Basics of polyhedral theory, flows and networks

Martin Grötschel

ADM I Vorlesung

20.12.2012

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Contents

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Contents

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Linear Programming

$$\max c_1 x_1 + c_2 x_2 + \ldots + c_n x_n$$

$$subject \quad to$$

$$a_{11}x_1 + a_{12}x_2 + \ldots + a_{1n}x_n = b_1$$

$$a_{21}x_1 + a_{22}x_2 + \ldots + a_{2n}x_n = b_2$$

$$\cdot$$

$$a_{m1}x_1 + a_{m2}x_2 + \ldots + a_{mn}x_n = b_m$$

$$x_1, x_2, \ldots, x_n \geq 0$$

$$\max c^T x$$

$$Ax = b$$

$$x \geq 0$$

linear program
in standard form

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Linear Programming

$$\max c^T x \quad Ax = b \quad x \geq 0$$

linear program in standard form

$\Rightarrow$

$$\max c^T x \quad Ax \leq b \quad -Ax \leq -b \quad -x \leq 0$$

$$\max c^T x \quad Ax \leq b$$

linear program in "polyhedral form"

$\Rightarrow$

$$\max c^T x^+ - c^T x^- \quad Ax^+ + Ax^- + Is = b \quad x^+, x^-, s \geq 0 \quad (x = x^+ - x^-)$$

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Contents

CO@W

1. Linear programs
2. Polyhedra
3. Algorithms for polyhedra
   - Fourier-Motzkin elimination
   - some Web resources
4. Semi-algebraic geometry
5. Faces of polyhedra

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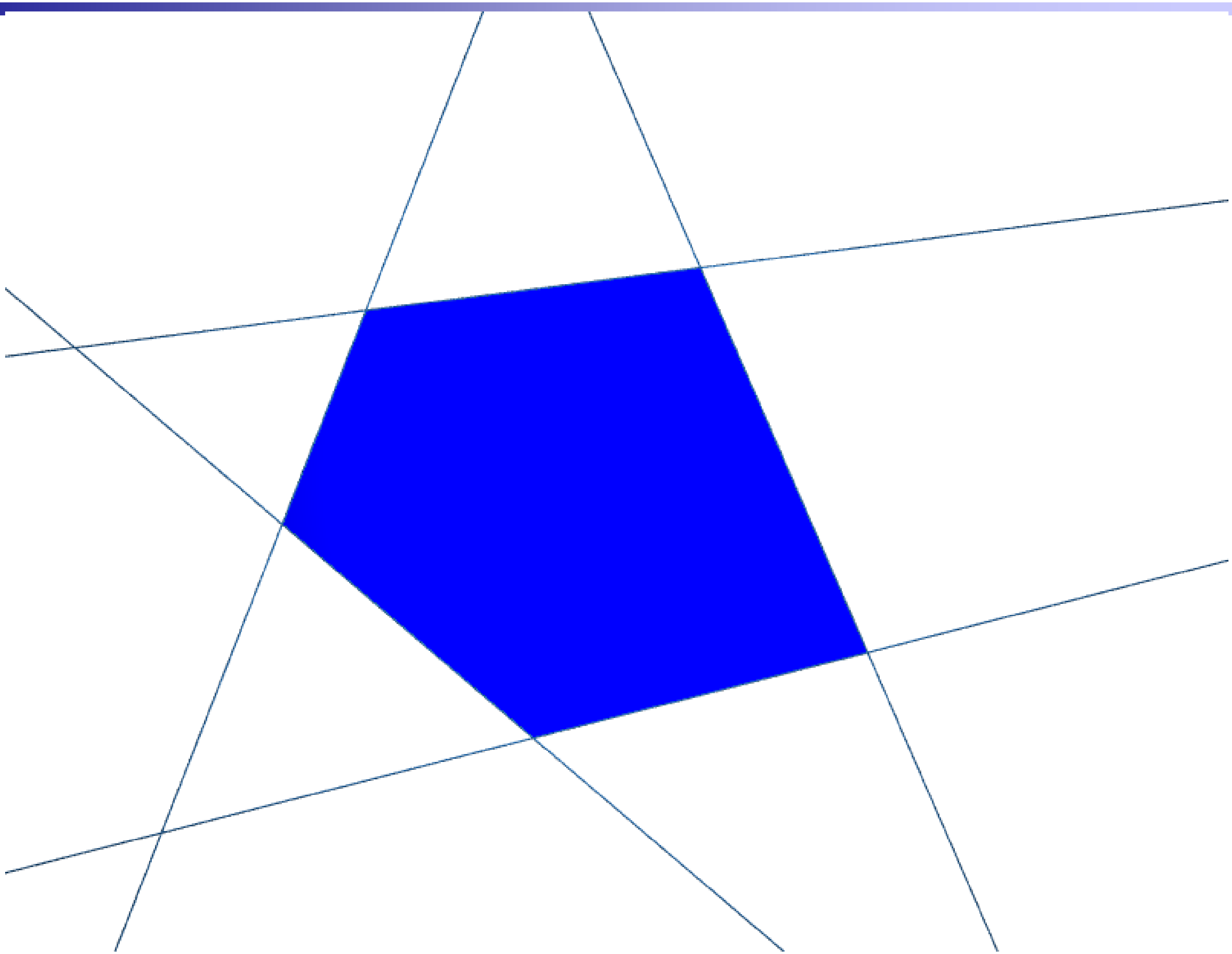
A Polytope in the Plane



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A Polytope in 3-dimensional space

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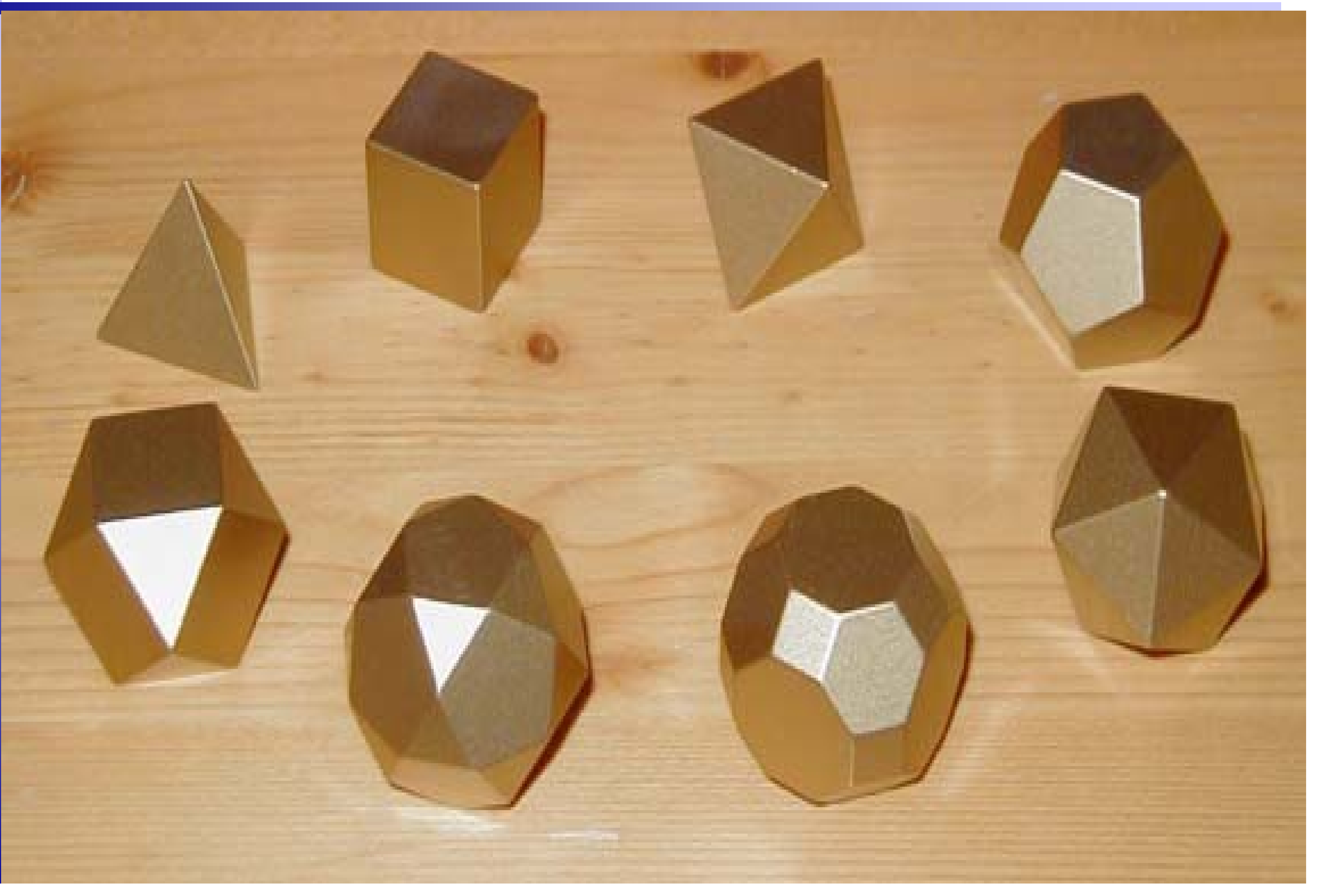
„beautiful“ polyehedra



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Polyhedra-Poster

http://www.peda.com/posters/Welcome.html

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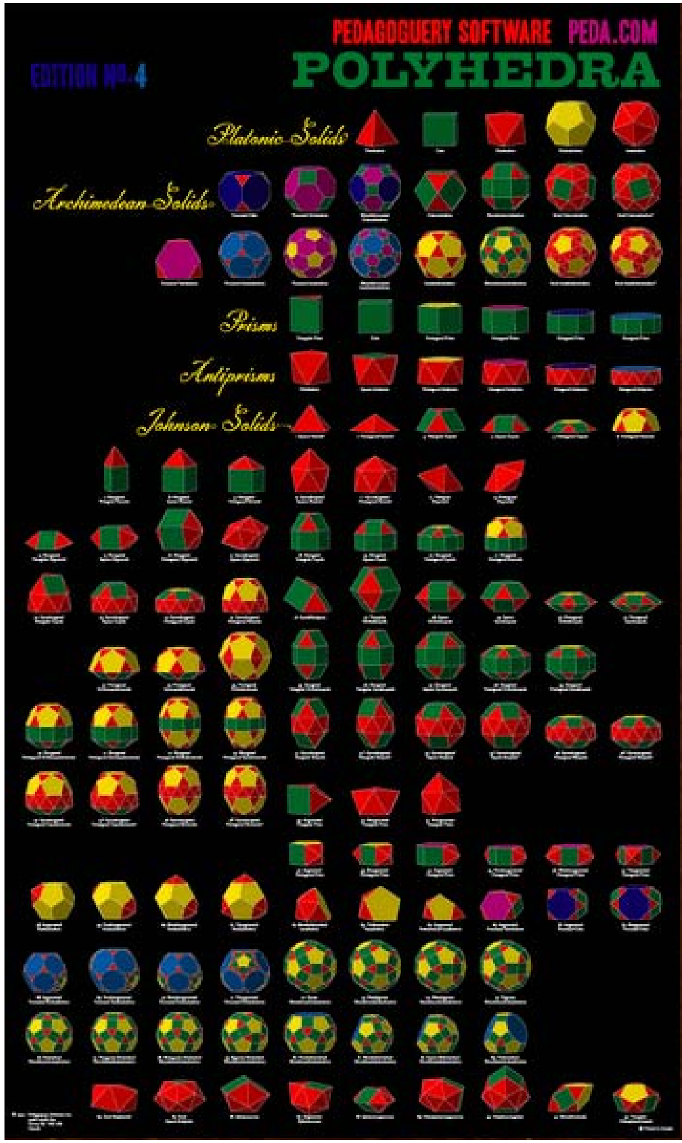

We currently offer one poster for secure online purchasing: our *Polyhedra* poster, which displays all convex polyhedra with regular polygonal faces (a finite sampling of prisms and anti-prisms are included).

It measures 22" x 37" and is printed on glosssy paper. A protective coating was applied during printing.

The poster is shown on the left; to see a close-up of a portion of the poster, move your mouse over the image.

This is the fourth edition of the poster. Other versions of the poster are shown in our Posters Archive.

