Embedding Formulations and Complexity for Unions of Polyhedra

Juan Pablo Vielma

Massachusetts Institute of Technology

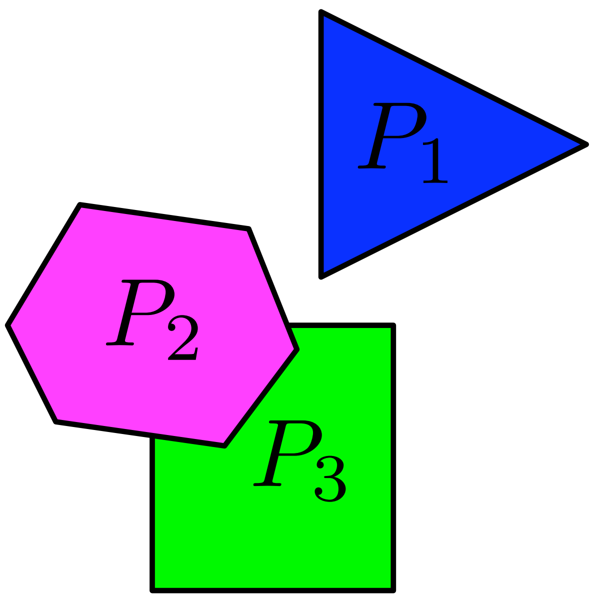
IEOR-DRO Seminar,
Columbia University
New York, NY. September, 2015.

Supported by NSF grant CMMI-1351619

(Linear) Mixed 0-1 Integer Formulations

- Modeling Finite Alternatives = Unions of Polyhedra

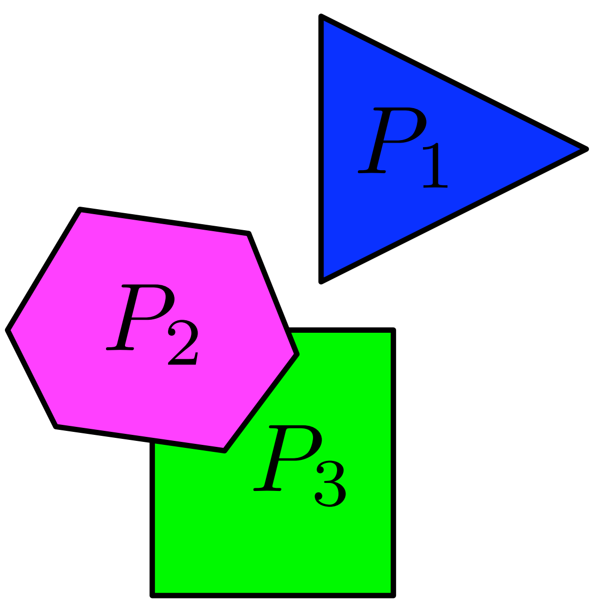
$$x \in \bigcup_{i=1}^{n} P_i \subseteq \mathbb{R}^d$$

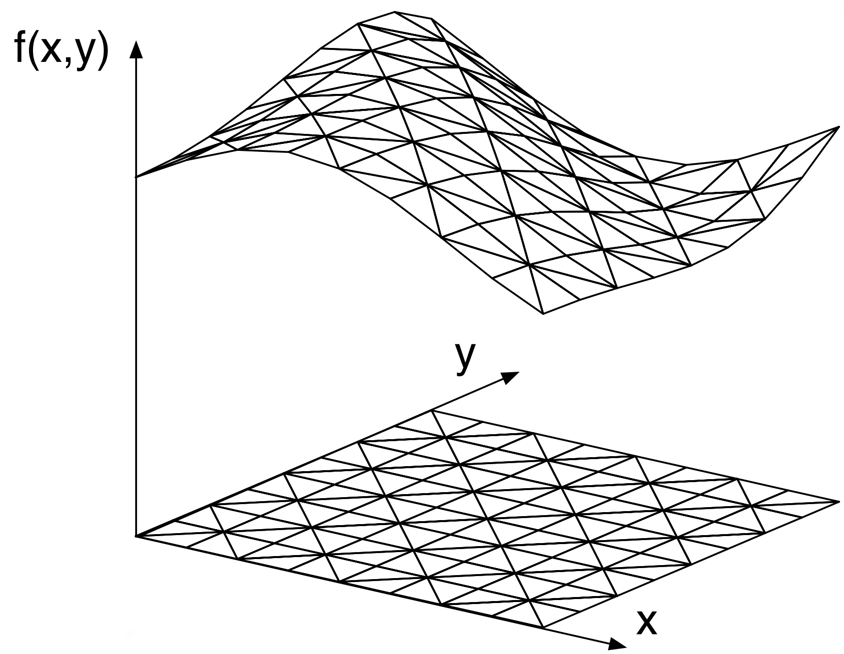


(Linear) Mixed <u>0-1</u> Integer Formulations

- Modeling Finite Alternatives = Unions of Polyhedra

$$x \in \bigcup_{i=1}^{n} P_i \subseteq \mathbb{R}^d$$



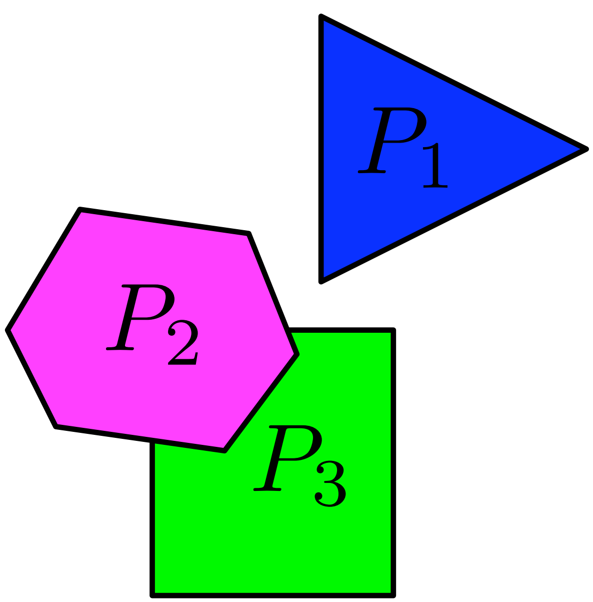


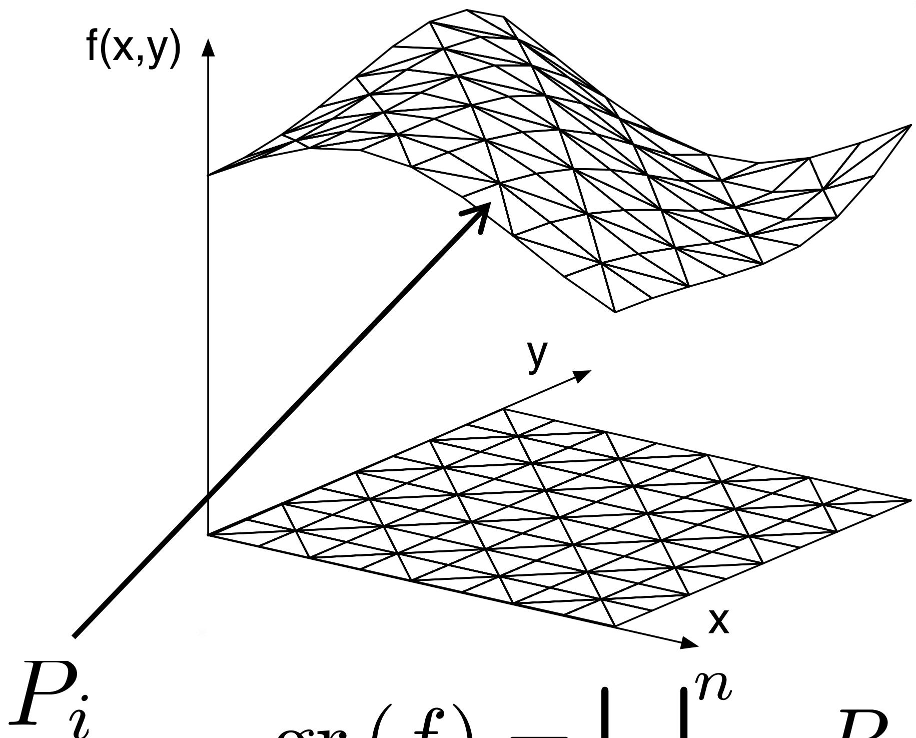
$$\mathrm{gr}(f) = \bigcup_{i=1}^{n} P_i$$

(Linear) Mixed 0-1 Integer Formulations

- Modeling Finite Alternatives = Unions of Polyhedra

$$x \in \bigcup_{i=1}^{n} P_i \subseteq \mathbb{R}^d$$





$$\operatorname{gr}(f) = \bigcup_{i=1}^{n} P_i$$

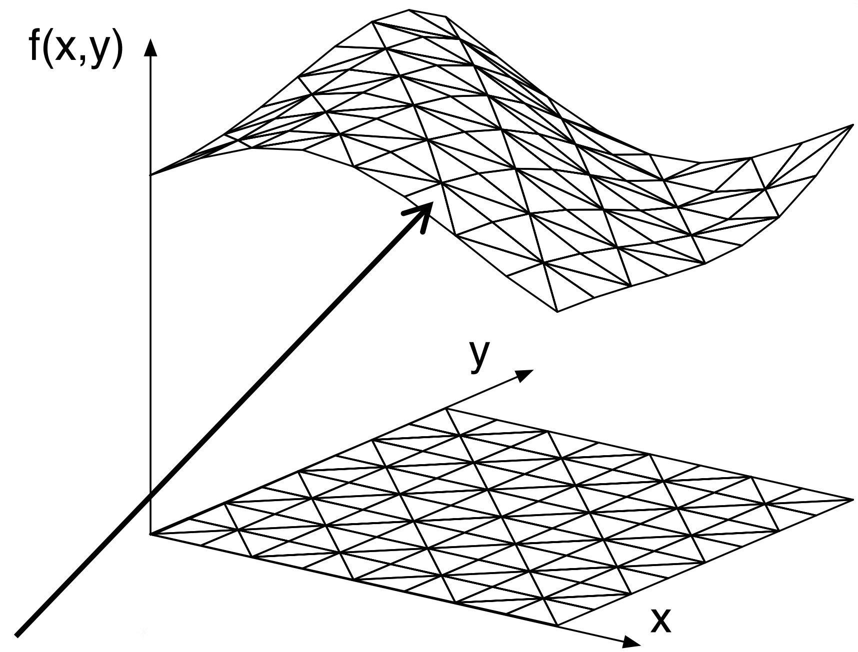
(Linear) Mixed 0-1 Integer Formulations

- Modeling Finite Alternatives = Unions of Polyhedra

$$\min \quad \sum_{j=1}^{m} f_j(x_j, y_j)$$

$$s.t.$$

$$(x, y) \in X$$



$$P_i$$

$$\text{gr}\,(f) = \bigcup_{i=1}^{n} P_i$$

Size of Smallest 0-1 Formulation for $x \in \bigcup_{i=1}^{n} P_i$

- Standard **ideal (integral)** **extended** formulation for $P_i = \left\{ x \in \mathbb{R}^d \,:\, A^i x \leq b^i \right\}$ (Balas, Jeroslow and Lowe):

$$
\begin{aligned}
A^i x^i &\leq b^i y_i & & \forall i \in \{1, \ldots, n\} \\
\sum_{i=1}^{n} x^i &= x, & x^i \in \mathbb{R}^d & \quad \forall i \in \{1, \ldots, n\} \\
\sum_{i=1}^{n} y_i &= 1, & y \in \{0,1\}^n &
\end{aligned}
$$

