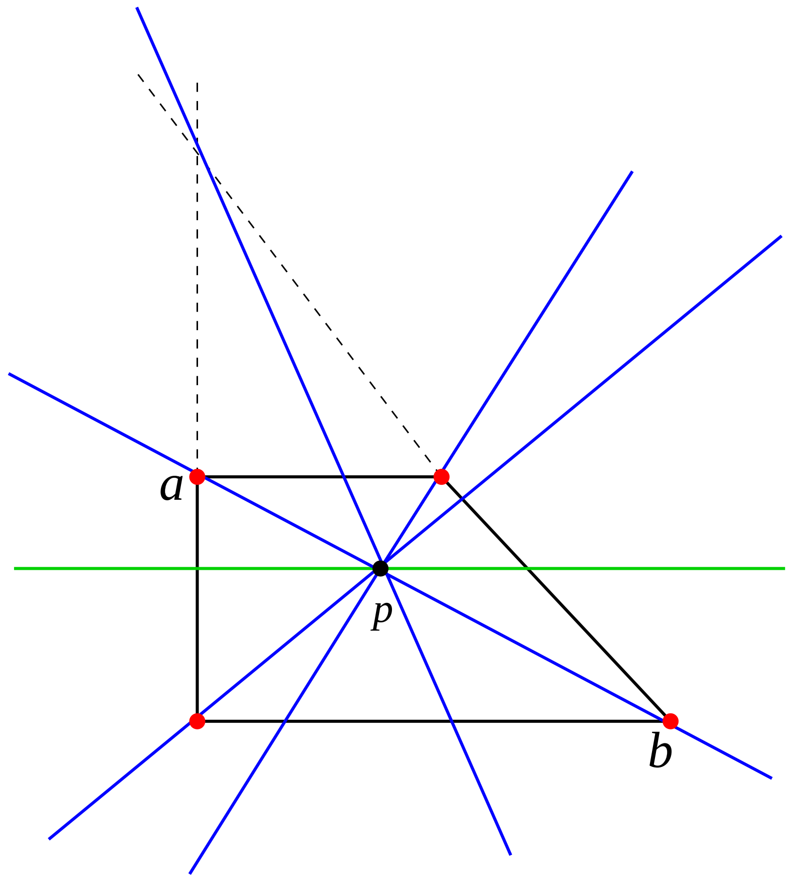
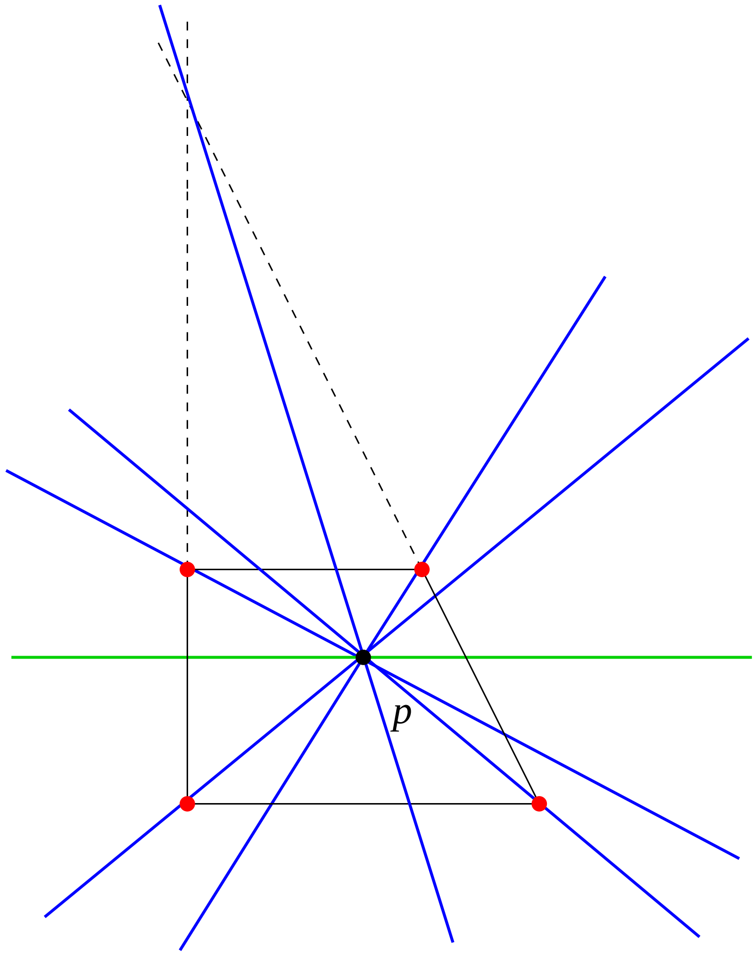
Line shellings at p are in bijection with regions of $\mathrm{ls}(\mathcal{P}, p)$.