$14 FOR 1 POSTER
$28 FOR 4 POSTERS
FREE SHIPPING

Poster which displays all convex polyhedra with regular polygonal faces

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http://www.eg-models.de/

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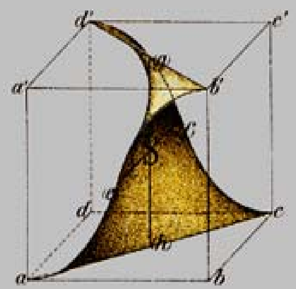


H.A. Schwarz Ges.Math.Abh
Springer Berlin 1890

Note: Some browser versions do not display Java applets. Please, press the 'No Applet' button in the navigation bar to avoid using Java.

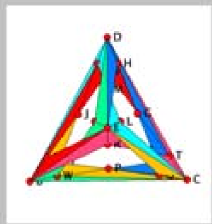
Anschauliche Geometrie - A tribute to Hilbert, Cohn-Vossen, Klein and all other geometers.

Electronic Geometry Models

This archive is open for any geometer to publish new geometric models, or to browse this site for material to be used in education and research. These geometry models cover a broad range of mathematical topics from geometry, topology, and to some extent from numerics.

Click "Models" to see the full list of published models. See here for details on the submission and review process.

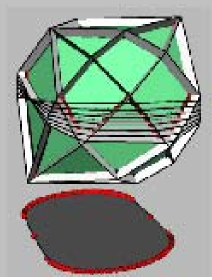
Selection of recently published models



Model 2008.11.001 by Frank H. Lutz and Günter M. Ziegler *A Small Polyhedral Z-Acyclic 2-Complex in R4.*
Section: *Polytopal Complexes*

We present a 4-dimensional polyhedral realization of a 2-dimensional Z-acyclic but non-contractible simplicial complex with 23 vertices.

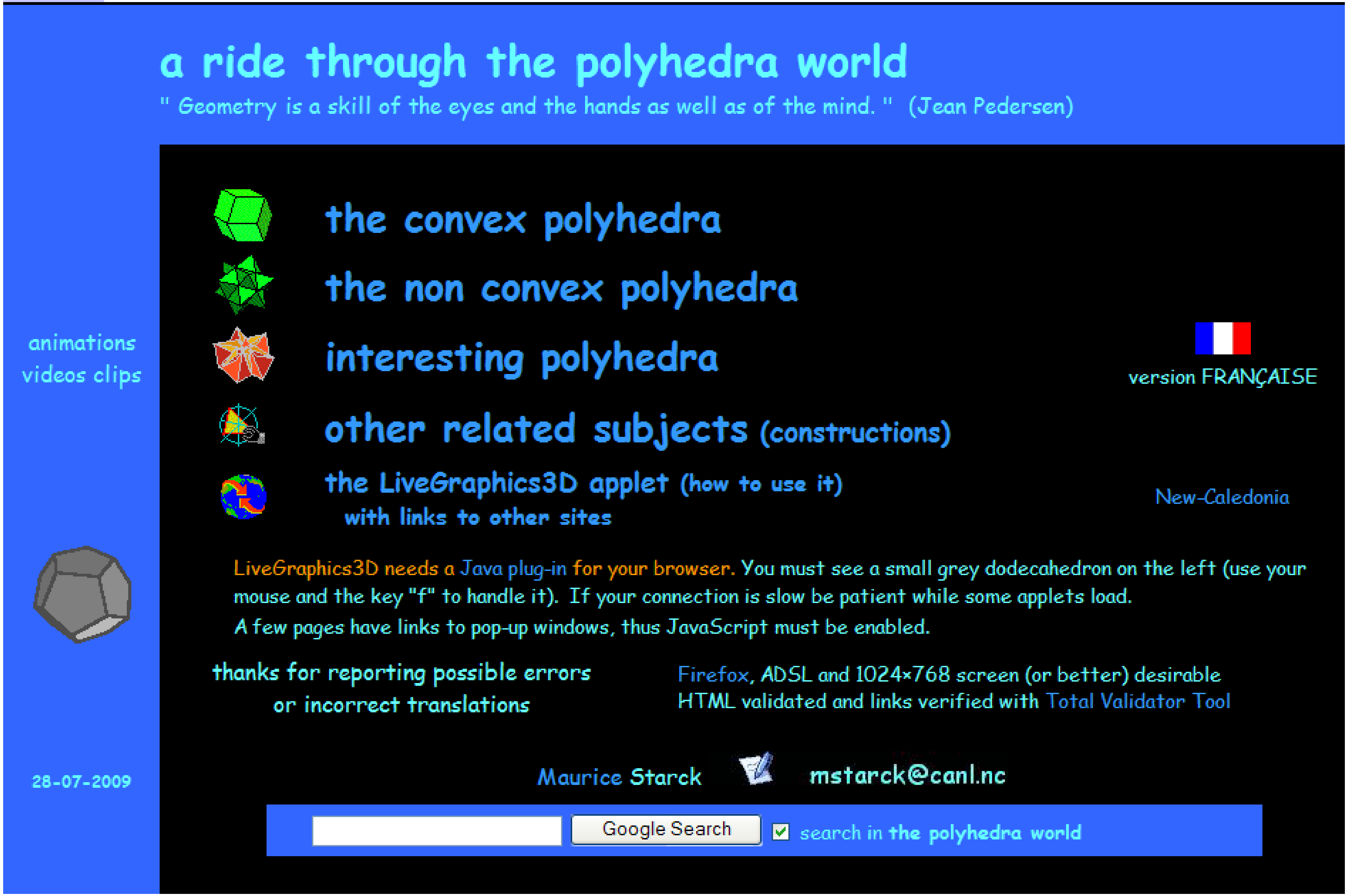
Our example answers a query by Lutz Hille (Hamburg), who in November 2006 had asked us for examples of Z-acyclic but non-contractible complexes realized in low dimensions. His question was motivated by toric geometry.



Model 2008.10.002 by Thilo Rörig, Nikolaus Witte, and Günter M. Ziegler *Zonotopes With Large 2D-Cuts.*
Section: *Polytopes*

For fixed $d \geq 2$ there are d-dimensional zonotopes with n zones for which a 2-dimensional central section has $\Omega(n^{d-1})$ vertices. The result is asymptotically optimal for all fixed $d \geq 2$.

http://www.ac-noumea.nc/maths/amc/polyhedr/index_.htm



Plato's five regular polyhedra

http://www.ac-noumea.nc/maths/polyhedr/index.htm

http://www.ac-noumea.nc/maths/amc/polyhedr/convex1.htm

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convex polyhedra 1 - Microsoft Internet Explorer

Datei Bearbeiten Ansicht Favoriten Extras ?

Zurück Suchen Favoriten Medien

Adresse http://www.ac-noumea.nc/maths/amc/polyhedr/convex1_.htm Wechseln zu Links

Plato's five regular polyhedra

The regular polyhedra are, in the space, the analogues of the regular polygons in the plane ; their faces are regular and identical polygons, and their vertices, regular and identical, are regularly distributed on a sphere. Their analogues in dimension four are the regular polytopes.

As we do for the polygons, we recognize a convex polyhedron by the very fact that all its diagonals (segments which join two vertices not joined by an edge) are inside the polyhedron.

Whereas there exist an infinity of regular convex polygons, the regular convex polyhedra are only five.

proof :

The angle of a regular polygon with n sides is 180°(n-2)/n : 60° (triangle), 90° (square), 108° (pentagon), 120° (hexagon)...

On a vertex of a regular polyhedron the sum of the face's angles (there are at least three) must be smaller than 360°.

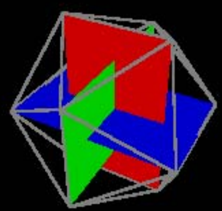
Since 6x60° = 4x90° = 3x120° = 360° < 4x108°, there are only five possibilities: 3, 4, or 5 triangles, 3 squares or 3 pentagons.

name	cube	octahedron	tetrahedron	icosahedron	dodecahedron
faces	6 squares	8 equil.triangles	4 equil.triangles	20 equil.triangles	12 regul.pentagons
vertices	8	6	4	12	20
edges	12	12	6	30	30
faces angle	90°	109°28'	70°32'	138°11'	116°34'

The LiveGraphics3D applet by Martin Kraus (University of Stuttgart) allows you to move these polyhedra with your mouse.

The regular octahedron's edges are the sides of three squares with the same centre and orthogonal by pairs.

The regular icosahedron's vertices are the vertices of three golden rectangles (sides in golden ratio 1.618...) with the same centre and orthogonal by pairs.



Four vertices of a cube are the vertices of a regular tetrahedron ; so we can make a regular tetrahedron by cutting four "corners" of a cube.

LiveGraphics3D 1.54: Please drag to rotate. Internet

Polyhedra have fascinated people during all periods of our history

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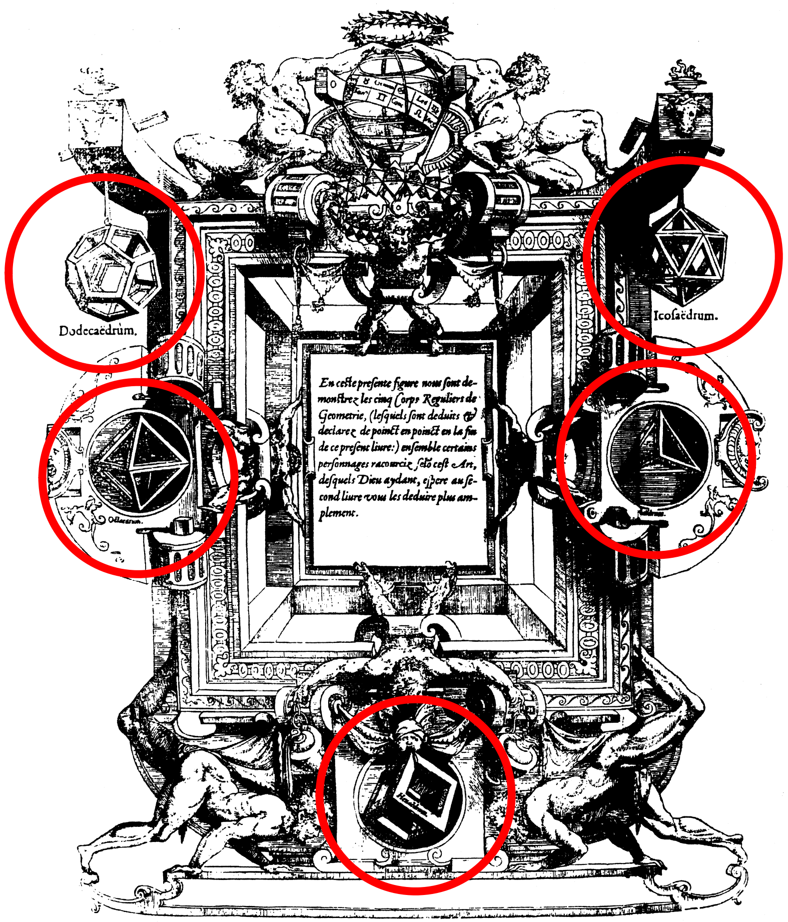

From *Livre de Perspective* by Jean Cousin, 1568.

- book illustrations
- magic objects
- pieces of art
- objects of symmetry
- models of the universe

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http://www.mathe.tu-freiberg.de/~hebisch/cafe/platonische.html

Das Hexaeder (Würfel) ist wohl in allen Hochkulturen des Altertums bekannt gewesen, das Dodekaeder soll Pythagoras entdeckt haben, dem auch das Tetraeder bekannt gewesen sein soll, allerdings noch unter dem Namen Pyramide. Die Bezeichnung Tetraeder hierfür stammt von Heron von Alexandria. Das Oktaeder und das Ikosaeder schließlich soll Theaitetos von Athen entdeckt haben. Im Buch XIII der Elemente des Euklid findet man bereits um 300 v. Chr. Konstruktionsbeschreibungen aller Platonischen Körper und den Nachweis, daß es nur diese regulären konvexen Polyeder gibt. Platon hat die später nach ihm benannten Körper in seine Philosophie eingebaut, indem er sie mit den vier Elementen Erde (Hexaeder), Wasser (Ikosaeder), Feuer (Tetraeder) und Luft (Oktaeder) in Verbindung brachte und das Dodekaeder mit einer geheimnisvollen quinta essentia, dem Himmelsäther.

http://www.mathe.tu-freiberg.de/~hebisch/cafe/platonische.html

Jeder Platonische Körper besitzt eine Innenkugel, auf der die Mittelpunkte sämtlicher Flächen des Körpers liegen, und eine Außenkugel, auf der sämtliche Körperecken liegen. Diese Eigenschaft nutzte Johannes Kepler 1596 in seinem Jugendwerk Mysterium Cosmographicum aus, um die Abstände der damals sechs bekannten Planeten des Sonnensystems zu erklären. Alle Planeten beschrieben danach Kreisbahnen auf Kugelschalen. Zwischen diese sechs Kugelschalen paßte Kepler die Platonischen Körper so ein, daß jeweils eine Kugel Innenkugel des Körpers und die folgende Kugel Außenkugel des Körpers war. Danach lag das Oktaeder zwischen Merkur und Venus, das Ikosaeder zwischen Venus und Erde, das Dodekaeder zwischen Erde und Mars, das Tetraeder zwischen Mars und Jupiter und der Würfel zwischen Jupiter und Saturn.