Size of Smallest 0-1 Formulation for $x \in \bigcup_{i=1}^{n} P_i$

- Standard **ideal (integral)** **extended** formulation for $P_i = \{x \in \mathbb{R}^d \; : \; A^i x \leq b^i\}$ (Balas, Jeroslow and Lowe):

$$A^i x^i \leq b^i y_i \qquad \forall i \in \{1, \ldots, n\}$$
$$\sum_{i=1}^{n} x^i = x, \qquad x^i \in \mathbb{R}^d \qquad \forall i \in \{1, \ldots, n\}$$
$$\sum_{i=1}^{n} y_i = 1, \qquad y \in \{0,1\}^n$$

•What about non-extended (i.e. no variables copies) ?

Size of Smallest 0-1 Formulation for $x \in \bigcup_{i=1}^{n} P_i$

- Standard **ideal (integral)** **extended** formulation for $P_i = \{x \in \mathbb{R}^d \,:\, A^i x \leq b^i\}$ (Balas, Jeroslow and Lowe):

$$
\begin{aligned}
A^i x^i &\leq b^i y_i & & \forall i \in \{1, \ldots, n\} \\
\sum_{i=1}^{n} x^i &= x, & x^i \in \mathbb{R}^d & \quad \forall i \in \{1, \ldots, n\} \\
\sum_{i=1}^{n} y_i &= 1, & y \in \{0,1\}^n &
\end{aligned}
$$

•What about non-extended (i.e. no variables copies) ?
•What about non-ideal? (i.e. **some** fractional extreme pts.)?

Size of Smallest 0-1 Formulation for $x \in \bigcup_{i=1}^{n} P_i$

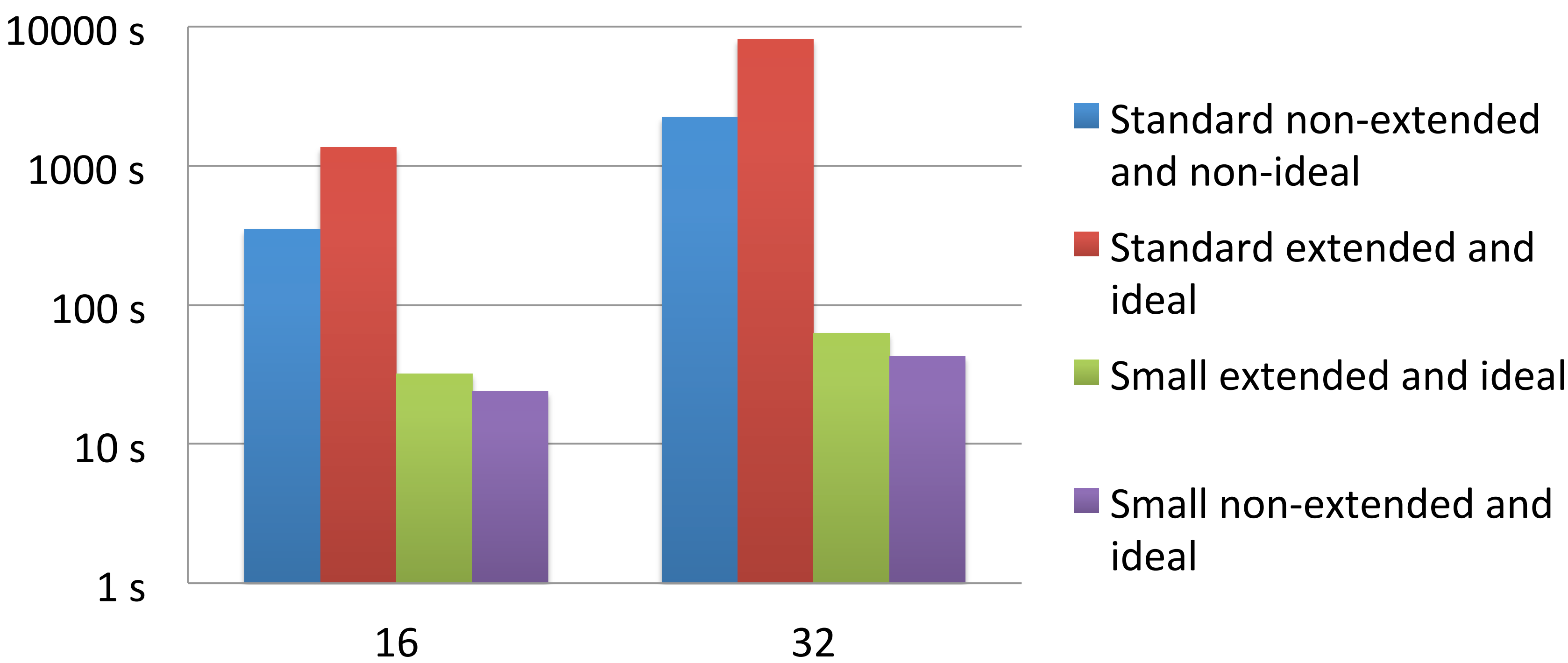
- Standard **ideal (integral)** **extended** formulation for $P_i = \left\{ x \in \mathbb{R}^d \ : \ A^i x \leq b^i \right\}$ (Balas, Jeroslow and Lowe):

$$
\begin{aligned}
A^i x^i &\leq b^i y_i & & \forall i \in \{1, \ldots, n\} \\
\sum_{i=1}^{n} x^i &= x, & x^i \in \mathbb{R}^d \quad & \forall i \in \{1, \ldots, n\} \\
\sum_{i=1}^{n} y_i &= 1, & y \in \{0,1\}^n &
\end{aligned}
$$

•What about non-extended (i.e. no variables copies) ?
•What about non-ideal? (i.e. **some** fractional extreme pts.)?
•What about **precise** lower/upper bounds on size?

Performance for Univariate Functions

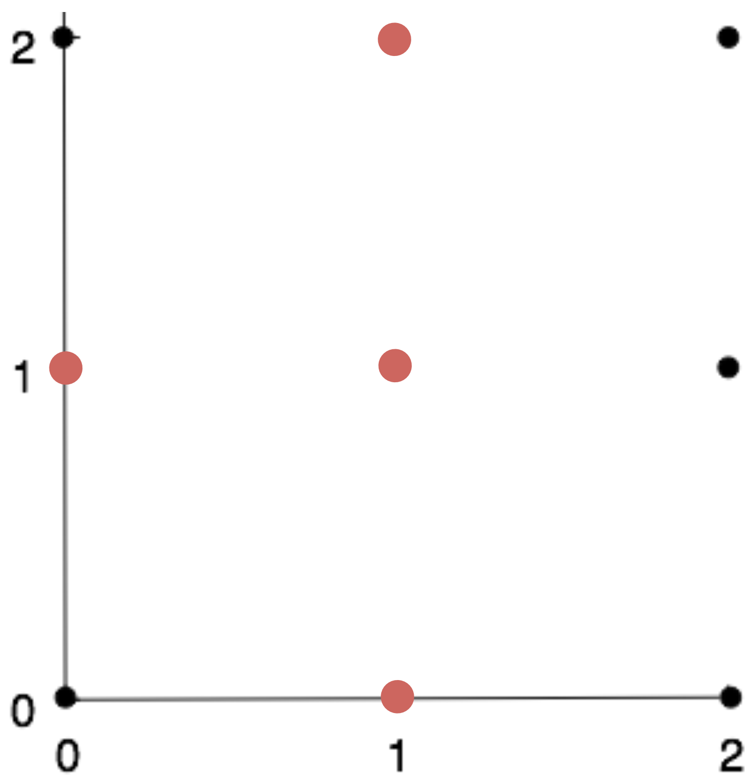
- Results from Nemhauser, Ahmed and V. '10 using CPLEX 11



- Non-extended and ideal formulations provide a significant computational advantage