A nongeneric example



p is not generic: $\overline{ap} = \overline{bp}$ (10 line shellings at p)

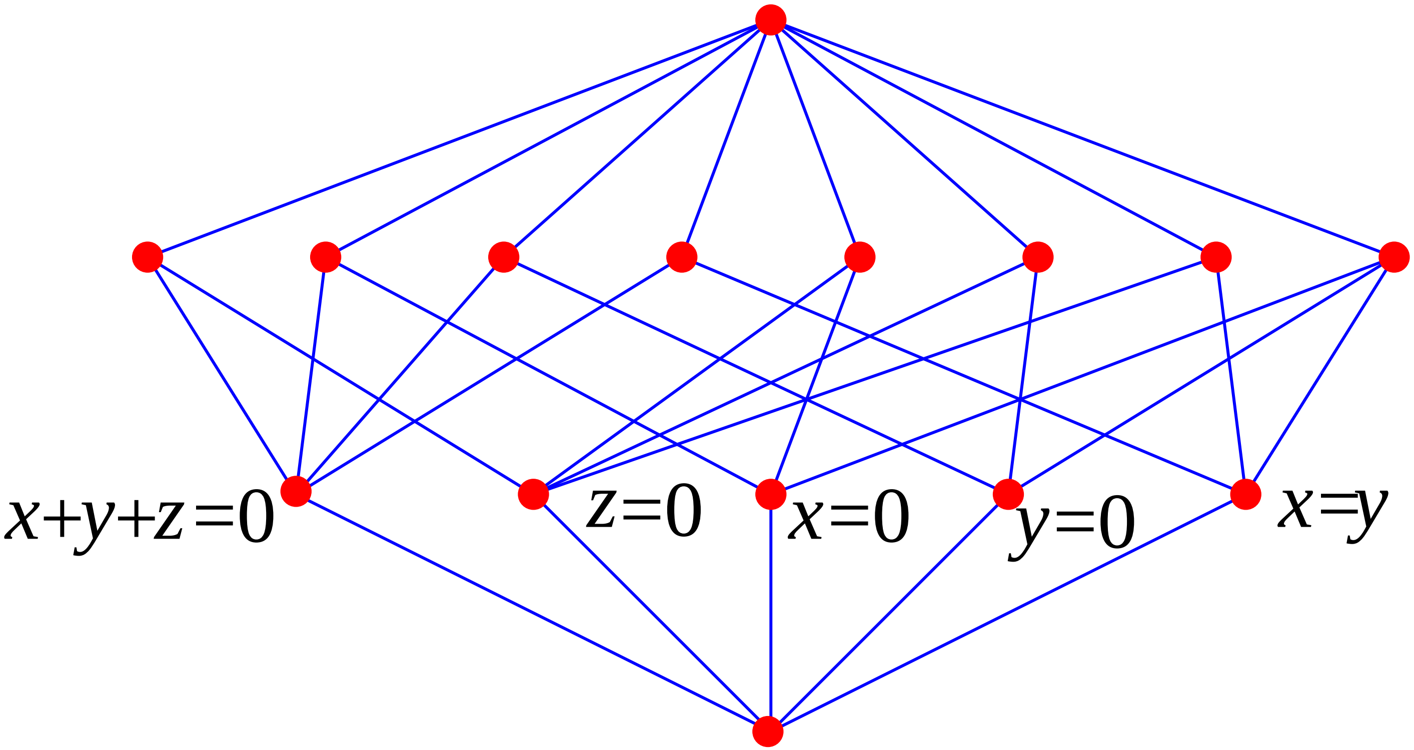
A generic example



One hyperplane for every pair of facets (12 line shellings at p)

Geometric lattices

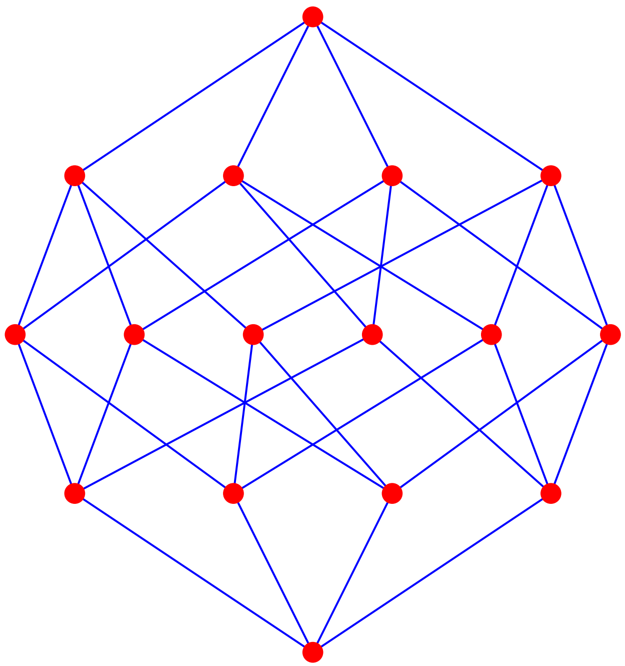
L: **geometric lattice**, e.g., the intersection poset of a central hyperplane arrangement



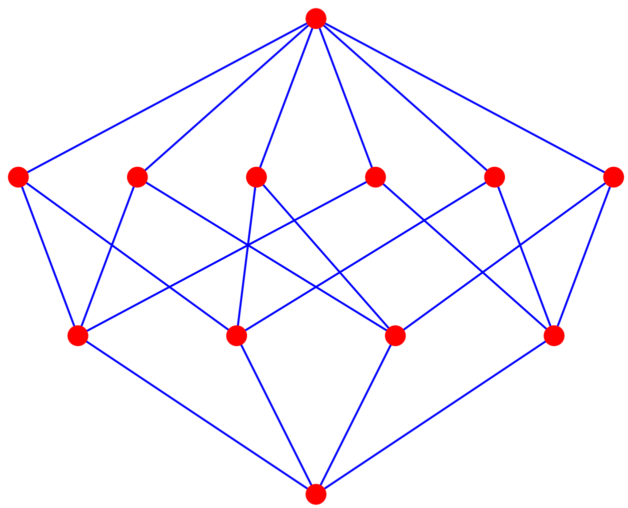
lattice of flats

Upper truncation

$\boldsymbol{T^k}(L)$: L with top k levels (excluding the maximum element) removed, called the kth **truncation** of L.



lattice L of flats of four independent points



$T^1(L)$

Upper truncation (cont.)