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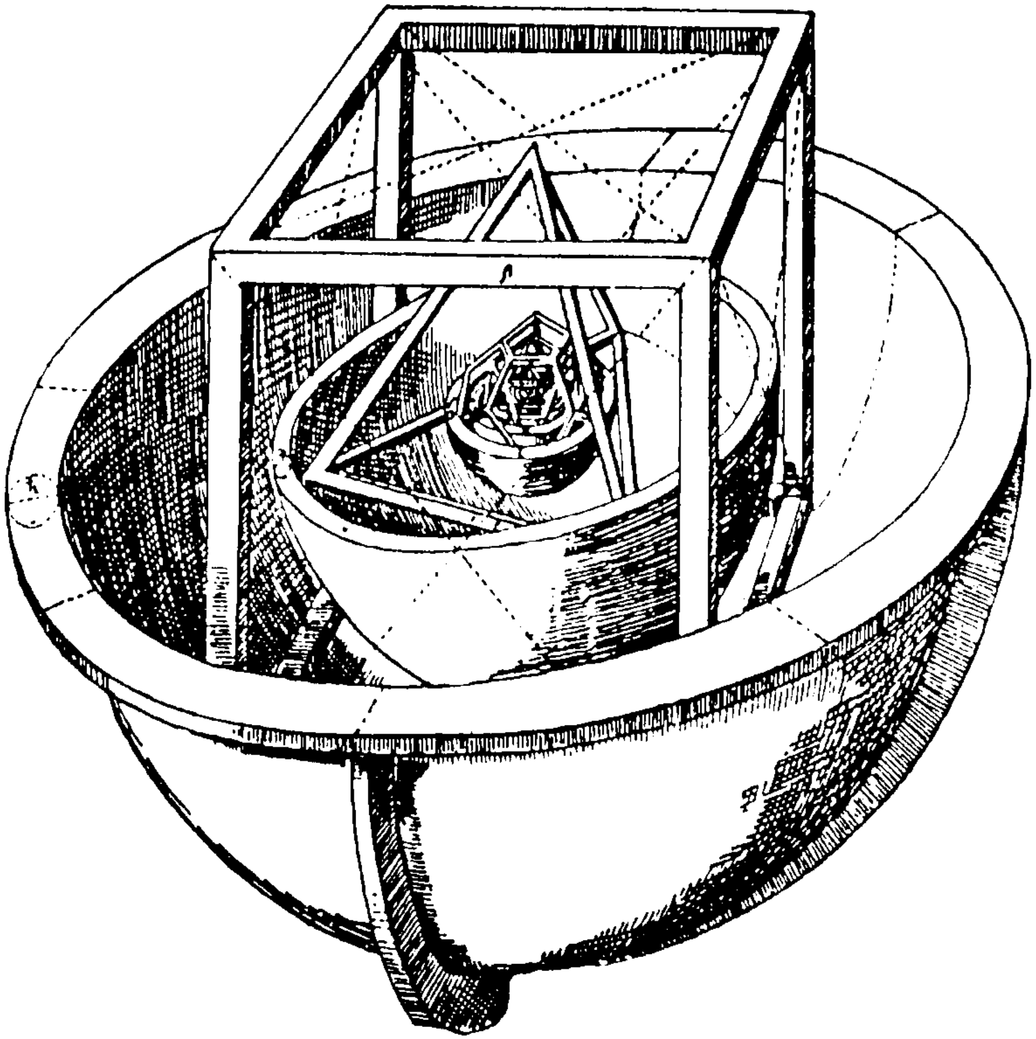
http://www.mathe.tu-freiberg.de/~hebisch/cafe/platonische.html



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Definitions

Linear programming lives (for our purposes) in the n-dimensional real (in practice: rational) vector space.

- convex polyhedral cone: conic combination (i. e., nonnegative linear combination or conical hull) of finitely many points
  K = cone(E), E a finite set in $\mathbb{R}^n$.
- polytope: convex hull of finitely many points:
  P = conv(V), V a finite set in $\mathbb{R}^n$.
- polyhedron: intersection of finitely many halfspaces

$$P = \{x \in \mathbb{R}^n \mid Ax \le b\}$$

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Important theorems of polyhedral theory (LP-view)

When is a polyhedron nonempty?

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Important theorems of polyhedral theory (LP-view)

When is a polyhedron nonempty?

The Farkas-Lemma (1908):

A polyhedron defined by an inequality system

$$Ax \leq b$$

is empty, if and only if there is a vector y such that

$$y \geq 0,\ y^T A = 0^T,\ y^T b < 0^T$$

Theorem of the alternative

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Important theorems of polyhedral theory (LP-view)

Which forms of representation do polyhedra have?

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Important theorems of polyhedral theory (LP-view)

Which forms of representation do polyhedra have?

Minkowski (1896), Weyl (1935), Steinitz (1916) Motzkin (1936)

Theorem: For a subset P of $\mathbb{R}^n$ the following are equivalent:

(1) P is a polyhedron.

(2) P is the intersection of finitely many halfspaces, i.e., there exist a matrix A und ein vector b with

$$P = \{x \in \mathbb{R}^n \mid Ax \leq b\}. \quad \text{(exterior representation)}$$

(3) P is the sum of a convex polytope and a finitely generated (polyhedral) cone, i.e., there exist finite sets V and E with

$$P = \text{conv(V)+cone(E)}. \quad \text{(interior representation)}$$

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Representations of polyhedra

Carathéodory's Theorem (1911), 1873 Berlin – 1950 München

Let $x \in P = \text{conv(V)+cone(E)}$, there exist

$$v_0, \ldots, v_s \in \text{V}, \; \lambda_0, \ldots, \lambda_s \in \mathbb{R}_+, \sum_{i=0}^{s} \lambda_i = 1$$

and $e_{s+1}, \ldots, e_t \in \text{E}, \; \mu_{s+1}, \ldots, \mu_t \in \mathbb{R}_+$ with $t \leq n$ such that

$$x = \sum_{i=1}^{s} \lambda_i v_i + \sum_{i=s+1}^{t} \mu_i e_i$$

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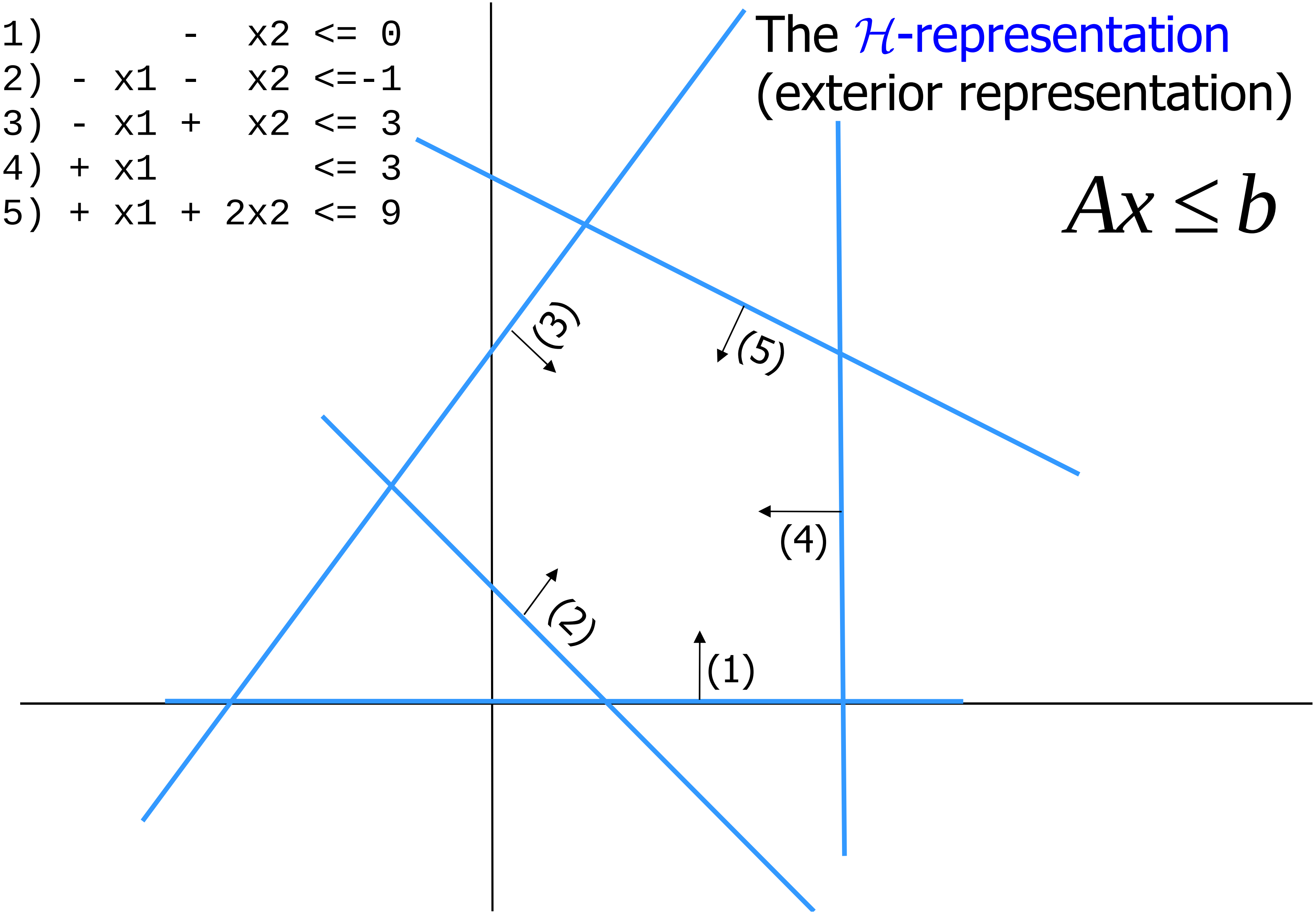
Representations of polyhedra

```
(1)         -   x2 <= 0
(2) - x1 -   x2 <=-1
(3) - x1 +   x2 <= 3
(4) + x1        <= 3
(5) + x1 + 2x2 <= 9
```

The $\mathcal{H}$-representation
(exterior representation)

$$Ax \le b$$



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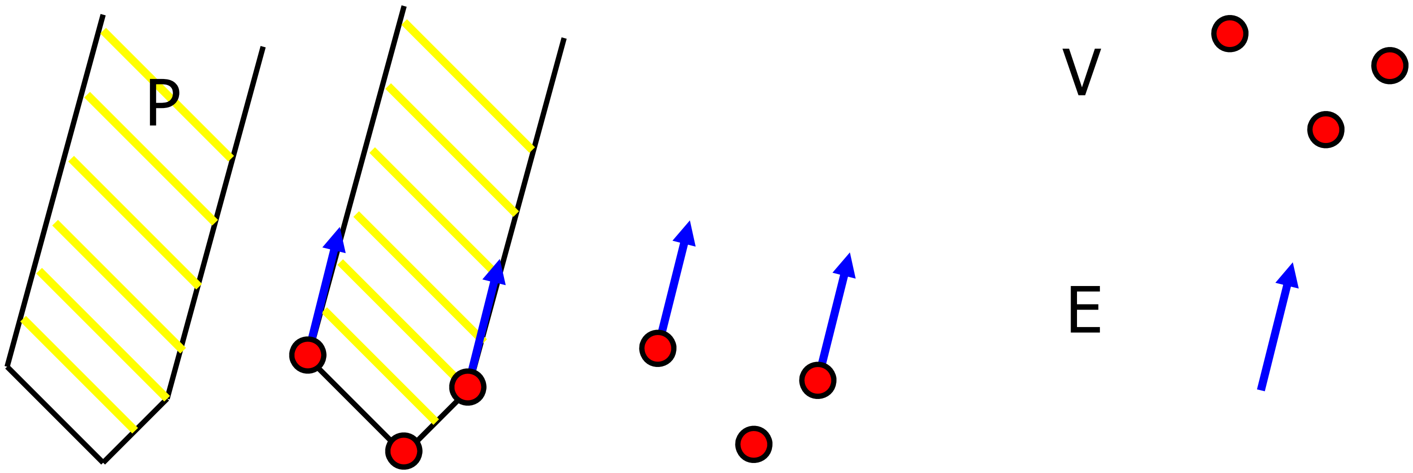
Representations of polyhedra