Constructing Non-extended Ideal Formulations

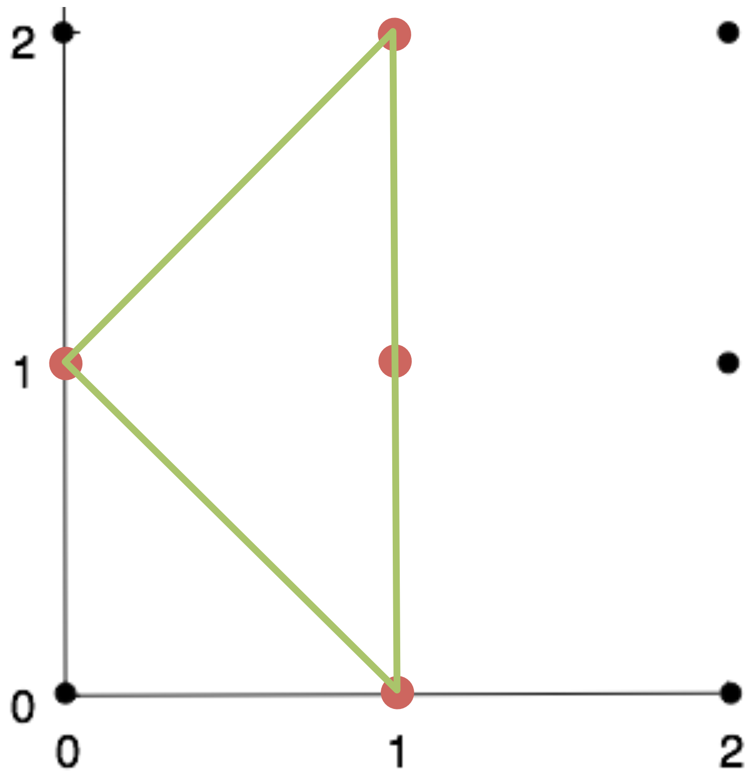
- Pure Integer :



Constructing Non-extended Ideal Formulations

- Pure Integer :

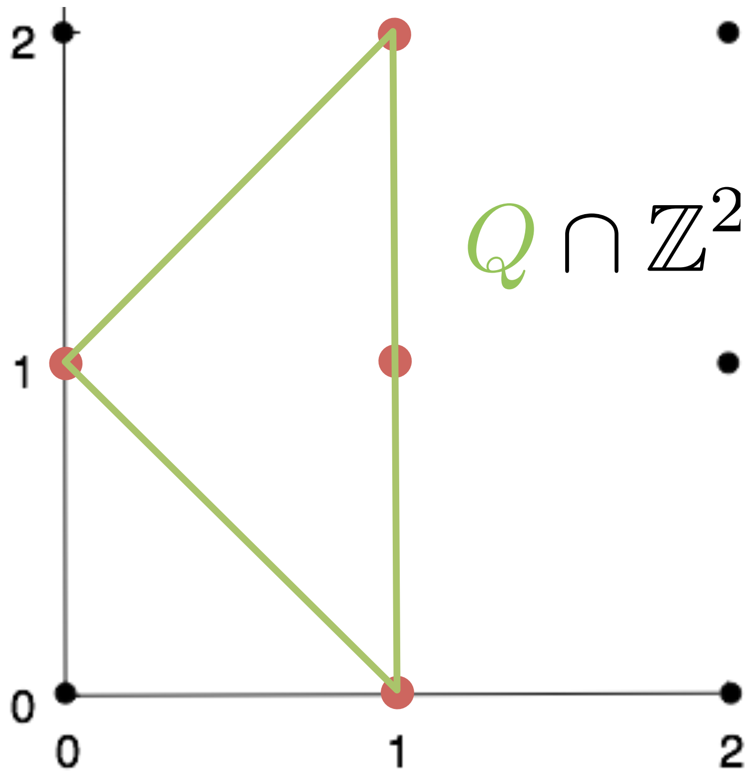
$$Q := \operatorname{conv}\left(\left\{p^i\right\}_{i=1}^{n}\right)$$



Constructing Non-extended Ideal Formulations

- Pure Integer :

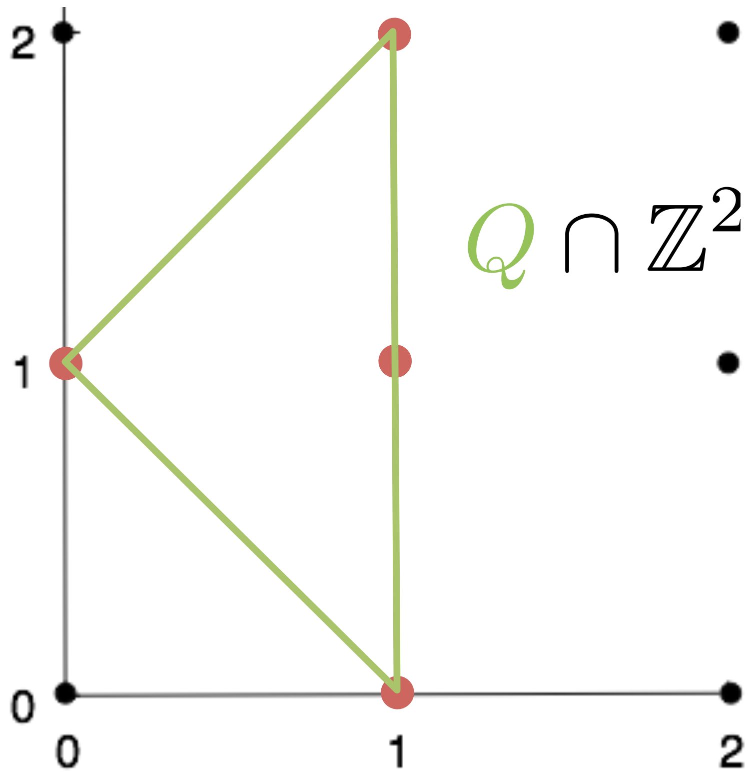
$$Q := \operatorname{conv}\left(\left\{p^i\right\}_{i=1}^{n}\right)$$



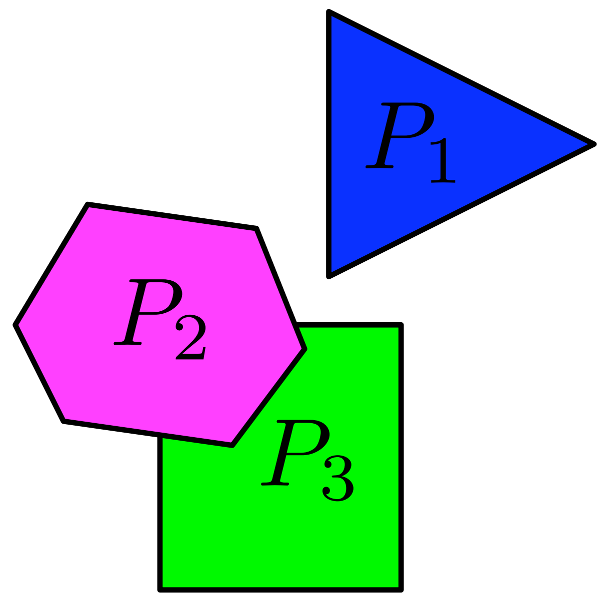
Constructing Non-extended Ideal Formulations

- Pure Integer :

$$Q := \text{conv}\left(\{p^i\}_{i=1}^n\right)$$



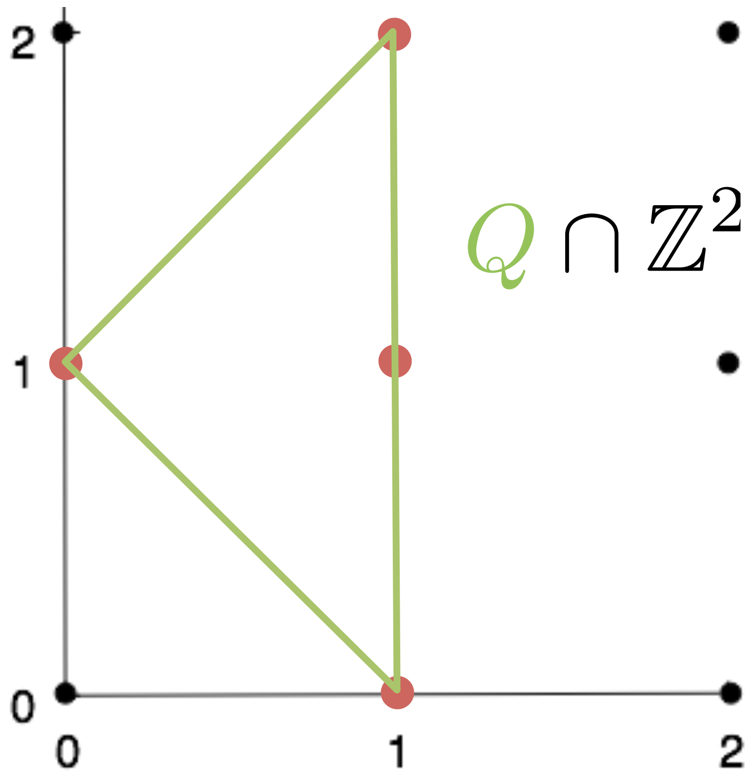
- Mixed Integer:



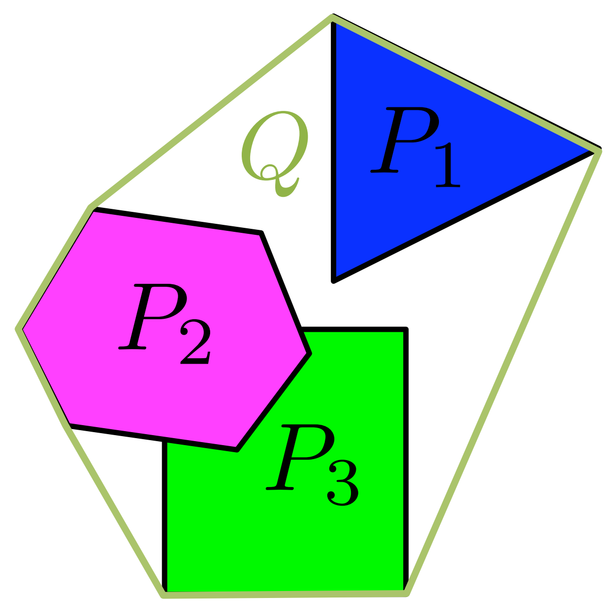
Constructing Non-extended Ideal Formulations

- Pure Integer :

$$Q := \operatorname{conv}\left(\left\{p^i\right\}_{i=1}^{n}\right)$$



- Mixed Integer:

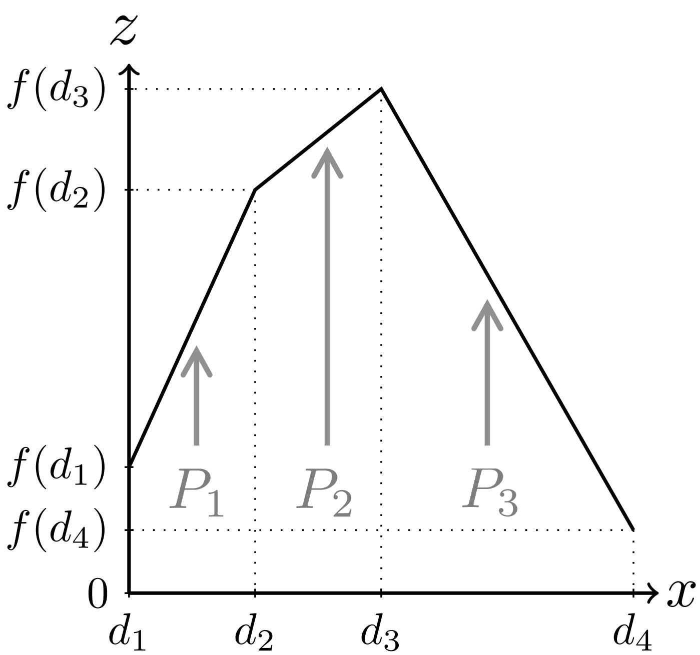


Outline

- Introduction
  - Simple class of polyhedra, formulations and complexity
- Smallest non-extended formulations (ideal or not)
  - Relaxation complexity
- Smallest non-extended ideal formulations
  - Embedding complexity
- Constructing formulations in practice
  - Multivariate piecewise linear functions
- Conclusions

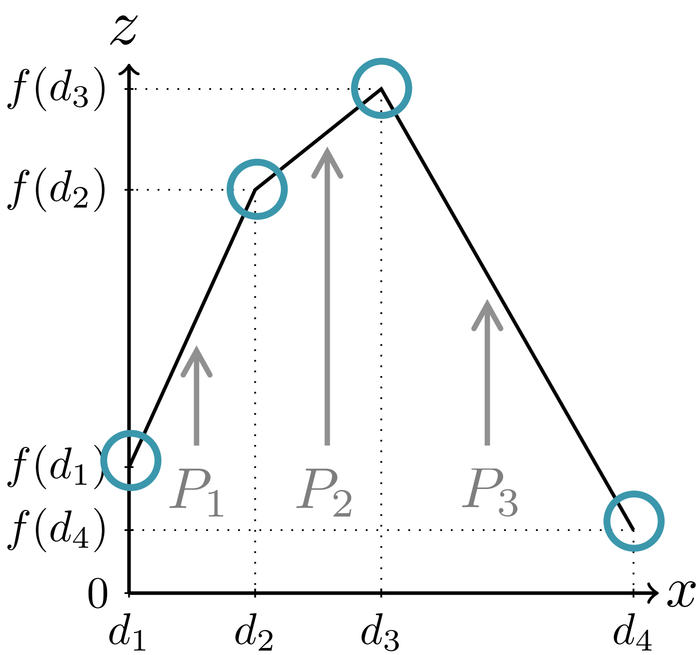
“Simple” Family of Polyhedra

$$(x, z) \in \mathrm{gr}\,(f) = \bigcup_{i=1}^{3} P_i$$



"Simple" Family of Polyhedra

$$(x, z) \in \mathrm{gr}(f) = \bigcup_{i=1}^{3} P_i$$

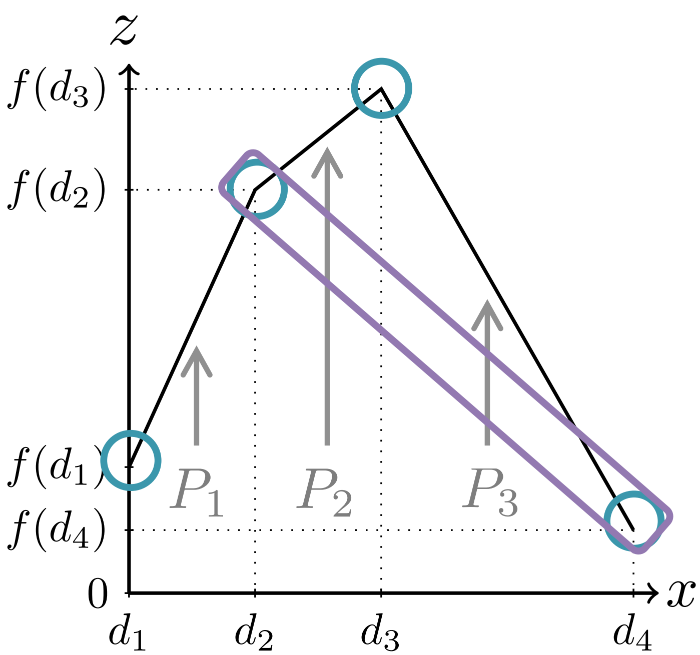


$$\begin{pmatrix} x \\ z \end{pmatrix} = \sum_{j=1}^{4} \begin{pmatrix} d_j \\ f(d_j) \end{pmatrix} \lambda_{d_j}$$

$$\lambda \in \Delta^4 := \left\{ \lambda \in \mathbb{R}_+^4 \; : \; \sum_{i=1}^{4} \lambda_i = 1 \right\}$$

“Simple” Family of Polyhedra

$$(x, z) \in \mathrm{gr}\,(f) = \bigcup_{i=1}^{3} P_i$$

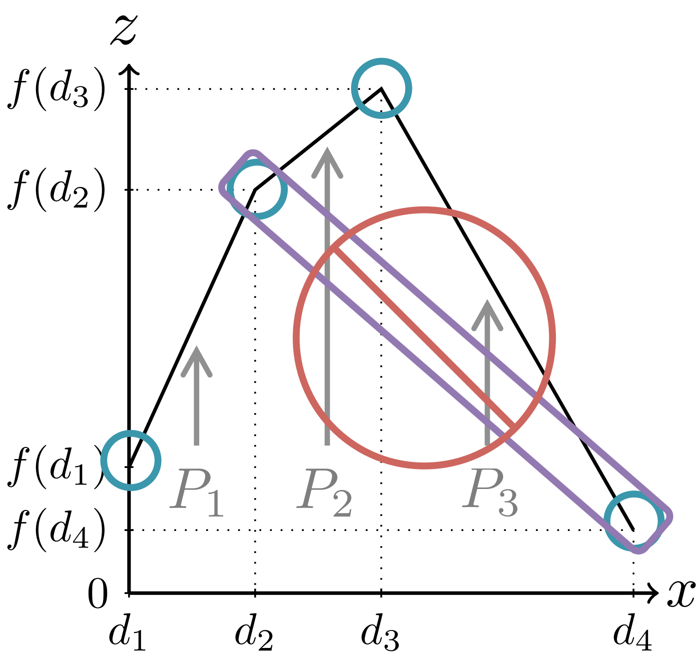


$$\begin{pmatrix} x \\ z \end{pmatrix} = \sum_{j=1}^{4} \begin{pmatrix} d_j \\ f(d_j) \end{pmatrix} \lambda_{d_j}$$

$$\lambda \in \Delta^4 := \left\{ \lambda \in \mathbb{R}^4_+ \;:\; \sum_{i=1}^{4} \lambda_i = 1 \right\}$$

“Simple” Family of Polyhedra

$$(x, z) \in \mathrm{gr}\,(f) = \bigcup_{i=1}^{3} P_i$$

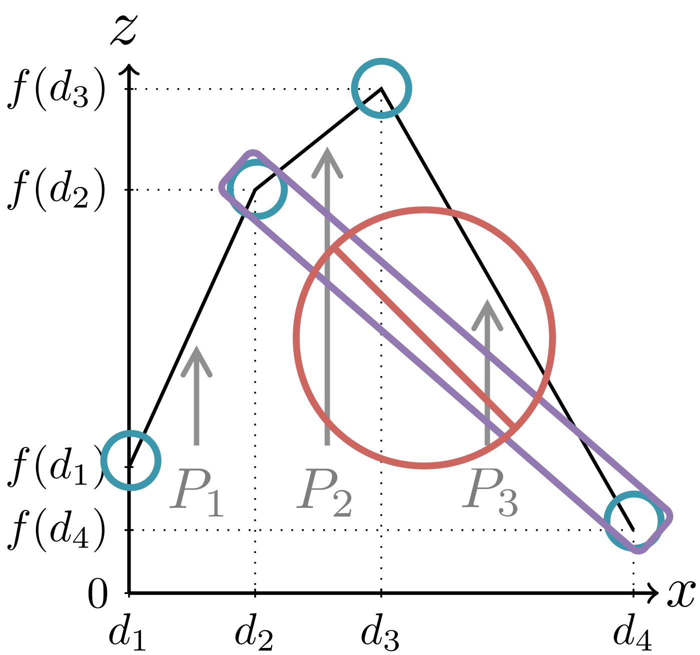


$$\begin{pmatrix} x \\ z \end{pmatrix} = \sum_{j=1}^{4} \begin{pmatrix} d_j \\ f\,(d_j) \end{pmatrix} \lambda_{d_j}$$

$$\lambda \in \Delta^4 := \left\{ \lambda \in \mathbb{R}^4_+ \;:\; \sum_{i=1}^{4} \lambda_i = 1 \right\}$$

"Simple" Family of Polyhedra

$$(x, z) \in \operatorname{gr}(f) = \bigcup_{i=1}^{3} P_i$$

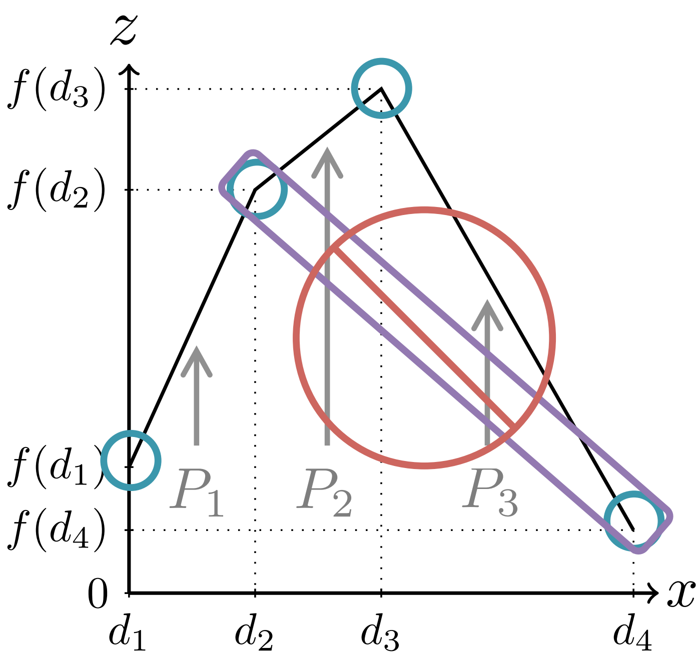


$$\begin{pmatrix} x \\ z \end{pmatrix} = \sum_{j=1}^{4} \begin{pmatrix} d_j \\ f(d_j) \end{pmatrix} \lambda_{d_j}$$

$$\lambda \in \Delta^4 := \left\{ \lambda \in \mathbb{R}^4_+ : \sum_{i=1}^{4} \lambda_i = 1 \right\}$$