$T^k(L)$ is still a **geometric lattice** (easy).

Lower truncation

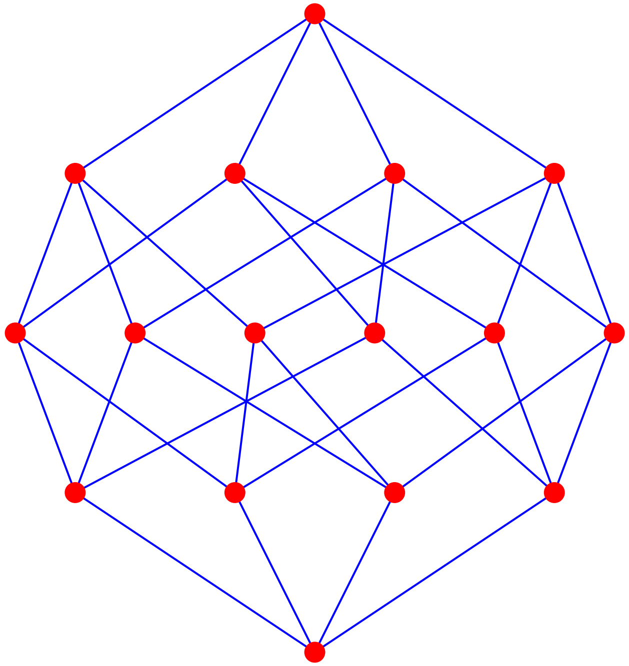
What if we remove the bottom k levels of L (excluding the minimal element)? Not a geometric lattice if rank is at least three.

Lower truncation

What if we remove the bottom k levels of L (excluding the minimal element)? Not a geometric lattice if rank is at least three.

Want to “fill in” the kth lower truncation with as many new elements as possible without adding new elements of rank one, increasing the rank of L, or altering the partial order relation of L.

Lower truncation is “bad”



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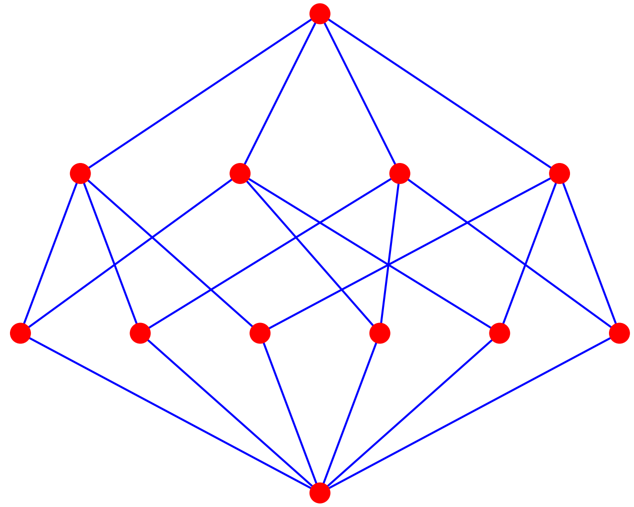
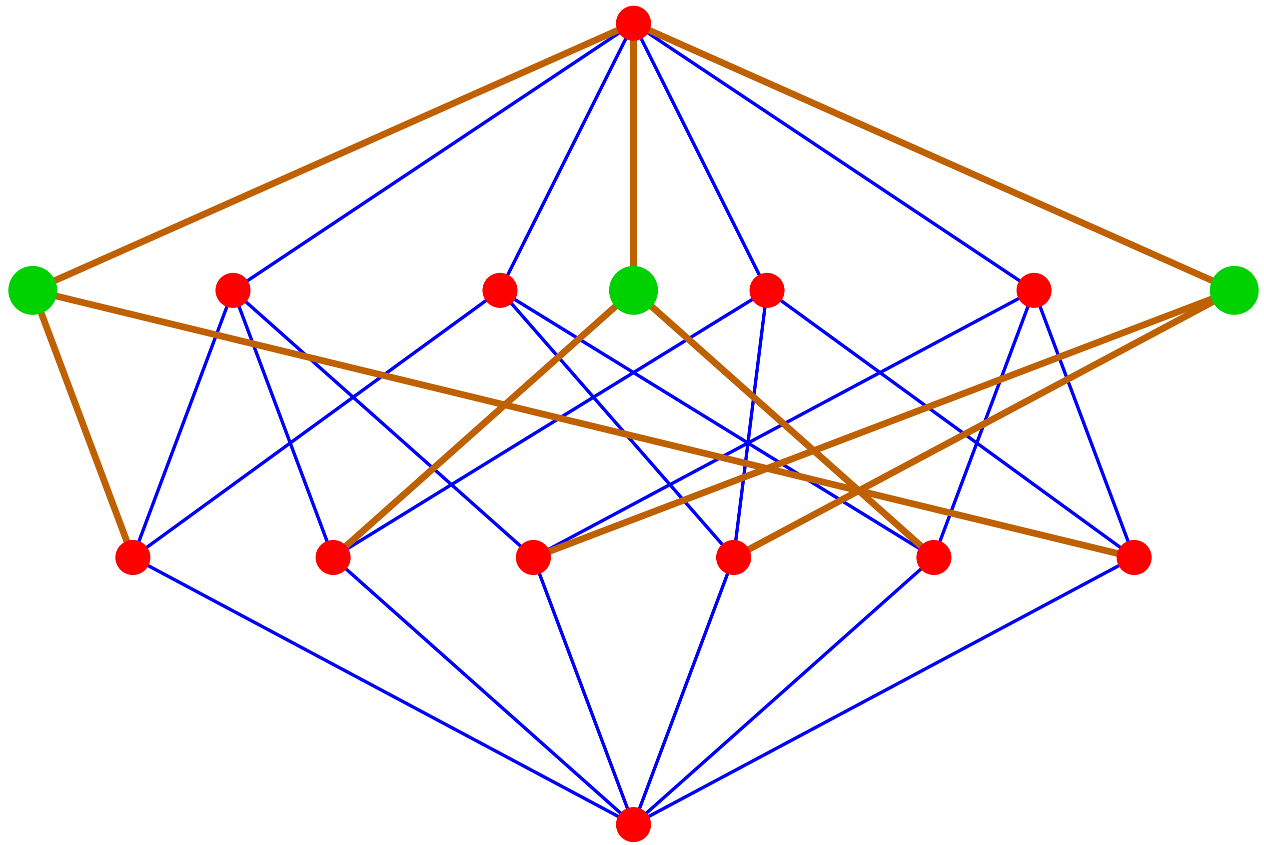