The $\mathcal{V}$-representation (interior representation)

$$P = \text{conv}(V) + \text{cone}(E).$$



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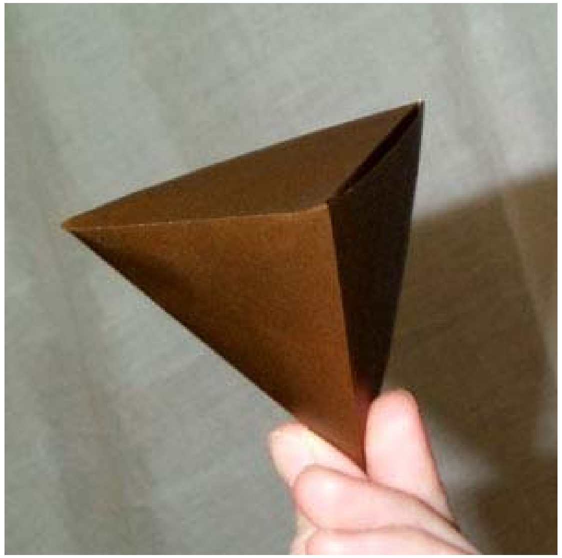
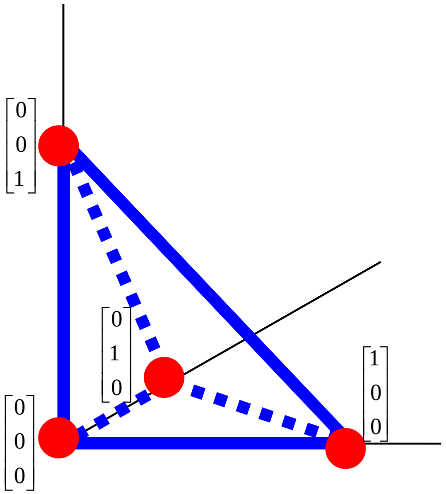
Example: the Tetrahedron



$$y \in conv\left\{ \begin{bmatrix}0\\0\\0\end{bmatrix}, \begin{bmatrix}1\\0\\0\end{bmatrix}, \begin{bmatrix}0\\1\\0\end{bmatrix}, \begin{bmatrix}0\\0\\1\end{bmatrix} \right\}$$



$$y_1 + y_2 + y_3 \leq 1$$
$$y_1 \geq 0$$
$$y_2 \geq 0$$
$$y_3 \geq 0$$

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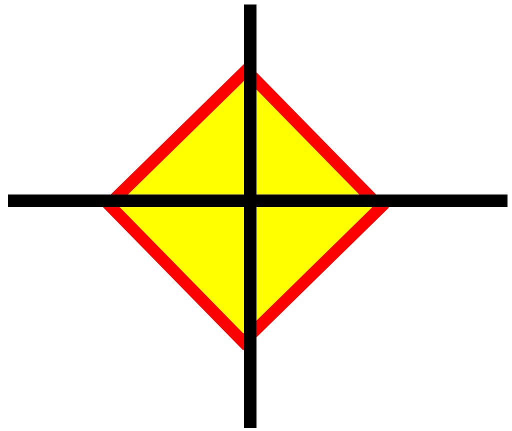
Example: the cross polytope

2n points

$$P = conv\{e_i, -e_i \mid i = 1, \ldots, n\} \subseteq \mathbb{R}^n$$



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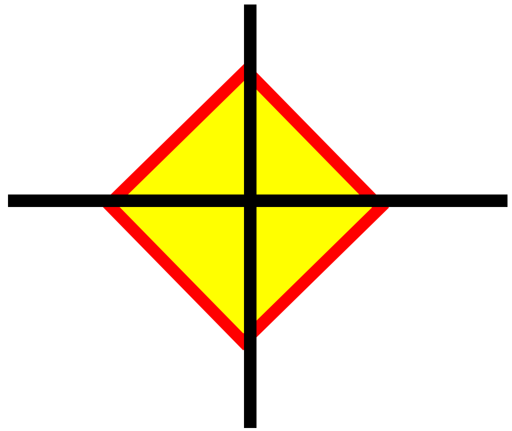
Example: the cross polytope

2n points

$$P = conv\{e_i, -e_i \mid i = 1, \ldots, n\} \subseteq \mathbb{R}^n$$



2^n inequalities

$$P = \left\{ x \in \mathbb{R}^n \mid a^T x \leq 1 \ \forall \ a \in \{-1,1\}^n \right\}$$

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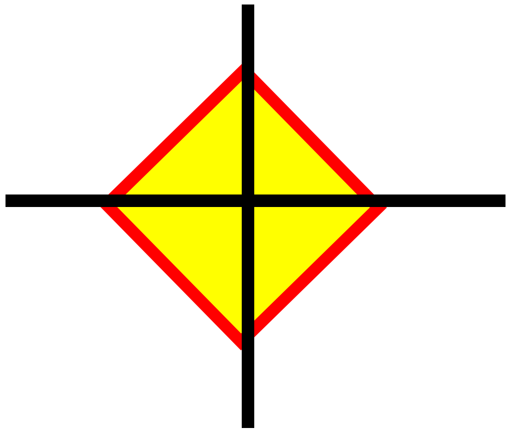
Example: the cross polytope

2n points

$$P = conv\{e_i, -e_i \mid i = 1, \ldots, n\} \subseteq \mathbb{R}^n$$

The "power" of |.|.

$$P = \left\{ x \in \mathbb{R}^n \mid \sum_{i=1}^{n} |x_i| \leq 1 \right\}$$



2^n inequalities

$$P = \left\{ x \in \mathbb{R}^n \mid a^T x \leq 1 \ \forall \ a \in \{-1, 1\}^n \right\}$$

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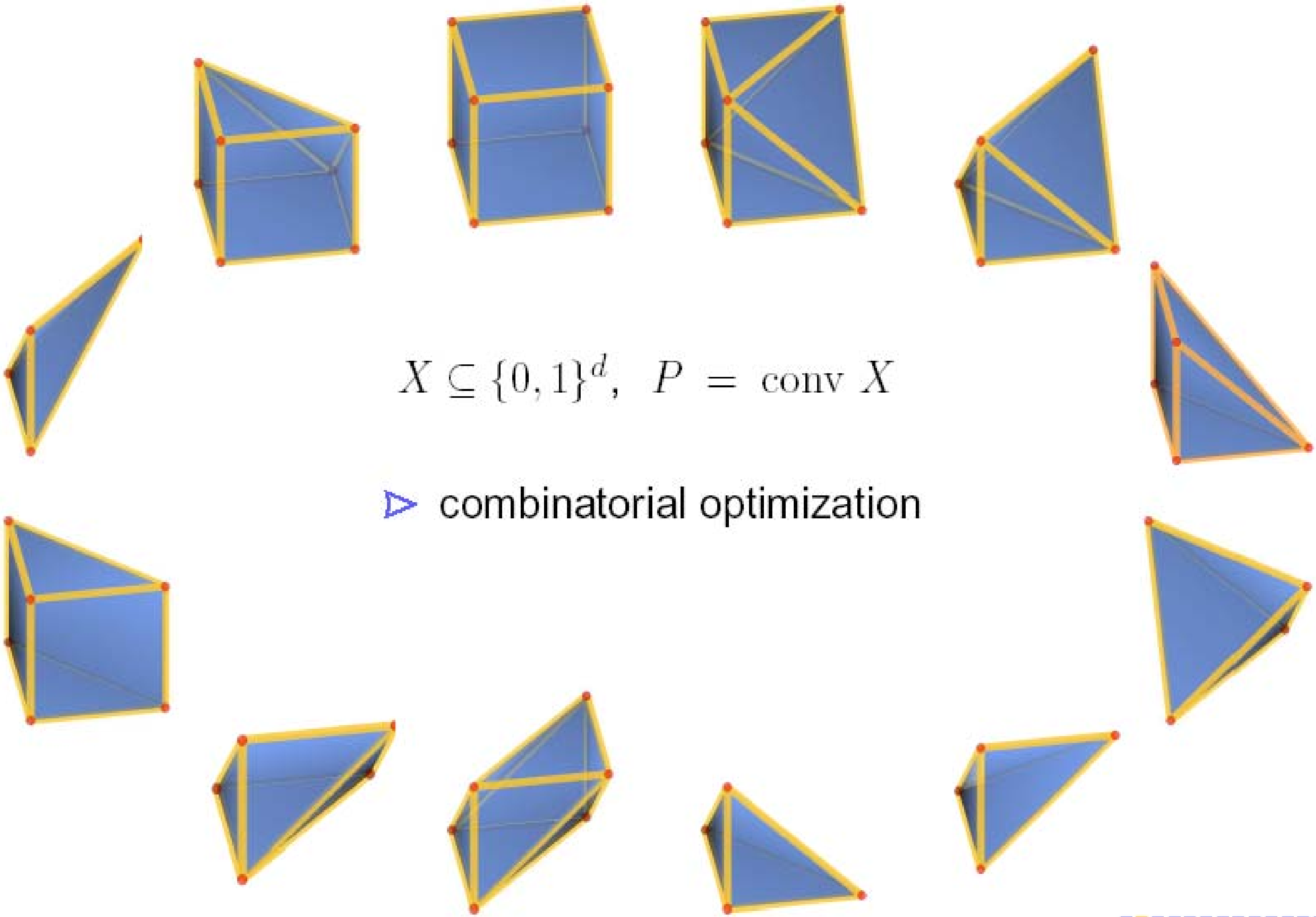
All 3-dimensional 0/1-polytopes



$$X \subseteq \{0,1\}^d, \quad P = \text{conv } X$$

▷ combinatorial optimization

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Contents

1. Linear programs
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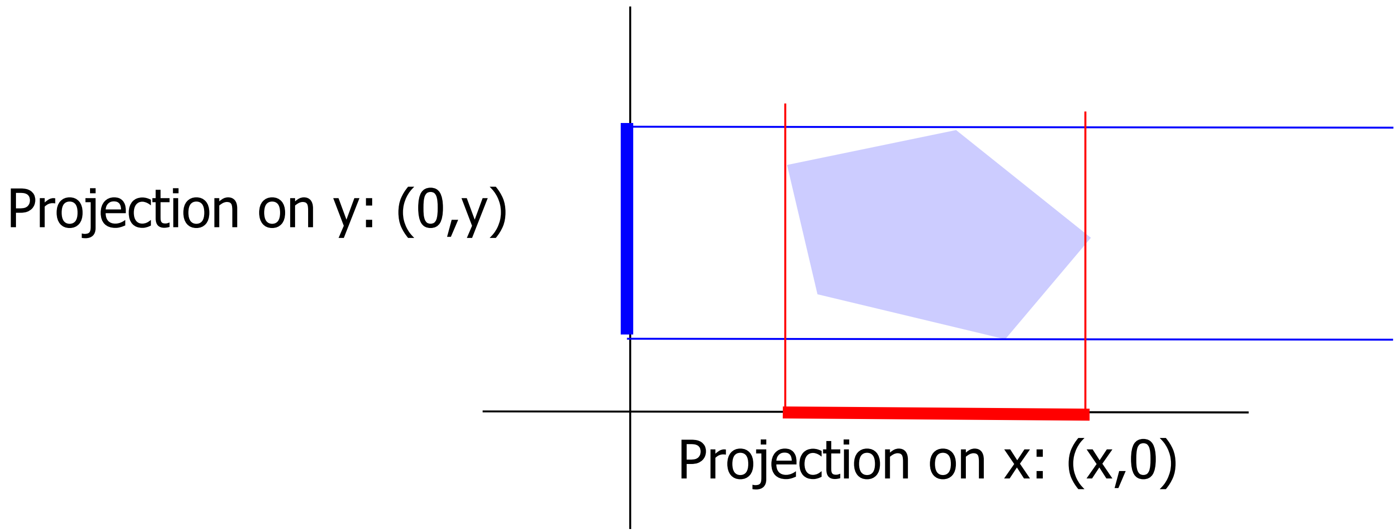
3. Algorithms for polyhedra
   - Fourier-Motzkin elimination
   - some Web resources
4. Semi-algebraic geometry
5. Faces of polyhedra
6. Flows, networks, min-max results