“Simple” Family of Polyhedra

$$(x,z) \in \mathrm{gr}\,(f) = \bigcup_{i=1}^{3} P_i$$



$$\begin{pmatrix} x \\ z \end{pmatrix} = \sum_{j=1}^{4} \begin{pmatrix} d_j \\ f(d_j) \end{pmatrix} \lambda_{d_j}$$

~~$\lambda \in \Delta^4 := \left\{ \lambda \in \mathbb{R}^4_+ \,:\, \sum_{i=1}^{4} \lambda_i = 1 \right\}$~~

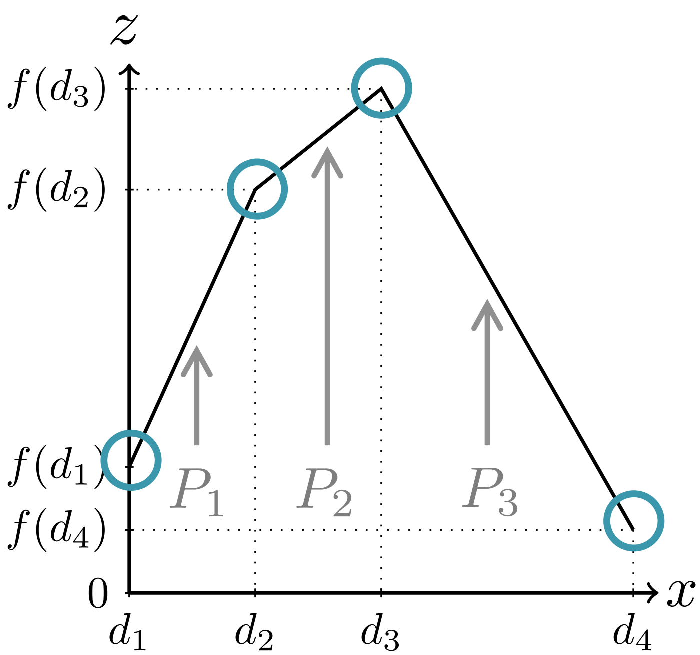
$$\lambda \in \bigcup_{i=1}^{3} P_i \subseteq \Delta^4$$

$$P_i := \left\{ \lambda \in \Delta^4 \,:\, \lambda_d = 0 \quad \forall d \notin T_i \right\}$$

$$T_i := \{ d_i, d_{i+1} \} \qquad i \in \{1, \ldots, 3\}$$

“Simple” Family of Polyhedra

$$(x, z) \in \mathrm{gr}(f) = \bigcup_{i=1}^{3} P_i$$



SOS2 Constraints

$$\begin{pmatrix} x \\ z \end{pmatrix} = \sum_{j=1}^{4} \begin{pmatrix} d_j \\ f(d_j) \end{pmatrix} \lambda_{d_j}$$

~~$\lambda \in \Delta^4 := \left\{ \lambda \in \mathbb{R}^4_+ : \sum_{i=1}^{4} \lambda_i = 1 \right\}$~~

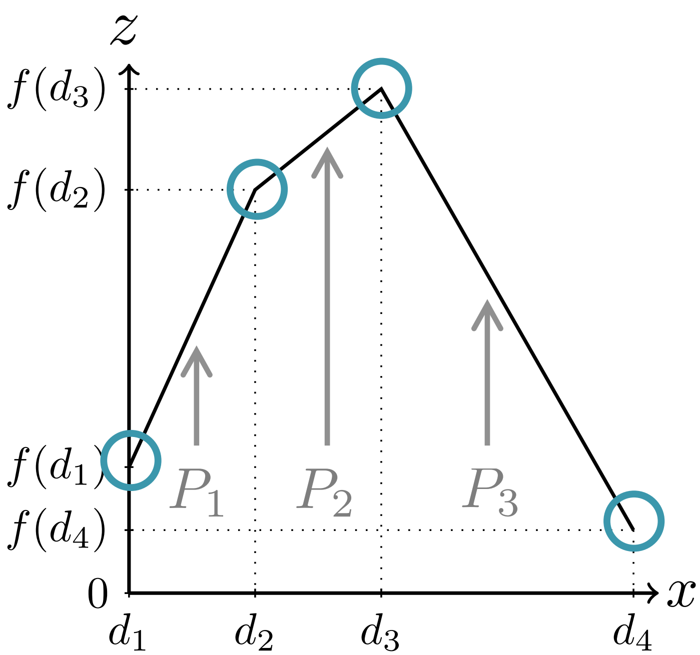
$$\lambda \in \bigcup_{i=1}^{3} P_i \subseteq \Delta^4$$

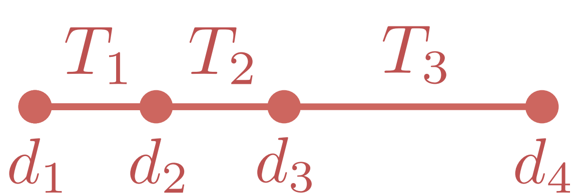
$$P_i := \left\{ \lambda \in \Delta^4 : \lambda_d = 0 \quad \forall d \notin T_i \right\}$$

$$T_i := \{ d_i, d_{i+1} \} \quad i \in \{1, \ldots, 3\}$$

“Simple” Family of Polyhedra

$$(x, z) \in \mathrm{gr}(f) = \bigcup_{i=1}^{3} P_i$$





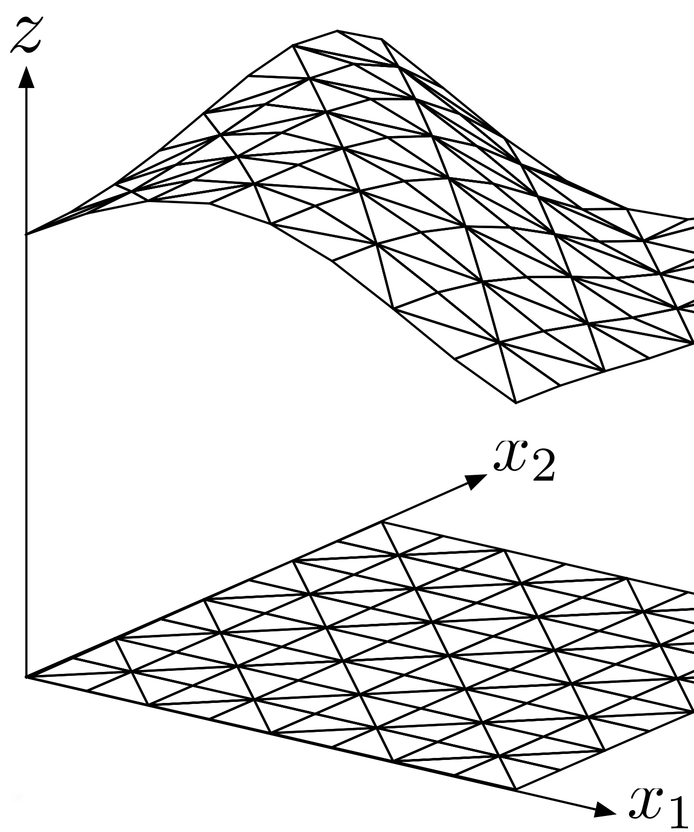
SOS2 Constraints

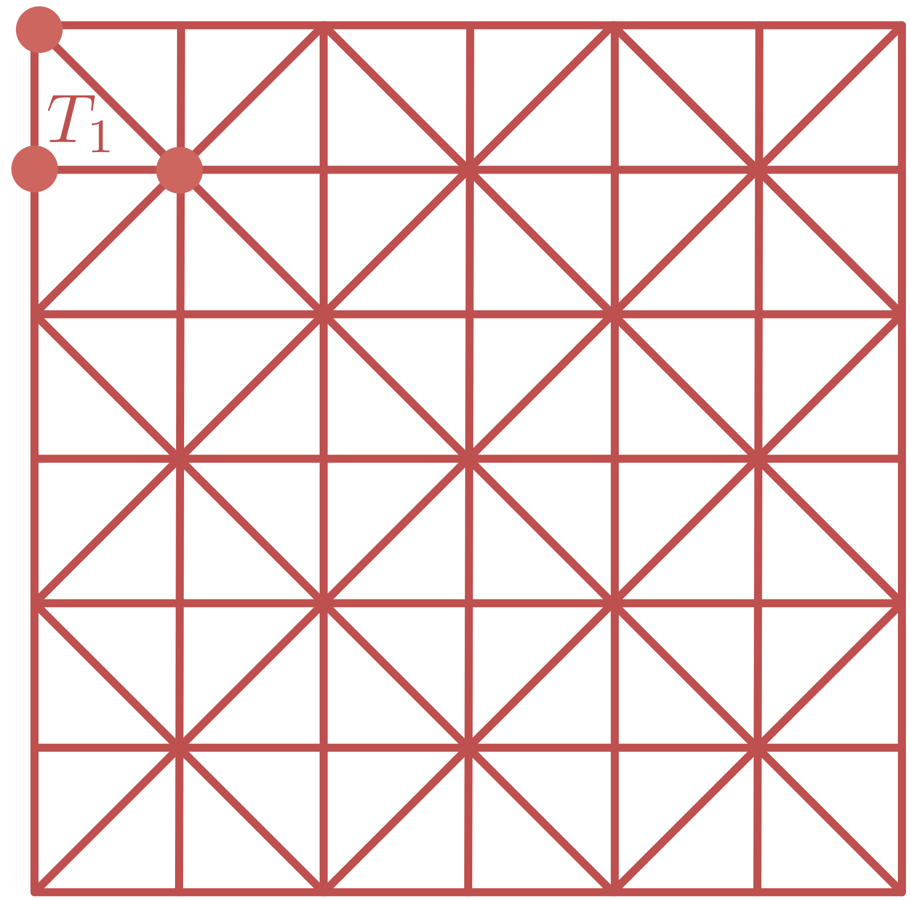
$$\lambda \in \bigcup_{i=1}^{3} P_i \subseteq \Delta^4$$