not a geometric lattice

An example of “filling in”



$D_1(B_4)$

The Dilworth truncation

Matroidal definition: Let M be a matroid on a set E of rank n, and let $1 \leq k < n$. The **kth Dilworth truncation** $D_k(M)$ has ground set $\binom{E}{k+1}$, and independent sets

$$\mathcal{I} = \left\{ I \subseteq \binom{E}{k+1} \ : \ \operatorname{rank}_M \left(\bigcup_{p \in I'} p \right) \geq \#I' + k, \right.$$

$$\left. \forall \emptyset \neq I' \subseteq I \right\}.$$

Geometric lattices

$D_k(M)$ “transfers” to $\boldsymbol{D_k(L)}$, where L is a geometric lattice.

rank$(L) = n \Rightarrow D_k(L)$ is a geometric lattice of rank $n - k$ whose atoms are the elements of L of rank $k + 1$.

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Details not explained here.

First Dilworth truncation of B_n

$L = \boldsymbol{B_n}$, the boolean algebra of rank n (lattice of flats of the matroid $\boldsymbol{F_n}$ of n independent points)

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$D_1(B_n) = \boldsymbol{\Pi_n}$ (lattice of partitions of an n-set)

$D_1(F_n)$ is the **braid arrangement** $x_i = x_j$, $1 \leq i < j \leq n$

Back to $\mathrm{vis}(\mathcal{P})$ and $\mathrm{ls}(\mathcal{P}, p)$

$\mathcal{A}$: an arrangement in $\mathbb{R}^n$ with hyperplanes

$$\boldsymbol{v_i \cdot x = \alpha_i}, \quad 0 \neq v_i \in \mathbb{R}^n, \quad \alpha_i \in \mathbb{R}, \quad 1 \leq i \leq m.$$

semicone $\boldsymbol{sc}(\mathcal{A})$ of $\mathcal{A}$: arrangement in $\mathbb{R}^{n+1}$ (with new coordinate $\boldsymbol{y}$) with hyperplanes

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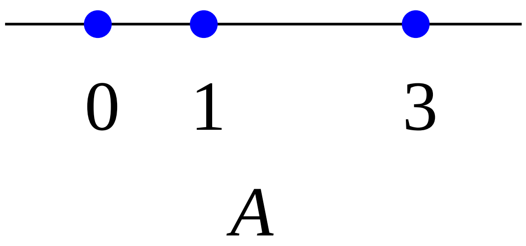
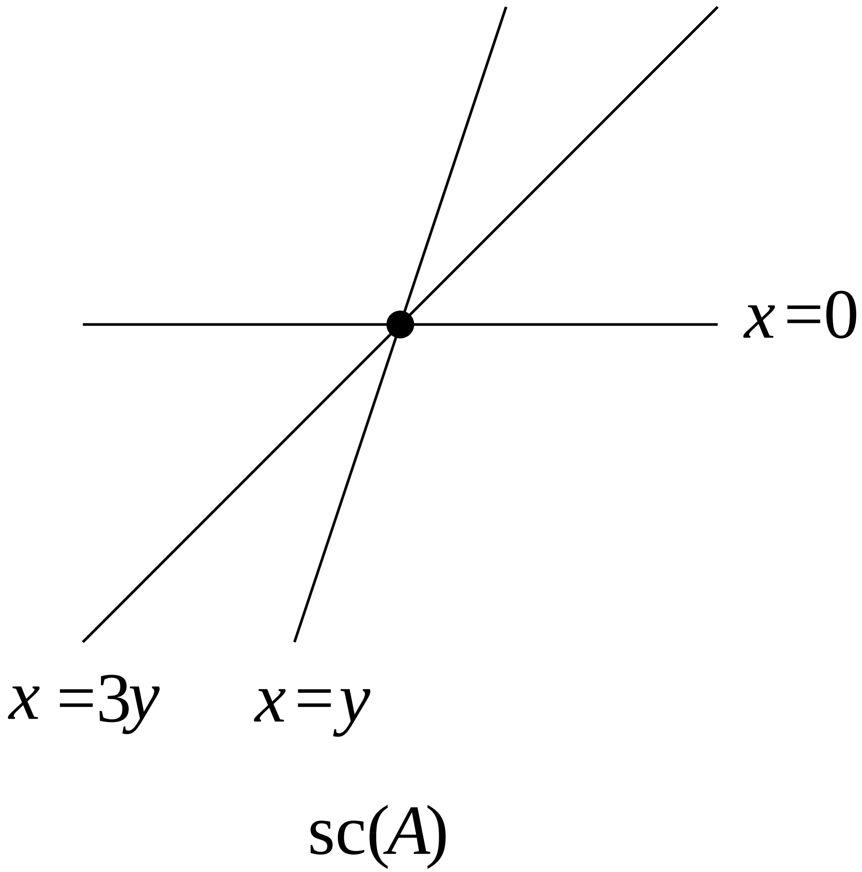
NOTE (for cognoscenti): do not confuse $\text{sc}(\mathcal{A})$ with the **cone** $\boldsymbol{c}(\mathcal{A})$, which has the additional hyperplane $y = 0$.