Polyedra in linear programming

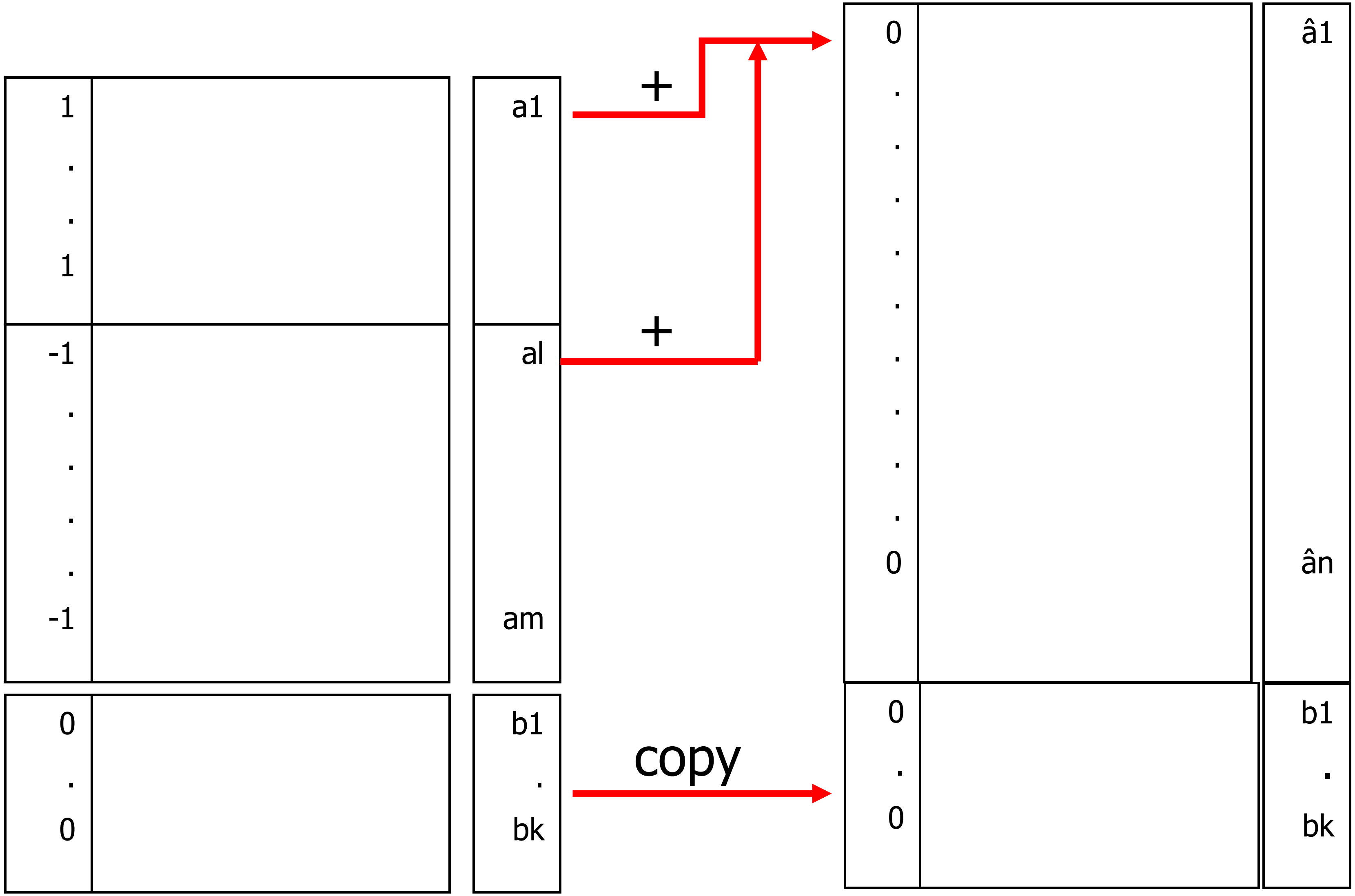
- The solution sets of linear programs are polyhedra.
- If a polyhedron $P = \mathrm{conv(V)+cone(E)}$ is given explicitly via finite sets V und E, linear programming is trivial.
- In linear programming, polyhedra are always given in $\mathcal{H}$-representation. Each solution method has its „standard form".

Fourier-Motzkin Elimination

- Fourier, 1847
- Motzkin, 1938
- **Method**: successive projection of a polyhedron in n-dimensional space into a vector space of dimension n-1 by elimination of one variable.



A Fourier-Motzkin step



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Fourier-Motzkin elimination proves the Farkas Lemma

When is a polyhedron nonempty?

The Farkas-Lemma (1908):

A polyhedron defined by an inequality system

$$Ax \leq b$$

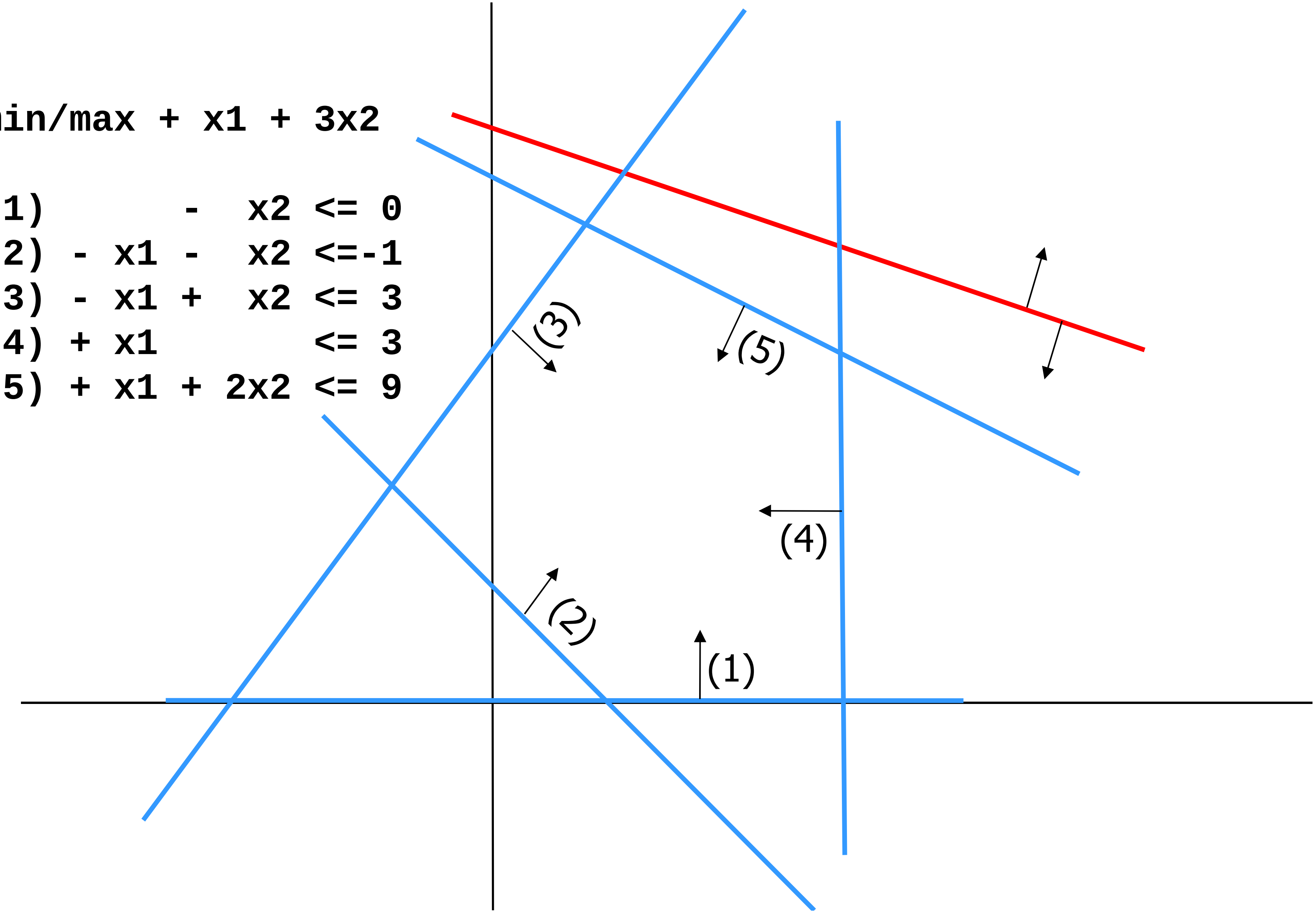
is empty, if and only if there is a vector y such that

$$y \geq 0,\ y^T A = 0^T,\ y^T b < 0^T$$

Fourier-Motzkin Elimination: an example


```
min/max + x1 + 3x2

(1)        -   x2 <= 0
(2) - x1 -   x2 <=-1
(3) - x1 +   x2 <= 3
(4) + x1          <= 3
(5) + x1 + 2x2 <= 9
```



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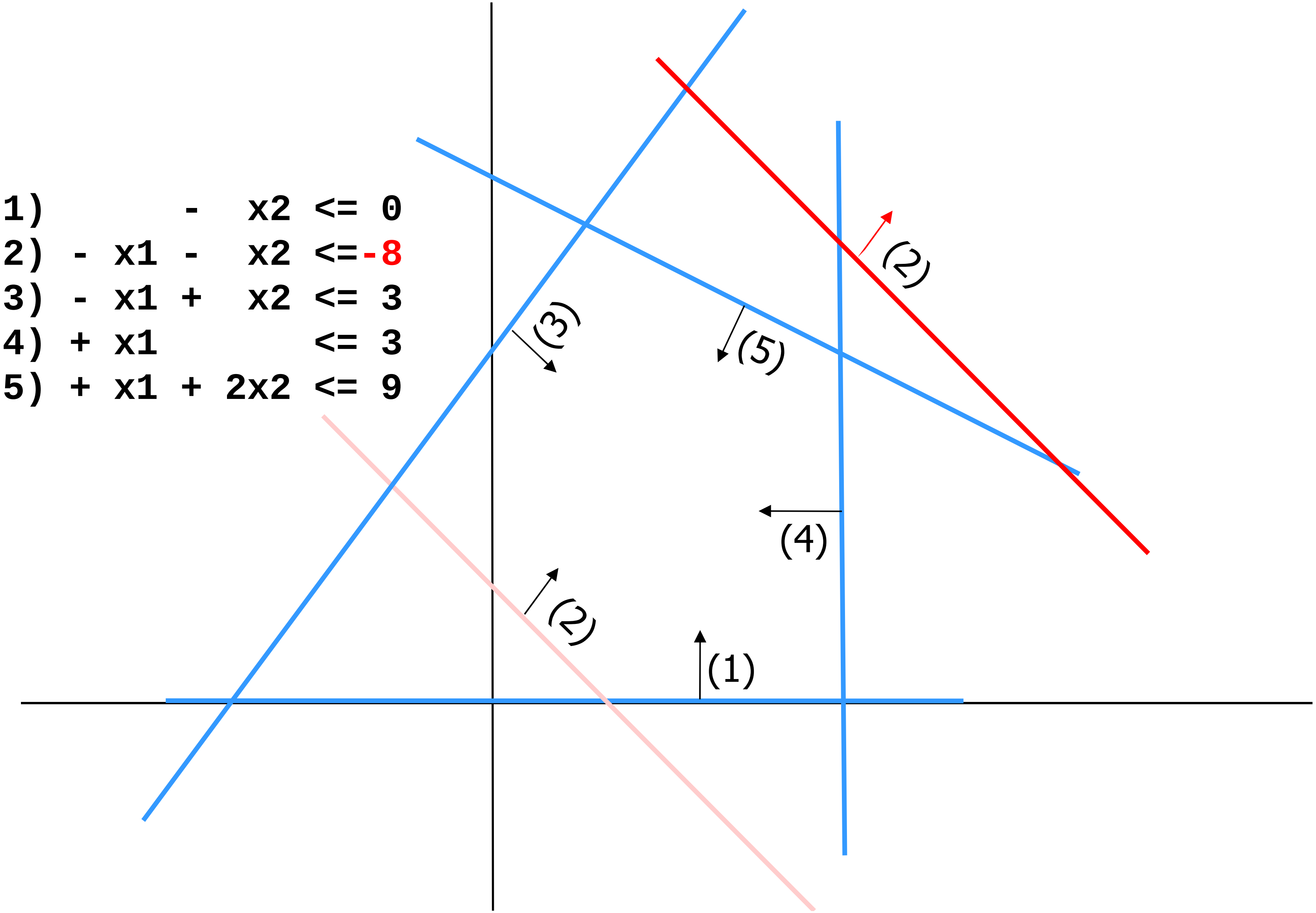
Fourier-Motzkin Elimination: an example


```
(1)        -   x2 <= 0
(2) - x1 -   x2 <=-8
(3) - x1 +   x2 <= 3
(4) + x1        <= 3
(5) + x1 + 2x2 <= 9
```