$$P_i := \left\{ \lambda \in \Delta^4 \ : \ \lambda_d = 0 \quad \forall d \notin T_i \right\}$$

$$T_i := \{d_i, d_{i+1}\} \quad i \in \{1, \ldots, 3\}$$

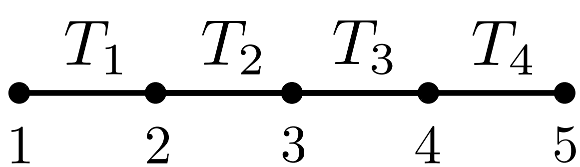
“Simple” Family of Polyhedra

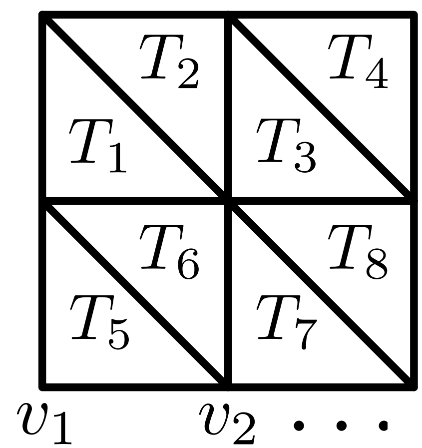




"Simple" Family of Polyhedra: Faces of a Simplex

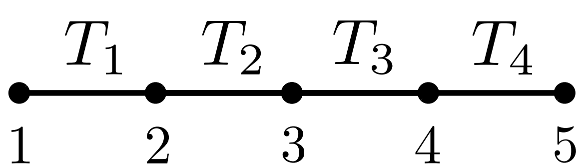
- $\Delta^V := \left\{\lambda \in \mathbb{R}^V_+ \; : \; \sum_{v \in V} \lambda_v = 1\right\}$,
- $P_i = \left\{\lambda \in \Delta^V \; : \; \lambda_v = 0 \quad \forall v \notin T_i\right\}$
- $\lambda \in \bigcup_{i=1}^{n} P_i$:

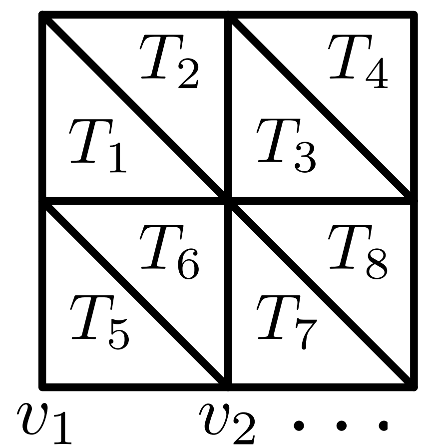




"Simple" Family of Polyhedra: Faces of a Simplex

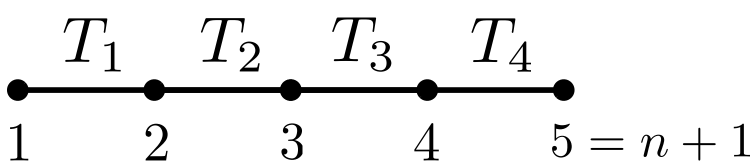
- $\Delta^V := \left\{ \lambda \in \mathbb{R}^V_+ \;:\; \sum_{v \in V} \lambda_v = 1 \right\},$
- $P_i = \{ \lambda \in \Delta^V \;:\; \lambda_v = 0 \quad \forall v \notin T_i \}$
- $\lambda \in \bigcup_{i=1}^n P_i :$





- $\operatorname{conv}\left(\bigcup_{i=1}^n P_i \right) = \Delta^V$

Standard **Non-ideal** Formulation for SOS2

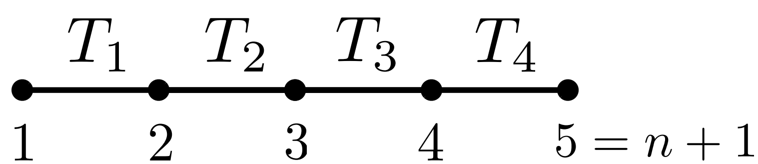


$$\sum_{i=1}^{5} \lambda_i = 1$$

$$y \in \{0,1\}^4, \quad \sum_{i=1}^{4} y_i = 1$$

$$\overbrace{\begin{aligned} 0 \le \lambda_1 &\le y_1 \\ 0 \le \lambda_2 &\le y_1 + y_2 \\ 0 \le \lambda_3 &\le y_2 + y_3 \\ 0 \le \lambda_4 &\le y_3 + y_4 \\ 0 \le \lambda_5 &\le y_4 \end{aligned}}^{2(n+1)}$$

Standard **Non-ideal** Formulation for SOS2



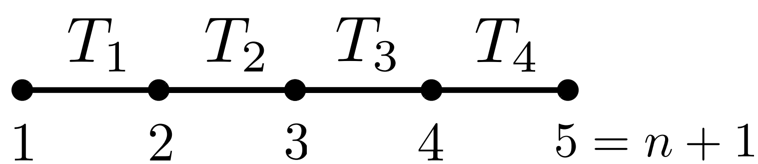
$$\sum_{i=1}^{5} \lambda_i = 1$$

$$y \in \{0,1\}^4, \quad \sum_{i=1}^{4} y_i = 1$$

$$\overbrace{\begin{aligned} 0 \le \lambda_1 &\le y_1 \\ 0 \le \lambda_2 &\le y_1 + y_2 \\ 0 \le \lambda_3 &\le y_2 + y_3 \\ 0 \le \lambda_4 &\le y_3 + y_4 \\ 0 \le \lambda_5 &\le y_4 \end{aligned}}^{2(n+1)}$$

General Inequalities

Standard **Non-ideal** Formulation for SOS2



$$\sum_{i=1}^{5} \lambda_i = 1$$

$$y \in \{0,1\}^4, \quad \sum_{i=1}^{4} y_i = 1$$

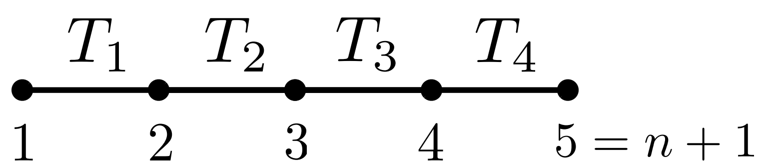
$2(n+1)$

$$0 \leq \lambda_1 \leq y_1$$
$$0 \leq \lambda_2 \leq y_1 + y_2$$
$$0 \leq \lambda_3 \leq y_2 + y_3$$
$$0 \leq \lambda_4 \leq y_3 + y_4$$
$$0 \leq \lambda_5 \leq y_4$$

Bounds

General Inequalities

Standard **Non-ideal** Formulation for SOS2



$$\sum_{i=1}^{5} \lambda_i = 1$$

$$y \in \{0,1\}^4, \quad \sum_{i=1}^{4} y_i = 1$$

$2(n+1)$

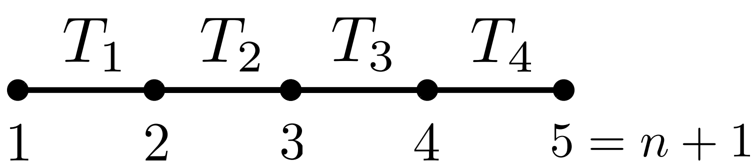
$$0 \leq \lambda_1 \leq y_1$$
$$0 \leq \lambda_2 \leq y_1 + y_2$$
$$0 \leq \lambda_3 \leq y_2 + y_3$$
$$0 \leq \lambda_4 \leq y_3 + y_4$$
$$0 \leq \lambda_5 \leq y_4$$

Bounds

General Inequalities

- Minimum # of (general) inequalities?
  - Ideal formulation:
  - Non-ideal formulation:

Standard **Non-ideal** Formulation for SOS2



$$\sum_{i=1}^{5} \lambda_i = 1$$

$$y \in \{0,1\}^4, \quad \sum_{i=1}^{4} y_i = 1$$

$2(n+1)$

$$0 \leq \lambda_1 \leq y_1$$
$$0 \leq \lambda_2 \leq y_1 + y_2$$
$$0 \leq \lambda_3 \leq y_2 + y_3$$
$$0 \leq \lambda_4 \leq y_3 + y_4$$
$$0 \leq \lambda_5 \leq y_4$$

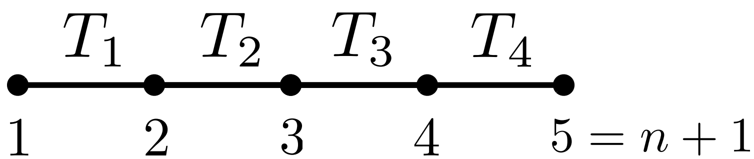
Bounds — General Inequalities

- Minimum # of (general) inequalities?
  - Ideal formulation:

    $$2\lceil \log_2 n \rceil$$

    $$n + 1 \leq \ldots \leq n + 1 + 2\lceil \log_2 n \rceil$$
  - Non-ideal formulation:

Standard **Non-ideal** Formulation for SOS2



$$\sum_{i=1}^{5} \lambda_i = 1$$

$$y \in \{0,1\}^4, \quad \sum_{i=1}^{4} y_i = 1$$

$2(n+1)$

$$0 \le \lambda_1 \le y_1$$

$$0 \le \lambda_2 \le y_1 + y_2$$

$$0 \le \lambda_3 \le y_2 + y_3$$

$$0 \le \lambda_4 \le y_3 + y_4$$

$$0 \le \lambda_5 \le y_4$$

Bounds

General Inequalities

- Minimum # of (general) inequalities?
  - Ideal formulation:

    $$2\lceil \log_2 n \rceil$$

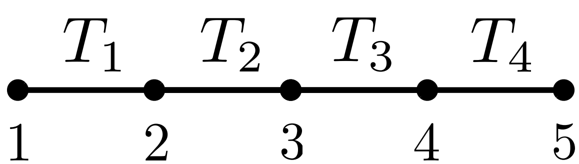
    $$n+1 \le \ldots \le n+1+2\lceil \log_2 n \rceil$$

  - Non-ideal formulation:

    $$2 \le \ldots \le 4$$

    $$2 \le \ldots \le 5+2n$$

What is a Formulation?



$$\sum_{i=1}^{5} \lambda_i = 1$$

$$y \in \{0,1\}^4, \quad \sum_{i=1}^{4} y_i = 1$$

$$0 \leq \lambda_1 \leq y_1$$

$$0 \leq \lambda_2 \leq y_1 + y_2$$

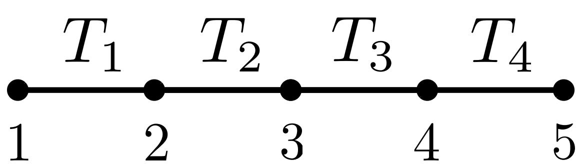
$$0 \leq \lambda_3 \leq y_2 + y_3$$

$$0 \leq \lambda_4 \leq y_3 + y_4$$

$$0 \leq \lambda_5 \leq y_4$$

$$P_i := \{\lambda \in \Lambda^5 \, : \, \lambda_j = 0 \quad j \notin \{i, i+1\}\}$$

What is a Formulation?



Q = LP relaxation

$$\sum_{i=1}^{5} \lambda_i = 1$$

$$y \in \{0,1\}^4, \quad \sum_{i=1}^{4} y_i = 1$$

$$0 \leq \lambda_1 \leq y_1$$

$$0 \leq \lambda_2 \leq y_1 + y_2$$

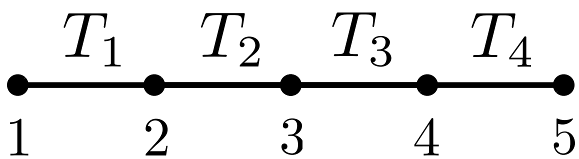
$$0 \leq \lambda_3 \leq y_2 + y_3$$

$$0 \leq \lambda_4 \leq y_3 + y_4$$

$$0 \leq \lambda_5 \leq y_4$$

$$P_i := \{\lambda \in \Lambda^5 \,:\, \lambda_j = 0 \quad j \notin \{i, i+1\}\}$$

What is a Formulation?



Q = LP relaxation →

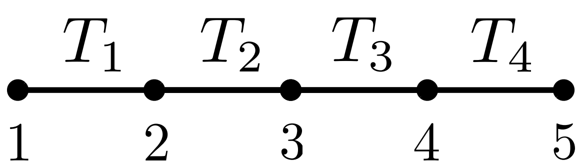
$$y \in \{0,1\}^4, \quad \sum_{i=1}^{5} \lambda_i = 1, \quad \sum_{i=1}^{4} y_i = 1$$

$$0 \leq \lambda_1 \leq y_1$$
$$0 \leq \lambda_2 \leq y_1 + y_2$$
$$0 \leq \lambda_3 \leq y_2 + y_3$$
$$0 \leq \lambda_4 \leq y_3 + y_4$$
$$0 \leq \lambda_5 \leq y_4$$

$$(\lambda, y) \in Q \cap \left(\mathbb{R}^5 \times \mathbb{Z}^4\right)$$
$$\Updownarrow$$
$$y = e^i \;\wedge\; \lambda \in P_i$$

$$P_i := \left\{\lambda \in \Lambda^5 \;:\; \lambda_j = 0 \quad j \notin \{i, i+1\}\right\}$$

What is a Formulation?



Q = LP relaxation →

$$\sum_{i=1}^{5} \lambda_i = 1$$

$$y \in \{0,1\}^4, \quad \sum_{i=1}^{4} y_i = 1$$

$$0 \le \lambda_1 \le y_1$$
$$0 \le \lambda_2 \le y_1 + y_2$$
$$0 \le \lambda_3 \le y_2 + y_3$$
$$0 \le \lambda_4 \le y_3 + y_4$$
$$0 \le \lambda_5 \le y_4$$

$$(\lambda, y) \in Q \cap \left(\mathbb{R}^5 \times \mathbb{Z}^4\right)$$

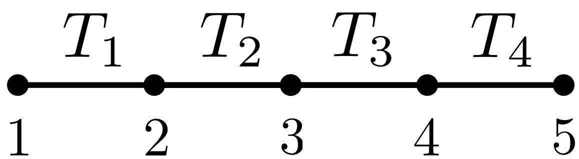
$$\Updownarrow$$

$$y = e^i \ \wedge \ \lambda \in P_i$$

Unary Encoding

$$P_i := \{\lambda \in \Lambda^5 \; : \; \lambda_j = 0 \quad j \notin \{i, i+1\}\}$$

Alternate Meaning of 0-1 Variables



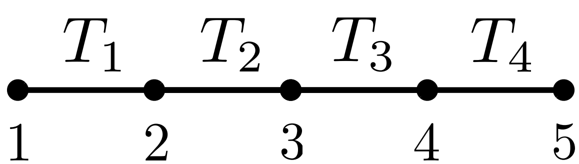
Q = LP relaxation → $\sum_{i=1}^{5} \lambda_i = 1$

- V. and Nemhauser '08.

$$
\begin{aligned}
0 &\leq \lambda_1 + \lambda_5 \leq 1 - y_1 \\
0 &\leq \lambda_3 \leq y_1 \\
0 &\leq \lambda_4 + \lambda_5 \leq 1 - y_2 \\
0 &\leq \lambda_1 + \lambda_2 \leq y_2
\end{aligned}
$$

$$P_i := \{\lambda \in \Lambda^5 \, : \, \lambda_j = 0 \quad j \notin \{i, i+1\}\}$$

Alternate Meaning of 0-1 Variables



Q = LP relaxation → $\sum_{i=1}^{5} \lambda_i = 1$

$$h^1 = \binom{0}{1},\ h^2 = \binom{1}{1},\ h^3 = \binom{1}{0},\ h^4 = \binom{0}{0}$$

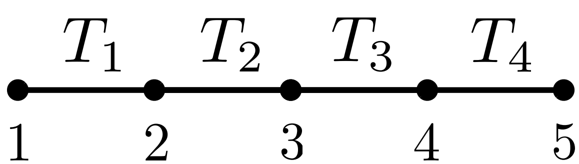
- V. and Nemhauser '08.

$$\begin{aligned} 0 &\le \lambda_1 + \lambda_5 \le 1 - y_1 \\ 0 &\le \lambda_3 \le y_1 \\ 0 &\le \lambda_4 + \lambda_5 \le 1 - y_2 \\ 0 &\le \lambda_1 + \lambda_2 \le y_2 \end{aligned}$$

$$(\lambda, y) \in Q \cap \left(\mathbb{R}^5 \times \mathbb{Z}^2\right)$$
$$\Updownarrow$$
$$y = h^i \ \wedge\ \lambda \in P_i$$

$$P_i := \{\lambda \in \Lambda^5 \,:\, \lambda_j = 0 \quad j \notin \{i, i+1\}\}$$

Alternate Meaning of 0-1 Variables



Q = LP relaxation → $\sum_{i=1}^{5} \lambda_i = 1$

$$h^1 = \begin{pmatrix}0\\1\end{pmatrix},\ h^2 = \begin{pmatrix}1\\1\end{pmatrix},\ h^3 = \begin{pmatrix}1\\0\end{pmatrix},\ h^4 = \begin{pmatrix}0\\0\end{pmatrix}$$

- V. and Nemhauser '08.

$$\begin{aligned}
0 \leq \lambda_1 + \lambda_5 &\leq 1 - y_1 \\
0 \leq \lambda_3 \qquad &\leq y_1 \\
0 \leq \lambda_4 + \lambda_5 &\leq 1 - y_2 \\
0 \leq \lambda_1 + \lambda_2 &\leq y_2
\end{aligned}$$

$$(\lambda, y) \in Q \cap \left(\mathbb{R}^5 \times \mathbb{Z}^2\right)$$

$$\Updownarrow$$

$$y = h^i \ \wedge \ \lambda \in P_i$$

Binary Encoding

$$P_i := \{\lambda \in \Lambda^5 : \lambda_j = 0 \quad j \notin \{i, i+1\}\}$$

Embedding Formulations for Union of Polyhedra

- **Non-Extended** formulation of $\lambda \in \bigcup_{i=1}^{n} P_i \subseteq \mathbb{R}^V$:
  - Encoding $H := \{h^i\}_{i=1}^{n} \subseteq \{0,1\}^k, \quad h^i \neq h^j$
  - Polyhedron $Q \subseteq \mathbb{R}^V \times \mathbb{R}^k$, s.t.

$$(\lambda, y) \in Q \cap \left(\mathbb{R}^V \times \mathbb{Z}^k\right) \quad \Leftrightarrow \quad y = h^i \ \wedge \ \lambda \in P_i$$

Embedding Formulations for Union of Polyhedra

- **Non-Extended** formulation of $\lambda \in \bigcup_{i=1}^{n} P_i \subseteq \mathbb{R}^V$:
  - Encoding $H := \{h^i\}_{i=1}^{n} \subseteq \{0,1\}^k, \quad h^i \neq h^j$
  - Polyhedron $Q \subseteq \mathbb{R}^V \times \mathbb{R}^k$, s.t.

$$(\lambda, y) \in Q \cap \left(\mathbb{R}^V \times \mathbb{Z}^k\right) \quad \Leftrightarrow \quad y = h^i \;\wedge\; \lambda \in P_i$$