Example of a semicone





Main result

Theorem. *Let* $p \in \mathrm{int}(\mathcal{P})$ *be generic. Then*

$$L_{\mathrm{ls}(\mathcal{P},p)} \cong D_1\big(L_{\mathrm{sc}(\mathrm{vis}(\mathcal{P}))}\big).$$

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$$L_{\operatorname{ls}(\mathcal{P},p)} \cong D_1\big(L_{\operatorname{sc}(\operatorname{vis}(\mathcal{P}))}\big).$$

Proof omitted here, but straightforward.

The n-cube

Let $\mathcal{P}$ be an n-cube. Can one describe in a reasonable way $L_{\mathrm{ls}(\mathcal{P},p)}$ and/or $\chi_{\mathrm{ls}(\mathcal{P},p)}(q)$?

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Let $\mathcal{P}$ have vertices $(a_1, \ldots, a_n)$, $a_i = 0, 1$. If $p = (\frac{1}{2}, \frac{1}{2}, \ldots, \frac{1}{2})$, then $\mathrm{ls}(\mathcal{P}, p)$ is isomorphic to the Coxeter arrangement of type B_n, with

$$\begin{aligned} \chi_{\mathrm{ls}(\mathcal{P},p)}(q) &= (q-1)(q-3)\cdots(q-(2n-1)) \\ r(\mathrm{ls}(\mathcal{P},p)) &= 2^n\, n!. \end{aligned}$$

The 3-cube

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Let p be generic. Then

$$\chi(q) = q(q-1)(q^2 - 14q + 53), \quad r = 136 = 2^3 \cdot 17.$$

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Total number of line shellings of the 3-cube is 288. Total number of shellings is 480.

Three asides

1. Let $f(n)$ be the total number of shellings of the n-cube. Then

$$\sum_{n\geq 1} f(n)\frac{x^n}{n!} = 1 - \frac{1}{\sum_{n\geq 0}(2n)!\frac{x^n}{n!}}.$$

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2. Total number of line shellings of the n-cube is $2^n n!^2$.

3. Total number of line shellings of the n-cube where the line L passes through the center is $2^n n!$.

Two more asides

4. **Every** shelling of the n-cube C_n can be realized as a line shelling of a polytope combinatorially equivalent to C_n (**M. Develin**).

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5. Total number of line shellings of the n-cube where the line L passes through a generic point p: **open**.

Two consequences

- The number of line shellings from a generic $p \in \mathrm{int}(\mathcal{P})$ depends only on which sets of facet normals of $\mathcal{P}$ are linearly independent, i.e., matroid structure of $\mathrm{vis}(\mathcal{P})$.

Two consequences

- The number of line shellings from a generic $p \in \mathrm{int}(\mathcal{P})$ depends only on which sets of facet normals of $\mathcal{P}$ are linearly independent, i.e., matroid structure of $\mathrm{vis}(\mathcal{P})$.

Recall **Minkowski's theorem**: There exists a convex d-polytope with outward facet normals $v_1, \ldots, v_m$ and corresponding facet $(d-1)$-dimensional volumes $c_1, \ldots, c_m$ if and only if the v_i's span a d-dimensional space and

$$\sum c_i v_i = 0.$$

Second consequence

- $\boldsymbol{\mathcal{P}}$: $\boldsymbol{d}$-polytope with $\boldsymbol{m}$ facets, $\boldsymbol{p} \in \mathrm{int}(\mathcal{P})$

  $\boldsymbol{c(n,k)}$: signless Stirling number of first kind (number of $w \in \mathfrak{S}_n$ with k cycles)

  Then

  $$\mathrm{ls}(\mathcal{P},p) \leq 2(c(m,m-d+1)+c(m,m-d+3)$$
  $$+c(m,m-d+5)+\cdots)$$

  (best possible).

Proof.

Immediate from

$$T^j D_k = D_k T^j$$

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Here we apply $D_1 T^j$ to the boolean algebra B_n and use $D_1 B_n \cong \Pi_n$.