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Fourier-Motzkin Elimination: an example, call of PORTA


```
(1)       -   x2 <= 0
(2) - x1 -   x2 <=-8
(3) - x1 +   x2 <= 3
(4) + x1        <= 3
(5) + x1 + 2x2 <= 9
```

→

```
DIM = 3

INEQUALITIES_SECTION

(1)       -   x2       <= 0
(2) - x1 -   x2       <=-8
(3) - x1 +   x2       <= 3
(4) + x1              <= 3
(5) + x1 + 2x2       <= 9


ELIMINATION_ORDER
1 0
```

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Fourier-Motzkin Elimination: an example, call of PORTA


```
DIM = 3

INEQUALITIES_SECTION

(1)   (1) - x2      <=  0
(2,4) (2) - x2      <=  -5
(2,5) (3) + x2      <=  1
(3,4) (4) + x2      <=  6
(3,5) (5) + x2      <=  4
```

```
DIM = 3

INEQUALITIES_SECTION

(1)       -  x2      <= 0
(2) - x1 -   x2      <=-8
(3) - x1 +   x2      <= 3
(4) + x1             <= 3
(5) + x1 + 2x2       <= 9


ELIMINATION_ORDER
1 0
```

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Fourier-Motzkin Elimination: an example, call of PORTA


```
DIM = 3

INEQUALITIES_SECTION

(1)   (1) - x2      <=  0
(2,4) (2) - x2      <=  -5
(2,5) (3) + x2      <=  1
(3,4) (4) + x2      <=  6
(3,5) (5) + x2      <=  4

ELIMINATION_ORDER

0 1
```

→

```
DIM = 3

INEQUALITIES_SECTION

(2,3) 0 <= -4
```

Fourier-Motzkin elimination proves the Farkas Lemma

When is a polyhedron nonempty?

The Farkas-Lemma (1908):

A polyhedron defined by an inequality system

$$Ax \leq b$$

is empty, if and only if there is a vector y such that

$$y \geq 0,\ y^T A = 0^T,\ y^T b < 0^T$$

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Which LP solvers are used in practice?

- Fourier-Motzkin: hopeless
- Ellipsoid Method: total failure
- primal Simplex Method: good
- dual Simplex Method: better
- Barrier Method: for LPs frequently even better
- For LP relaxations of IPs: dual Simplex Method

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Fourier-Motzkin works reasonably well for polyhedral transformations:

Example: Let a polyhedron be given (as usual in combinatorial optimization implicitly) via:

$$P = \text{conv(V)+cone(E)}$$

Find a non-redundant representation of *P* in the form:

$$P = \{x \in \mathbb{R}^d \mid Ax \leq b\}$$

Solution: Write P as follows

$$P = \{x \in \mathbb{R}^d \mid Vy + Ez - x = 0, \sum_{i=1}^{d} y_i = 1, y \geq 0, z \geq 0\}$$

and eliminate y und z.

Relations between polyhedra representations

- Given V and E, then one can compute A und b as indicated above.
- Similarly (polarity): Given A und b, one can compute V und E.
- The Transformation of a $\mathcal{V}$-representation of a polyhedron P into a $\mathcal{H}$-representation and vice versa requires exponential space, and thus, also exponential running time.
- Examples: Hypercube and cross polytope.
- That is why it is OK to employ an exponential algorithm such as Fourier-Motzkin Elimination (or Double Description) for polyhedral transformations.
- Several codes for such transformations can be found in the Internet, e.g.. PORTA at ZIB and in Heidelberg.

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The Schläfli Graph S

Claw-free Graphs VI. Colouring Claw-free Graphs

Maria Chudnovsky
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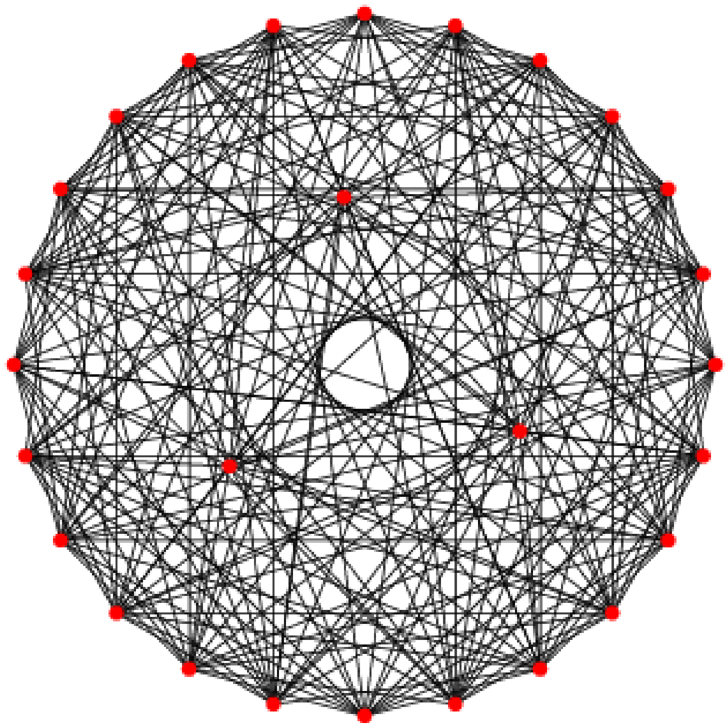
Abstract

In this paper we prove that if G is a connected claw-free graph with three pairwise non-adjacent vertices, with chromatic number χ and clique number ω, then $\chi \leq 2\omega$ and the same for the complement of G. We also prove that the choice number of G is at most 2ω, except possibly in the case when G can be obtained from a subgraph of the Schläfli graph by replicating vertices. Finally, we show that the constant 2 is best possible in all cases.

The Schläfli Graph S



Clique and stability number

Maximal cliques in S have size 6.
Maximal stable sets in S have size 3.
S has chromatic number 9 and there are two essentially different ways to color S with 9 colors. The complementary graph has chromatic number 6.

The Schläfli graph is a strongly regular graph on 27 nodes which is the graph complement of the generalized quadrangle $GQ(2, 4)$. It is the unique strongly regular graph with parameters $(27, 16, 10, 8)$ (Godsil and Royle 2001, p. 259).

http://mathworld.wolfram.com/SchlaefliGraph.html

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The Polytope of stable sets of the Schläfli Graph

input file Schlaefli.poi
dimension : 27
number of cone-points : 0
number of conv-points : 208

The incidence vectors of the stable sets of the Schläfli graph

sum of inequalities over all iterations : 527962
maximal number of inequalities : 14230

transformation to integer values
sorting system

number of equations : 0
number of inequalities : 4086

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The Polytope of stable sets of the Schläfli Graph

FOURIER - MOTZKIN - ELIMINATION:

iter-ation	upper bound # ineq	# ineq	max bit-length	long arithmetic	non-zeros in %	mem used in kB	time used in sec
180	29	29	1	n	0.04	522	1.00
179	30	29	1	n	0.04	522	1.00
10	8748283	13408	3	n	0.93	6376	349.00
9	13879262	12662	3	n	0.93	6376	368.00
8	12576986	11877	3	n	0.93	6376	385.00
7	11816187	11556	3	n	0.93	6376	404.00
6	11337192	10431	3	n	0.93	6376	417.00
5	9642291	9295	3	n	0.93	6376	429.00
4	10238785	5848	3	n	0.92	6376	441.00
3	3700762	4967	3	n	0.92	6376	445.00
2	2924601	4087	2	n	0.92	6376	448.00
1	8073	4086	2	n	0.92	6376	448.00

The Polytope of stable sets of the Schläfli Graph

INEQUALITIES_SECTION

(1) - x1 <= 0

(4086) +2x1+2x2+2x3+ x4+ x5+ x6 + x10+ x11+ x12+ x13+ x14+ x15
+x16+ x17+ x18+ x19+2x20 + x22+2x23 + x25+2x26 <= 3

8 different classes of inequalities found in total, among these, 5 classes have been unknown so far.

Web resources

Linear Programming: Frequently Asked Questions

http://www-unix.mcs.anl.gov/otc/Guide/faq/linear-programming-faq.html

- Q1. "What is Linear Programming?"
- Q2. "Where is there good software to solve LP problems?"
  - "Free" codes
  - Commercial codes and modeling systems
  - Free demos of commercial codes
- Q3. "Oh, and we also want to solve it as an integer program."
- Q4. "I wrote an optimization code. Where are some test models?"
- Q5. "What is MPS format?"

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Web resources

- A Short Course in Linear Programming

  by Harvey J. Greenberg

  http://carbon.cudenver.edu/~hgreenbe/courseware/LPshort/intro.html

- *OR/MS Today* : 2005 LINEAR PROGRAMMING SOFTWARE SURVEY (~60 commercial codes)

  http://www.lionhrtpub.com/orms/surveys/LP/LP-survey.html

- INFORMS OR/MS Resource Collection

  http://www.informs.org/Resources/

- NEOS Server for Optimization

  http://www-neos.mcs.anl.gov/

Data resources at ZIB, open access

- MIPLIB
- FAPLIB
- STEINLIB

ZIB offerings

- **PORTA** - POlyhedron Representation Transformation Algorithm
- **SoPlex** - The **S**equential **o**bject-oriented sim**plex** class library
- **Zimpl** - A mathematical modelling language
- **SCIP** - Solving constraint integer programs (IP & MIP)

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Semi-algebraic Geometry
Real-algebraic Geometry

$\mathfrak{f}_i(x), g_j(x), h_k(x)$ are polynomials in d real variables

$S_{\geq} := \{x \in \mathbb{R}^d : \mathfrak{f}_1(x) \geq 0, \ldots, \mathfrak{f}_{\mathfrak{l}}(x) \geq 0\}$ basic closed

$S_{>} := \{x \in \mathbb{R}^d : g_1(x) > 0, \ldots, g_{\mathfrak{m}}(x) > 0\}$ basic open

$S_{=} := \{x \in \mathbb{R}^d : h_1(x) = 0, \ldots, h_{\mathfrak{n}}(x) = 0\}$

$S := S_{\geq} \bigcup S_{>} \bigcup S_{=}$ is a semi-algebraic set

Theorem of Bröcker(1991) & Scheiderer(1989) basic closed case

Every basic closed semi-algebraic set of the form

$$S = \{x \in \mathbb{R}^d : \mathfrak{f}_1(x) \geq 0, \ldots, \mathfrak{f}_l(x) \geq 0\},$$

where $\mathfrak{f}_i \in \mathbb{R}[x_1, \ldots, x_d], 1 \leq i \leq l,$ are polynomials,

can be represented by at most $d(d+1)/2$

polynomials, i.e., there exist polynomials

such that

$$\mathfrak{p}_1, \ldots, \mathfrak{p}_{d(d+1)/2} \in \mathbb{R}[x_1, \ldots, x_d]$$

$$S = \{x \in \mathbb{R}^d : \mathfrak{p}_1(x) \geq 0, \ldots, \mathfrak{p}_{d(d+1)/2}(x) \geq 0\}.$$

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Theorem of Bröcker(1991) & Scheiderer(1989) basic open case

Every basic open semi-algebraic set of the form

$$S = \{x \in \mathbb{R}^d : \mathfrak{f}_1(x) > 0, \ldots, \mathfrak{f}_l(x) > 0\},$$

where $\mathfrak{f}_i \in \mathbb{R}[x_1, \ldots, x_d], 1 \le i \le l,$ are polynomials,

can be represented by at most d

polynomials, i.e., there exist polynomials

such that

$$\mathfrak{p}_1, \ldots, \mathfrak{p}_d \in \mathbb{R}[x_1, \ldots, x_d]$$

$$S = \{x \in \mathbb{R}^d : \mathfrak{p}_1(x) > 0, \ldots, \mathfrak{p}_d(x) > 0\}.$$

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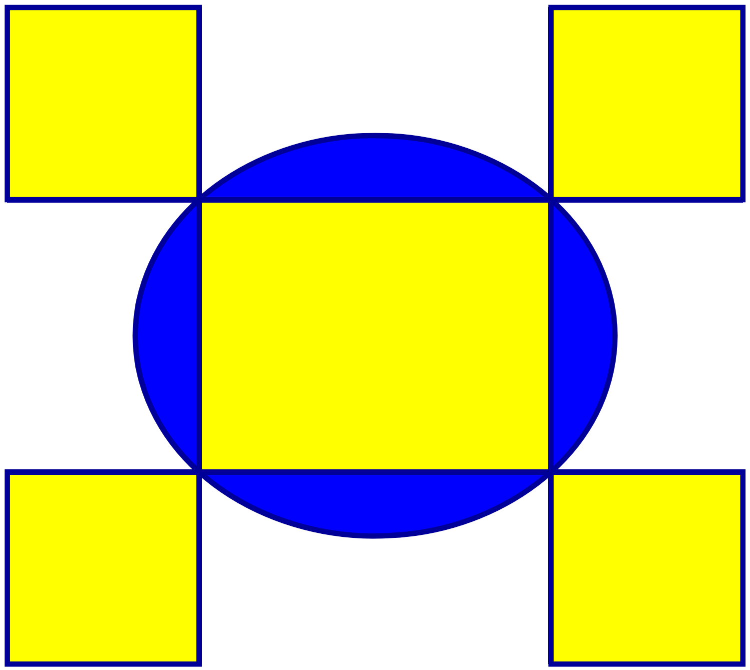
A first constructive result

Bernig [1998] proved that, for $d=2$, every convex polygon can be represented by two polynomial inequalities.

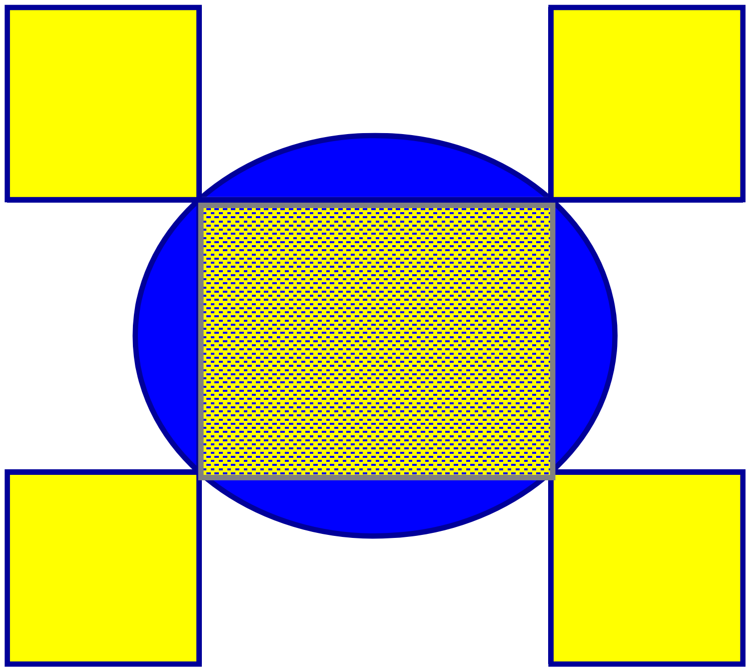


p(1)= product of all linear inequalities

p(2)= ellipse

A first Constructive Result

Bernig [1998] proved that, for d=2, every convex polygon can be represented by two polynomial inequalities.



p(1)= product of all linear inequalities

p(2)= ellipse

Our first theorem

Theorem Let $P \subset \mathbb{R}^n$ be a n-dimensional polytope given by an inequality representation. Then

k≤n^n polynomials $\mathfrak{p}_i \in \mathbb{R}[x_1, \ldots, x_n]$

can be constructed such that

$$P = \mathcal{P}(\mathfrak{p}_1, \ldots, \mathfrak{p}_k).$$

Martin Grötschel, Martin Henk:

The Representation of Polyhedra by Polynomial Inequalities

Discrete & Computational Geometry, 29:4 (2003) 485-504

Our main theorem

Theorem Let $P \subset \mathbb{R}^n$ be a n-dimensional polytope given by an inequality representation. Then

2n polynomials $\mathfrak{p}_i \in \mathbb{R}[x_1, \ldots, x_n]$

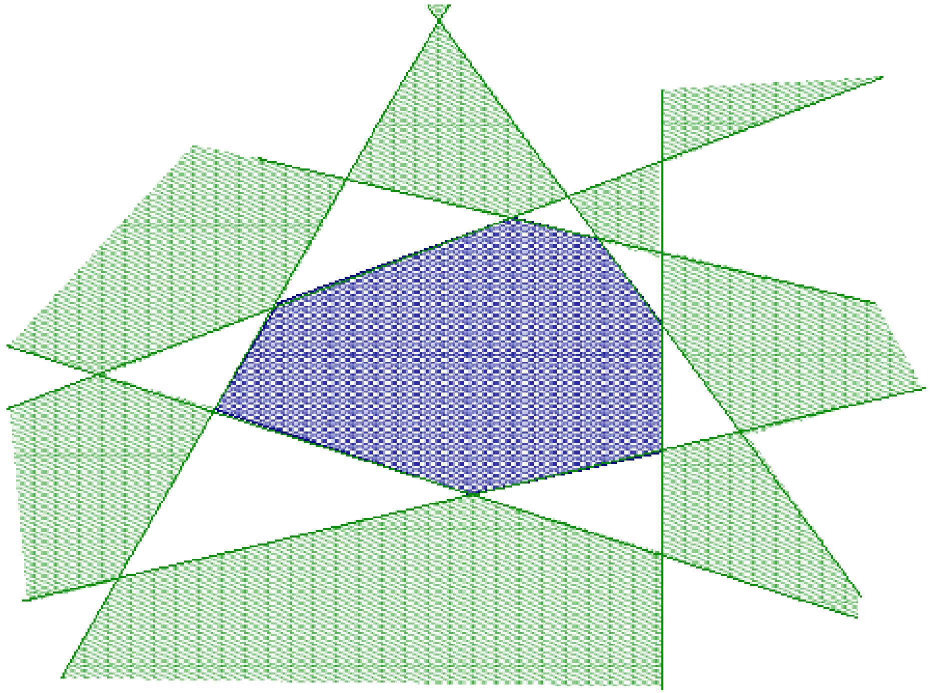
can be constructed such that

$$P = \mathcal{P}(\mathfrak{p}_1, \ldots, \mathfrak{p}_{2n}).$$

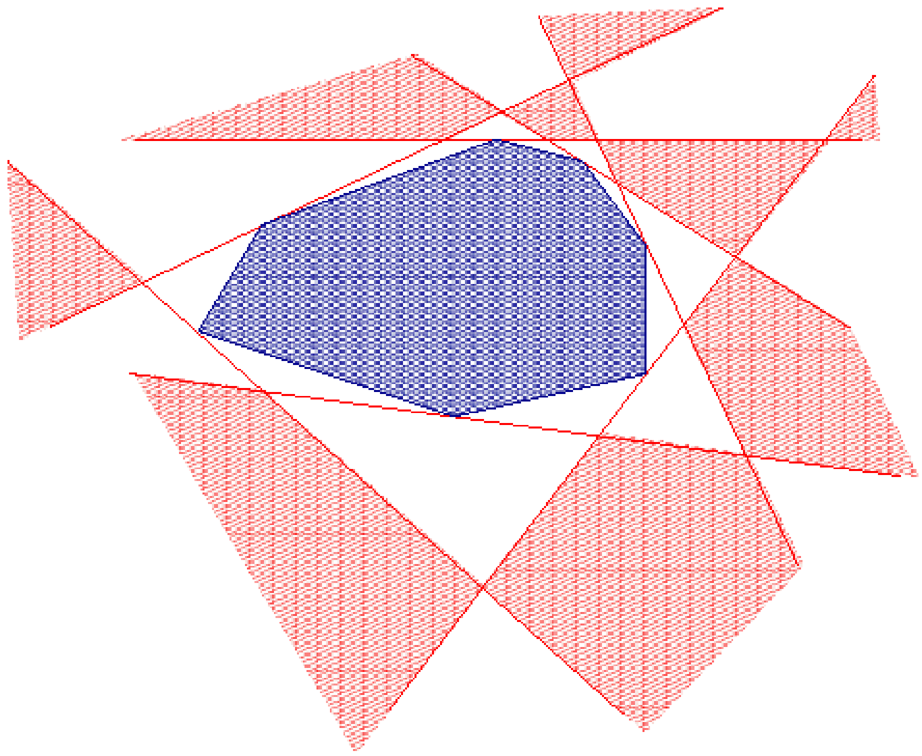
Hartwig Bosse, Martin Grötschel, Martin Henk:
Polynomial inequalities representing polyhedra
Mathematical Programming 103 (2005)35-44

http://www.springerlink.com/index/10.1007/s10107-004-0563-2

The construction in the 2-dimensional case

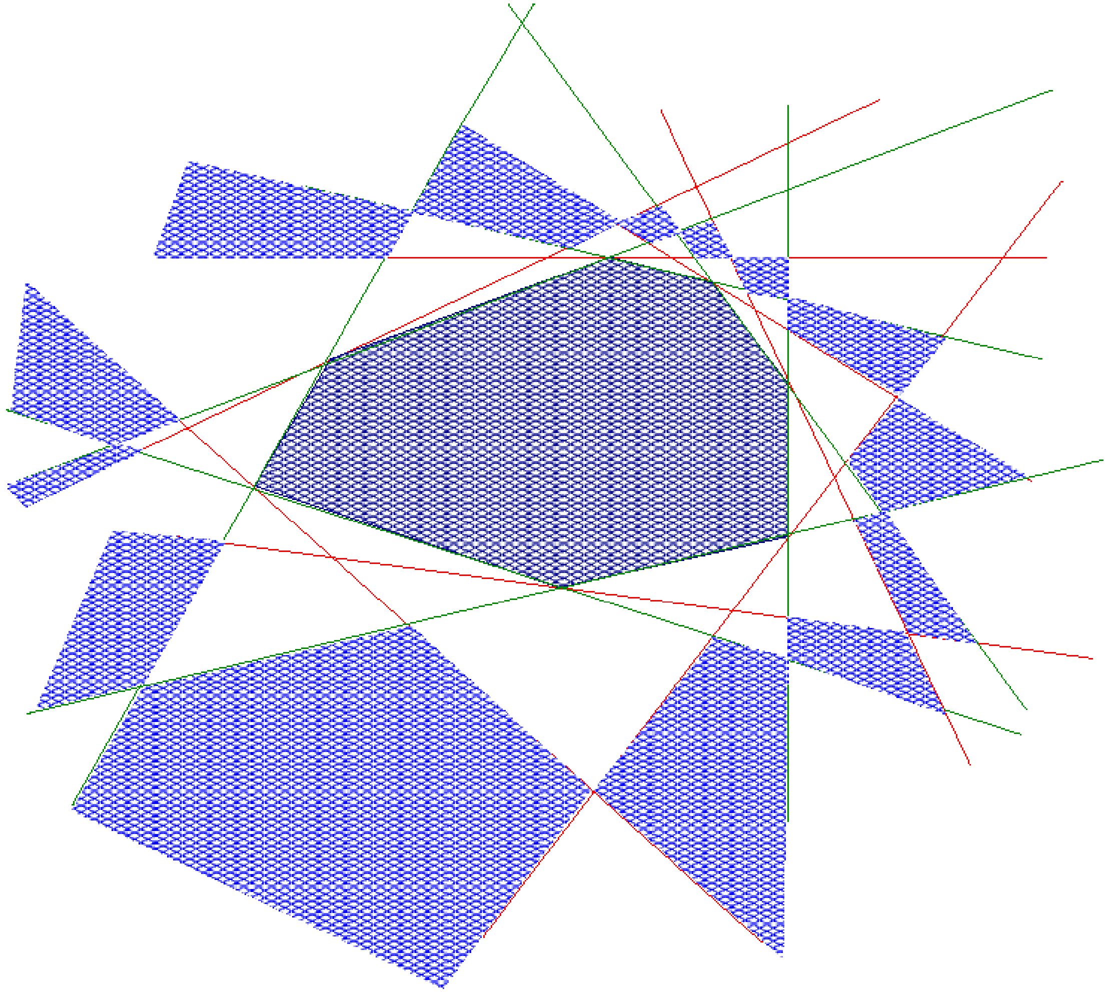


$$\{x \in \mathbb{R}^d : \mathfrak{p}_1(x) \geq 0\}$$



$$\{x \in \mathbb{R}^d : \mathfrak{p}_0(x) \geq 0\}$$

The construction in the 2-dimensional case



$$\{x \in \mathbb{R}^d : \mathfrak{p}_1(x) \geq 0 \text{ and } \mathfrak{p}_0(x) \geq 0\}$$

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Recent “Semi-algebraic Progress”

three-dimensional polyhedra can be described by three polynomial inequalities

jointly with Gennadiy Averkov

Discrete Comput. Geom.,**42**(2), 2009, 166-186; arXiv:0807.2137

representing simple d-dimensional polytopes by d polynomials

jointly with Gennadiy Averkov

to appear in Math. Prog. (A); arXiv:0709.2099v1

http://fma2.math.unimagdeburg.de/~henk/preprints/henk&polynomdarstellungen%20von%20polyedern.pdf

Bröcker

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Faces etc.