Many further directions

Valid hyperplane orders. We can extend the result

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$\mathcal{A}$: any (finite) arrangement in $\mathbb{R}^n$

p: any point not on any $H \in \mathcal{A}$

L: sufficiently generic directed line through p

Valid orders

$H_1, H_2, \ldots, H_k$: order in which hyperplanes are crossed by L coming in from ∞

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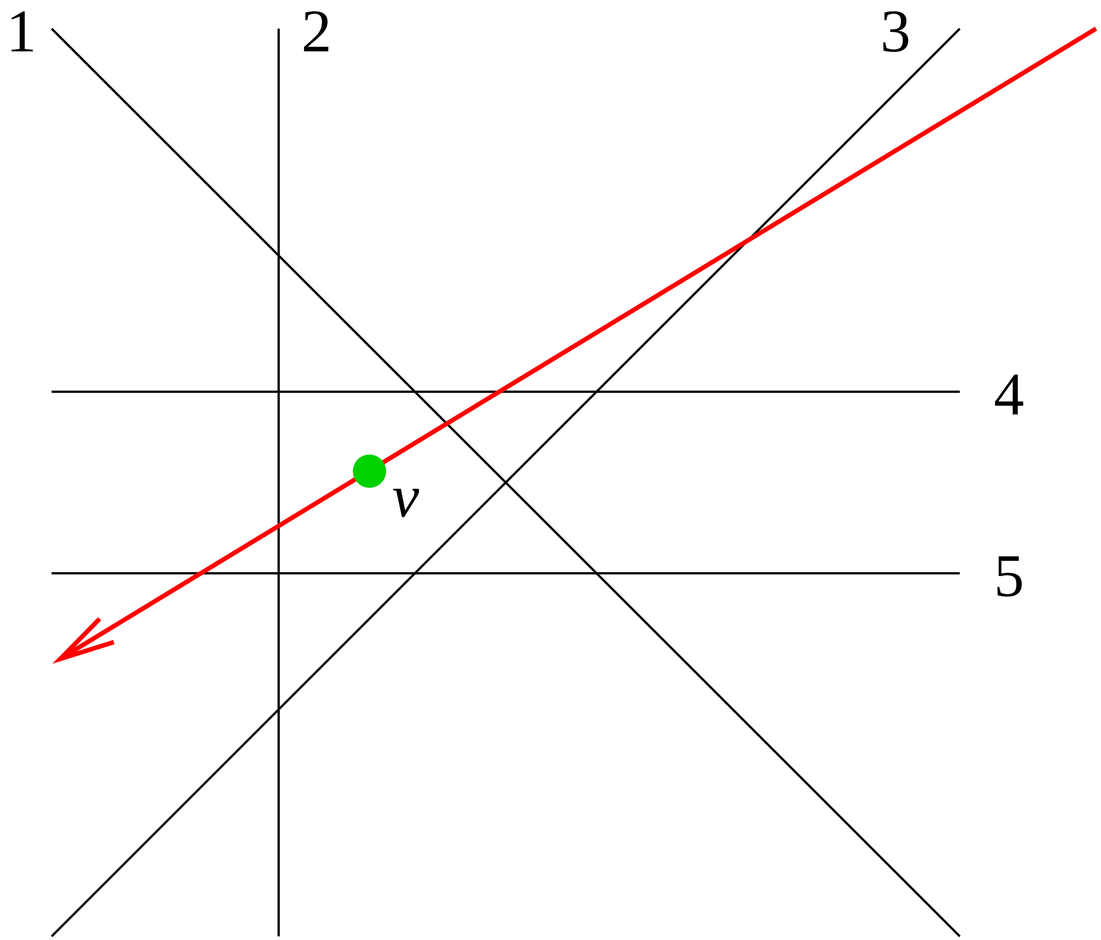
Call this a **valid order** of $(\mathcal{A}, p)$.

An example



valid order: 3, 4, 1, 2, 5

The valid order arrangment

vo$(\mathcal{A}, p)$: hyperplanes through p and every intersection of two hyperplanes in $\mathcal{A}$, together with all hyperplanes through p parallel to (at least) two hyperplanes of $\mathcal{A}$

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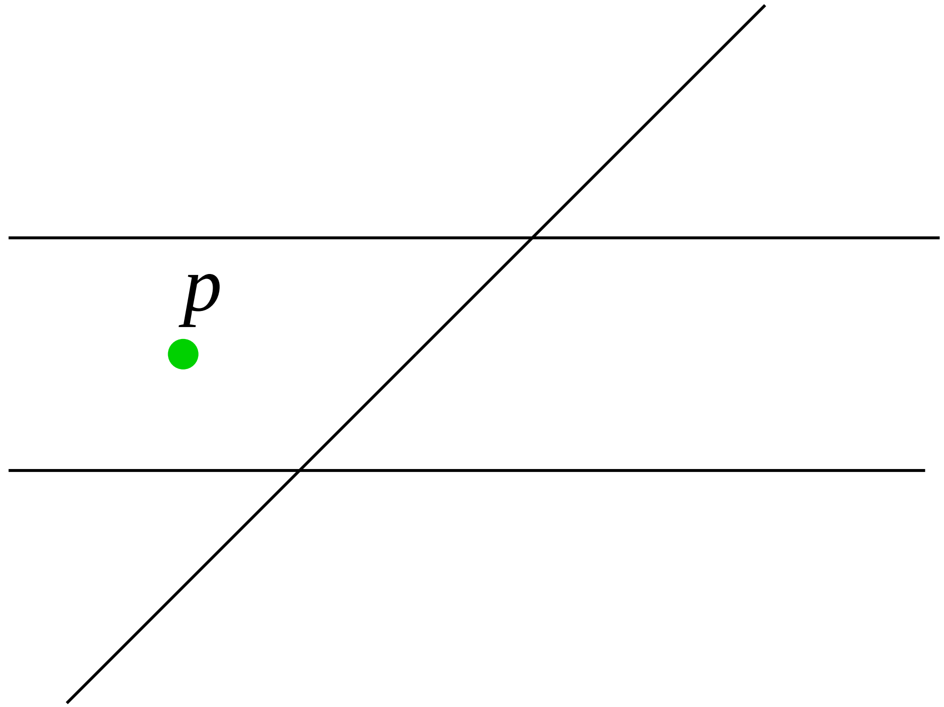