- Important concept: dimension

- face
- vertex
- edge
- (neighbourly polytopes)
- ridge = subfacet
- facet

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Linear Programming: The DualityTheorem

The most important and influential theorem in optimization.

$$\min\{wx \mid Ax \geq b\} = \max\{yb \mid y \geq 0, yA = w\}$$

A good research idea is to try to mimic this result:

$$\min\{\mathit{something}\} = \max\{\mathit{something}\}$$

A relation of this type is called min-max result.

Max-flow min-cut theorem

(Ford & Fulkerson, 1956)

CO@W

Let $D=(V,A)$ be a directed graph, let $r,s\in V$ and let $c:A\to\mathbb{R}_+$ be a capacity function. Then the maximum value of an r-s -flow subject to the capacity c is equal to the minimum capacity of an r-s -cut.

If all capacities are integer, there exists an integer optimum flow.

Here an r-s-flow is a vector $x:A\to\mathbb{R}$ such that

(1) (i) $x(a)\geq 0 \quad \forall a\in A$

(ii) $x(\delta^-(v))=x(\delta^+(v)) \quad \forall v\in V,\ r\neq v\neq s$

The value of the flow is the net amount of flow leaving r, i.e., is

(2) $x(\delta^+(r))-x(\partial^-(r))$

(which is equal to the net amount of flow entering s). The flow x is *subject to* c if $x(a)\leq c(a)$ for all a in A.

Ford-Fulkerson animation

- http://www.cse.yorku.ca/~aaw/Wang/MaxFlowStart.htm

Flow Algorithms

- The Ford-Fulkerson Algorithm
  The grandfather of augmenting paths algorithms
- The Dinic-Malhorta-Kumar-Maheshwari Algorithm
- Preflow (Push-Relabel) Algorithms

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Complexity survey

from Schrijver, *Combinatorial Optimization - Polyhedra and Efficiency*, 2003 Springer

10.8b. Complexity survey for the maximum flow problem

Complexity survey ($*$ indicates an asymptotically best bound in the table):

$O(n^2mC)$	Dantzig [1951a] simplex method
$O(nmC)$	Ford and Fulkerson [1955,1957b] augmenting path
$O(nm^2)$	Dinits [1970], Edmonds and Karp [1972] shortest augmenting path
$O(n^2m\log nC)$	Edmonds and Karp [1972] fattest augmenting path
$O(n^2m)$	Dinits [1970] shortest augmenting path, layered network
$O(m^2\log C)$	Edmonds and Karp [1970,1972] capacity-scaling
$O(nm\log C)$	Dinits [1973a], Gabow [1983b,1985b] capacity-scaling
$O(n^3)$	Karzanov [1974] (preflow push); cf. Malhotra, Kumar, and Maheshwari [1978], Tarjan [1984]
$O(n^2\sqrt{m})$	Cherkasskiĭ [1977a] blocking preflow with long pushes
$O(nm\log^2 n)$	Shiloach [1978], Galil and Naamad [1979,1980]
$O(n^{5/3}m^{2/3})$	Galil [1978,1980a]

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Complexity survey

from Schrijver, *Combinatorial Optimization - Polyhedra and Efficiency*, 2003 Springer

continued

	$O(nm \log n)$	Sleator [1980], Sleator and Tarjan [1981,1983a] dynamic trees
*	$O(nm \log(n^2/m))$	Goldberg and Tarjan [1986,1988a] push-relabel+dynamic trees
	$O(nm + n^2 \log C)$	Ahuja and Orlin [1989] push-relabel + excess scaling
	$O(nm + n^2\sqrt{\log C})$	Ahuja, Orlin, and Tarjan [1989] Ahuja-Orlin improved
*	$O(nm \log((n/m)\sqrt{\log C} + 2))$	Ahuja, Orlin, and Tarjan [1989] Ahuja-Orlin improved + dynamic trees
*	$O(n^3/\log n)$	Cheriyan, Hagerup, and Mehlhorn [1990,1996]
	$O(n(m + n^{5/3} \log n))$	Alon [1990] (derandomization of Cheriyan and Hagerup [1989,1995])
	$O(nm + n^{2+\varepsilon})$	(for each $\varepsilon > 0$) King, Rao, and Tarjan [1992]
*	$O(nm \log_{m/n} n + n^2 \log^{2+\varepsilon} n)$	(for each $\varepsilon > 0$) Phillips and Westbrook [1993,1998]
*	$O(nm \log_{\frac{m}{n \log n}} n)$	King, Rao, and Tarjan [1994]
*	$O(m^{3/2} \log(n^2/m) \log C)$	Goldberg and Rao [1997a,1998]
*	$O(n^{2/3} m \log(n^2/m) \log C)$	Goldberg and Rao [1997a,1998]

Here $C := \|c\|_\infty$ for integer capacity function c. For a complexity survey for unit capacities, see Section 9.6a.

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Complexity survey

from Schrijver, *Combinatorial Optimization - Polyhedra and Efficiency*, 2003 Springer

Research problem: Is there an $O(nm)$-time maximum flow algorithm?
For the special case of *planar* undirected graphs:

	$O(n^2 \log n)$	Itai and Shiloach [1979]
	$O(n \log^2 n)$	Reif [1983] (minimum cut), Hassin and Johnson [1985] (maximum flow)
	$O(n \log n \log^* n)$	Frederickson [1983b]
*	$O(n \log n)$	Frederickson [1987b]

For *directed* planar graphs:

	$O(n^{3/2} \log n)$	Johnson and Venkatesan [1982]
	$O(n^{4/3} \log^2 n \log C)$	Klein, Rao, Rauch, and Subramanian [1994], Henzinger, Klein, Rao, and Subramanian [1997]
*	$O(n \log n)$	Weihe [1994b,1997b]

Min-cost flow

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Let $D = (V, A)$ be a directed graph, let $r, s \in V$, let $c: A \to \mathbb{R}_+$ be a capacity function, $w: A \to \mathbb{R}$ a cost function, and f a flow value. Find a flow x of value f subject to c with minimum value $w^T x$.

$$\min \sum_{a \in A} w(a)x(a)$$

$$0 \leq x(a) \leq c(a) \quad \forall a \in A$$

$$x\left(\delta^+(v)\right) - x\left(\partial^-(v)\right) = 0 \quad \forall r \neq v \neq s$$

$$x\left(\delta^+(r)\right) - x\left(\partial^-(r)\right) = f$$

There is a similarly large number of algorithms with varying complexity, see Schrijver (2003).

Min-Max Results

CO@W

König´s Matching Theorem (1931) (Frobenius, 1912)

The maximum size of a matching in a bipartite graph is equal to the minimum number of vertices covering all edges, i. e.,

$$\nu(G) = \tau(G)$$

for bipartite graphs G.

Tutte-Berge Formula (Tutte(1947), Berge(1958))

$$\max\{|M| : M \subseteq E \; matching\} = \min_{W \subseteq V} \frac{1}{2}(|V| + |W| - O(G-W))$$

where G=(V,E) is an arbitrary graph.

Total unimodularity

A matrix A is called *totally unimodular* if each square submatrix of A has determinant 0, +1 or –1. In particular, each entry of A is 0, +1 or –1.

The interest of totally unimodular matrices for optimization was discovered by the following theorem of Hoffman and Kruskal (1956):

If A is totally unimodular and b and w are integer vectors, then both sides of the LP-duality equation

$$\max\{wx \mid Ax \leq b\} = \min\{yb \mid y \geq 0, yA = w\}$$

have integer optimum solutions.

Total unimodularity

CO@W

There have been many characterizations of totally unimodular matrices:

Ghouila-Houri (1962)

Camion (1965)

Padberg (1976)

Truemper(1977)

....

Full understanding was achieved by establishing a link to regular matroids, Seymour (1980). This connection also yields a polynomial time algorithm to recognize totally unimodular matrices.

Min-Max Results

CO@W

Dilworth's theorem (1950)

The maximum size of an antichain in a partially ordered set (P, <) is equal to the minimum number of chains needed to cover P.

Fulkerson's optimum branching theorem (1974)

Let $D=(V,A)$ be a directed graph, let $r \in V$ and let $l: A \to R_+$ be a length function. Then the minimum length of an r-arborescence is equal to the maximum number t of r-cuts $C_1, \ldots, C_t$ (repetition allowed) such that no arc a is in more than $l(a)$ of the C_i.

Edmonds' disjoint branching theorem (1973)

Let $D=(V,A)$ be a directed graph, and let $r \in V$. Then the maximum number of pairwise disjoint r-arborescences is equal to the minimum size of an r-cut.

Min-Max Results

CO@W

Edmonds' matroid intersection theorem (1970)

Let $M_1 = (S, \mathcal{J}_1)$ and $M_2 = (S, \mathcal{J}_2)$ be matroids, with rank functions r_1 and r_2, respectively. Then the maximum size of a set in $\mathcal{J}_1 \cap \mathcal{J}_2$ is equal to

$$\min_{S' \subseteq S} \left(r_1(S') + r_2(S \setminus S') \right).$$

Min-Max Results and Polyhedra

- Min-max results almost always provide polyhedral insight and can be employed to prove integrality of polyhedra.
- For instance, the matroid intersection theorem can be used to prove a theorem on the integrality of the intersection of two matroid polytopes.

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Min-Max Results and Polyhedra

Let M=(E, $\mathcal{I}$) be a matroid with rank function *r*.

Define IND($\mathcal{I}$):=conv{x^I | I is an Element of $\mathcal{I}$}.

IND($\mathcal{I}$) is called matroid polytope. Let

$$P(\mathcal{I}) := \left\{ x \in \mathbb{R}^E : \sum_{e \in F} x_e \le r(F) \ \forall \ F \subseteq E, \ x_e \ge 0 \ \forall \ e \in E \ \right\}$$

Theorem: P($\mathcal{I}$) = IND($\mathcal{I}$).

Theorem: Let M_1=(E, $\mathcal{I}_1$) and M_2=(E, $\mathcal{I}_2$) be two matroids

with rank functions r_1 and r_2, respectively. Then

IND($\mathcal{I}_1 \cap \mathcal{I}_2$) = P($\mathcal{I}_1$)$\cap$P($\mathcal{I}_2$)

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Min-Max Results and Polyhedra

In other words, if $M_1=(E, \mathcal{I}_1)$ and $M_2=(E, \mathcal{I}_2)$ are two matroids on the same ground set E with rank functions r_1 and r_2, respectively, and if c_e is a weight for all elements e of E, then a set that is independent in M_1 and M_2 and has the largest possible weight can be found via the following linear program

$$\max \sum_{e \in E} c_e x_e$$

$$\sum_{e \in F} x_e \leq r_1(F) \quad \forall\ F \subseteq E$$

$$\sum_{e \in F} x_e \leq r_2(F) \quad \forall\ F \subseteq E$$

$$x_e \geq 0 \quad \forall\ e \in E$$

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Basics of polyhedral theory, flows and networks

The End

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