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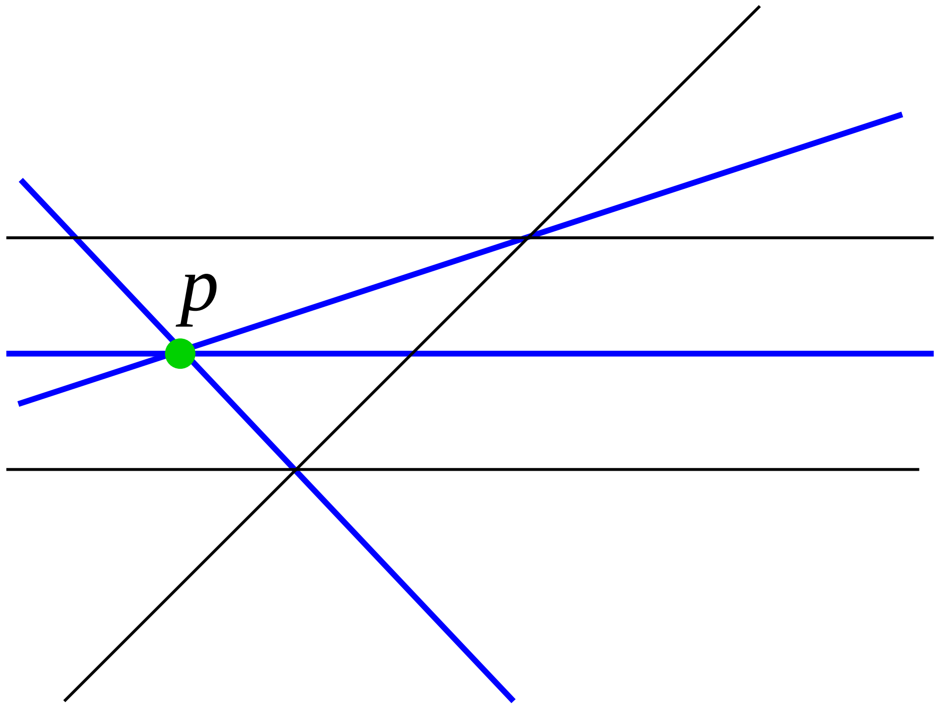

The Dilworth truncation of $\mathcal{A}$

The regions of $\mathrm{vo}(\mathcal{A}, p)$ correspond to valid orders of hyperplanes by lines through p (easy).

Theorem. *Let p be generic. Then*

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Note that right-hand side is independent of p.

m-planes

Rather than a line through p, pick an m-plane P through m generic points $p_1, \ldots, p_m$. For "sufficiently generic" P, get a "maximum size" induced arrangement

$$\boldsymbol{\mathcal{A}_P} = \{H \cap P : H \in \mathcal{A}\}$$

in P.

Define $\mathbf{vo}(\boldsymbol{\mathcal{A}}; \boldsymbol{p_1, \ldots, p_m})$ to consist of all hyperplanes passing through $p_1, \ldots, p_m$ and every intersection of $m+1$ hyperplanes of $\mathcal{A}$ (including "intersections at ∞").

mth Dilworth truncation

Theorem. *If* $p_1, \ldots, p_m$ *are generic, then*

$$L_{\mathrm{vo}(\mathcal{A};p_1,\ldots,p_m)} \cong L_{D_m(\mathrm{sc}(\mathcal{A}))}.$$

mth Dilworth truncation

Theorem. *If $p_1, \ldots, p_m$ are generic, then*

$$L_{\mathrm{vo}(\mathcal{A};p_1,\ldots,p_m)} \cong L_{D_m(\mathrm{sc}(\mathcal{A}))}.$$

Proof is straightforward.

Non-generic base points

For simplicity, consider only the original case $m = 1$. Recall:

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What if p is not generic?

Non-generic base points

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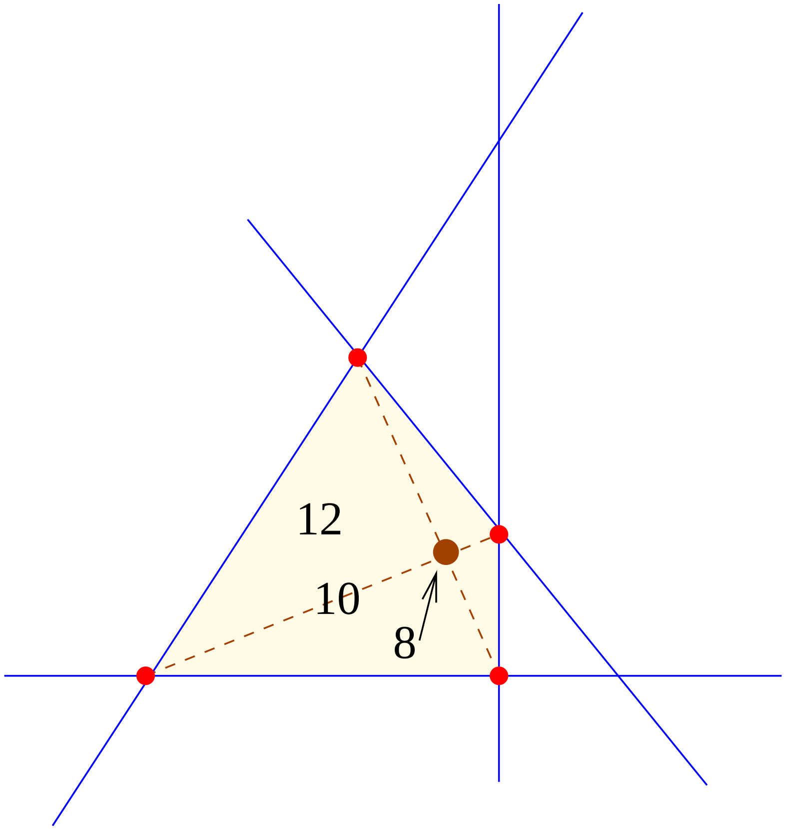
What if p is not generic?

Then we get "smaller" arrangements than the generic case.

We obtain a polyhedral subdivision of $\mathbb{R}^n$ depending on which arrangement corresponds to p.

An example



Numbers are number of line shellings from points in the interior of the face.

Order polytopes

$\boldsymbol{P} = \{t_1, \ldots, t_d\}$: a poset (partially ordered set)

Order polytope of P:

$$\mathcal{O}(P) =$$

$$\{(x_1, \ldots, x_d) \in \mathbb{R}^d \,:\, 0 \leq x_i \leq x_j \leq 1 \text{ if } t_i \leq t_j\}$$

Generalized chromatic polynomials

G: finite graph with vertex set V

$\mathbb{P} = \{1, 2, 3, \ldots\}$

$\sigma : V \rightarrow 2^{\mathbb{P}}$ such that $\#\sigma(v) < \infty, \; \forall v \in V$

$\chi_{G,\sigma}(q)$, $q \in \mathbb{P}$: number of proper colorings $f : V \rightarrow \{1, 2, \ldots, q\}$ such that

$$f(v) \notin \sigma(v), \; \forall v \in V$$

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Each f is a **list coloring**, but the definition of $\chi_{G,\sigma}(q)$ seems to be new.

The arrangement $\mathcal{A}_{G,\sigma}$

$\boldsymbol{d} = \#V = \#\{v_1, \ldots, v_d\}$

$\mathcal{A}_{G,\sigma}$: the arrangement in $\mathbb{R}^d$ given by

$$\begin{aligned} x_i &= x_j, \text{ if } v_i v_j \text{ is an edge} \\ x_i &= \alpha_j, \text{if } \alpha_j \in \sigma(v_i) \end{aligned}$$

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Theorem (easy). $\chi_{\mathcal{A}_{G,\sigma}}(q) = \chi_{G,\sigma}(q)$ for $q \gg 0$

Consequences

Since $\chi_{G,\sigma}(q)$ is the characteristic polynomial of a hyperplane arrangement, it has such properties as a **deletion-contraction recurrence**, **broken circuit theorem**, **Tutte polynomial**, etc.

vis($\mathcal{O}(P)$) and $\mathcal{A}_{H,\sigma}$

Theorem (easy). *Let* H *be the Hasse diagram of* P*, considered as a graph. Define* $\boldsymbol{\sigma} : H \to \mathbb{P}$ *by*

$$\sigma(v) = \begin{cases} \{1,2\}, & v = \text{ isolated point} \\ \{1\}, & v \text{ minimal, not maximal} \\ \{2\}, & v \text{ maximal, not minimal} \\ \emptyset, & \text{otherwise.} \end{cases}$$

Then $\mathrm{vis}(\mathcal{O}(P)) = \mathcal{A}_{H,\sigma}$.

Rank one posets

Suppose that P has rank at most one (no three-element chains).

$\boldsymbol{H}(P) =$ Hasse diagram of P, with vertex set $\boldsymbol{V}$

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Theorem.

$$v(\mathcal{O}(P)) = (-1)^{\#P} \sum_{W \subseteq V} \chi_{H_W}(-3)$$

Supersolvable and free

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- G is a **chordal** graph, i.e., can order vertices $v_1, \ldots, v_d$ so that v_{i+1} connects to previous vertices along a clique. (Numerous other characterizations.)

Generalize to (G, σ)

Theorem (easy). *Suppose that we can order the vertices of G as $v_1, \ldots, v_p$ such that:*

- v_{i+1} *connects to previous vertices along a clique (so G is chordal).*
- *If $i < j$ and v_i is adjacent to v_j, then $\sigma(v_j) \subseteq \sigma(v_i)$.*

Then $\mathcal{A}_{G,\sigma}$ is supersolvable.

Open questions

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- Is it necessary for freeness? (In general, supersolvable $\Rightarrow$ free.)
- Are there characterizations of supersolvable arrangements $\mathcal{A}_{G,\sigma}$ analogous to the known characterizations of supersolvable $\mathcal{A}_G$?

The last slide

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The last slide