- **Embedding formulation** = strongest polyhedron (ideal):

$$Q(H) := \operatorname{conv}\left(\bigcup_{i=1}^{n} P_i \times \{h^i\}\right)$$

Embedding Formulations for Union of Polyhedra

- **Non-Extended** formulation of $\lambda \in \bigcup_{i=1}^{n} P_i \subseteq \mathbb{R}^V$:
  - Encoding $H := \{h^i\}_{i=1}^{n} \subseteq \{0,1\}^k, \quad h^i \neq h^j$
  - Polyhedron $Q \subseteq \mathbb{R}^V \times \mathbb{R}^k$, s.t.

$$(\lambda, y) \in Q \cap \left(\mathbb{R}^V \times \mathbb{Z}^k\right) \quad \Leftrightarrow \quad y = h^i \ \wedge \ \lambda \in P_i$$

- **Embedding formulation** = strongest polyhedron (ideal):

$$Q(H) := \operatorname{conv}\Big(\underbrace{\bigcup_{i=1}^{n} P_i \times \{h^i\}}_{\text{Cayley Embedding}}\Big)$$

For unary encoding:

$$h^i = e^i$$

Embedding Formulations for Union of Polyhedra

- **Non-Extended** formulation of $\lambda \in \bigcup_{i=1}^{n} P_i \subseteq \mathbb{R}^V$:
  - Encoding $H := \{h^i\}_{i=1}^{n} \subseteq \{0,1\}^k, \quad h^i \neq h^j$
  - Polyhedron $Q \subseteq \mathbb{R}^V \times \mathbb{R}^k$, s.t.

$$(\lambda, y) \in Q \cap \left(\mathbb{R}^V \times \mathbb{Z}^k\right) \quad \Leftrightarrow \quad y = h^i \ \wedge \ \lambda \in P_i$$

- **Embedding formulation** = strongest polyhedron (ideal):

$$Q(H) := \operatorname{conv}\left(\bigcup_{i=1}^{n} P_i \times \{h^i\}\right)$$

Embedding Formulations for Union of Polyhedra

- **Non-Extended** formulation of $\lambda \in \bigcup_{i=1}^{n} P_i \subseteq \mathbb{R}^V$:
  - Encoding $H := \{h^i\}_{i=1}^{n} \subseteq \{0,1\}^k, \quad h^i \neq h^j$
  - Polyhedron $Q \subseteq \mathbb{R}^V \times \mathbb{R}^k$, s.t.

$$(\lambda, y) \in Q \cap \left(\mathbb{R}^V \times \mathbb{Z}^k\right) \quad \Leftrightarrow \quad y = h^i \;\wedge\; \lambda \in P_i$$

- **Embedding formulation** = strongest polyhedron (ideal):

$$Q(H) := \operatorname{conv}\left(\bigcup_{i=1}^{n} P_i \times \{h^i\}\right)$$

$$\operatorname{size}(Q) := \#\text{ of facets of } Q \text{ (usually function of } n)$$

Complexity of Family of Polyhedra $\mathcal{P} := \{P_i\}_{i=1}^n$

Complexity of Family of Polyhedra $\mathcal{P} := \{P_i\}_{i=1}^n$

- Relaxation complexity = smallest formulation

$$\mathrm{rc}\,(\mathcal{P}) := \min_{Q,H} \{\mathrm{size}(Q)\ :\ (Q, H)\ \text{is formulation}\}$$

Complexity of Family of Polyhedra $\mathcal{P} := \{P_i\}_{i=1}^n$

- Relaxation complexity = smallest formulation

$$\operatorname{rc}(\mathcal{P}) := \min_{Q,H} \{\operatorname{size}(Q) \ : \ (Q, H) \text{ is formulation}\}$$

- Embedding complexity = smallest **ideal** formulation

$$\operatorname{mc}(\mathcal{P}) := \min_{H} \{\operatorname{size}(Q(H))\}$$

Complexity of Family of Polyhedra $\mathcal{P} := \{P_i\}_{i=1}^n$

- Relaxation complexity = smallest formulation

$$\mathrm{rc}\left(\mathcal{P}\right) := \min_{Q,H} \{\mathrm{size}(Q) \ : \ (Q, H) \text{ is formulation}\}$$

- Embedding complexity = smallest **ideal** formulation

$$\mathrm{mc}\left(\mathcal{P}\right) := \min_{H} \{\mathrm{size}\left(Q\left(H\right)\right)\}$$

- Hull complexity

$$\mathrm{hc}\left(\mathcal{P}\right) := \mathrm{size}\left(\mathrm{conv}\left(\bigcup_{i=1}^n P_i\right)\right)$$

Complexity of Family of Polyhedra $\mathcal{P} := \{P_i\}_{i=1}^n$

- Relaxation complexity = smallest formulation

$$\operatorname{rc}(\mathcal{P}) := \min_{Q,H} \{\operatorname{size}(Q) \ : \ (Q, H) \text{ is formulation}\}$$

- Embedding complexity = smallest **ideal** formulation

$$\operatorname{mc}(\mathcal{P}) := \min_{H} \{\operatorname{size}(Q(H))\}$$

- Hull complexity

$$\operatorname{hc}(\mathcal{P}) := \operatorname{size}\left(\operatorname{conv}\left(\bigcup_{i=1}^n P_i\right)\right)$$

- Extension complexity

$$\operatorname{xc}(\mathcal{P}) := \min_R \left\{\operatorname{size}(R) \ : \ \operatorname{proj}_x(R) = \operatorname{conv}\left(\bigcup_{i=1}^n P_i\right)\right\}$$

Complexity of Family of Polyhedra $\mathcal{P} := \{P_i\}_{i=1}^n$

- Relaxation complexity = smallest formulation

$$\mathrm{rc}\left(\mathcal{P}\right) := \min_{Q,H} \left\{\mathrm{size}(Q) \;:\; (Q, H) \text{ is formulation}\right\}$$

- Embedding complexity = smallest **ideal** formulation

$$\mathrm{xc}\left(\mathcal{P}\right) \leq \mathrm{mc}\left(\mathcal{P}\right) := \min_{H} \left\{\mathrm{size}\left(Q\left(H\right)\right)\right\}$$

- Hull complexity

$$\mathrm{xc}\left(\mathcal{P}\right) \leq \mathrm{hc}\left(\mathcal{P}\right) := \mathrm{size}\left(\mathrm{conv}\left(\bigcup_{i=1}^{n} P_i\right)\right)$$

- Extension complexity

$$\mathrm{xc}\left(\mathcal{P}\right) := \min_{R} \left\{\mathrm{size}\left(R\right) \;:\; \mathrm{proj}_x\left(R\right) = \mathrm{conv}\left(\bigcup_{i=1}^{n} P_i\right)\right\}$$

Complexity of Family of Polyhedra $\mathcal{P} := \{P_i\}_{i=1}^n$

- Relaxation complexity = smallest formulation

$$\mathrm{rc}(\mathcal{P}) := \min_{Q,H} \{\mathrm{size}(Q) \;:\; (Q, H) \text{ is formulation}\}$$

- Embedding complexity = smallest **ideal** formulation

$$\mathrm{xc}(\mathcal{P}) \leq \mathrm{mc}(\mathcal{P}) := \min_{H} \{\mathrm{size}(Q(H))\}$$

$$\mathrm{hc}\left(\{P_i \times h^i\}_{i=1}^n\right)$$

- Hull complexity

$$\mathrm{xc}(\mathcal{P}) \leq \mathrm{hc}(\mathcal{P}) := \mathrm{size}\left(\mathrm{conv}\left(\bigcup_{i=1}^n P_i\right)\right)$$

- Extension complexity

$$\mathrm{xc}(\mathcal{P}) := \min_{R} \left\{\mathrm{size}(R) \;:\; \mathrm{proj}_x(R) = \mathrm{conv}\left(\bigcup_{i=1}^n P_i\right)\right\}$$

Complexity of Family of Polyhedra $\mathcal{P} := \{P_i\}_{i=1}^n$

- Relaxation complexity = smallest formulation

$$\mathrm{rc}_G(\mathcal{P}) := \min_{Q,H} \{\mathrm{size}_G(Q) \; : \; (Q, H) \text{ is formulation}\}$$

- Embedding complexity = smallest **ideal** formulation

$$\mathrm{mc}_G(\mathcal{P}) := \min_H \{\mathrm{size}_G(Q(H))\}$$

General Inequalities

- Hull complexity

$$\mathrm{hc}(\mathcal{P}) := \mathrm{size}\left(\mathrm{conv}\left(\bigcup_{i=1}^n P_i\right)\right)$$

- Extension complexity

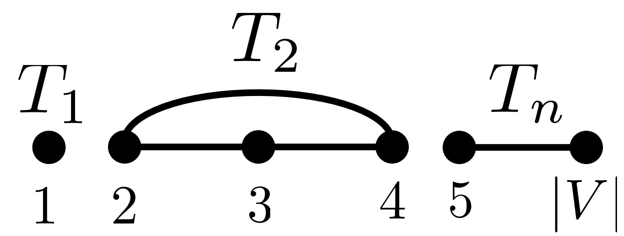
$$\mathrm{xc}(\mathcal{P}) := \min_R \left\{\mathrm{size}(R) \; : \; \mathrm{proj}_x(R) = \mathrm{conv}\left(\bigcup_{i=1}^n P_i\right)\right\}$$

Relaxation Complexity

Bounds on Relaxation Complexity

Bounds on Relaxation Complexity

- Disjoint Case : $T_i \cap T_j = \emptyset$

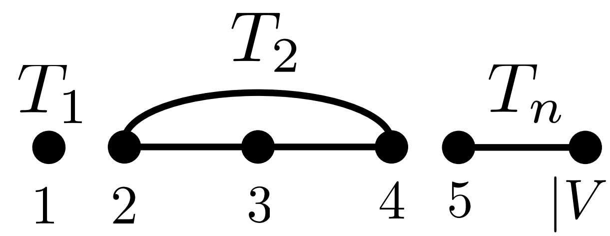


Bounds on Relaxation Complexity

- Disjoint Case : $T_i \cap T_j = \emptyset$

$$\mathrm{rc}_G\left(\mathcal{P}\right) = 2$$

$$2 \leq \mathrm{rc}\left(\mathcal{P}\right) \leq 2 + |V| + n$$

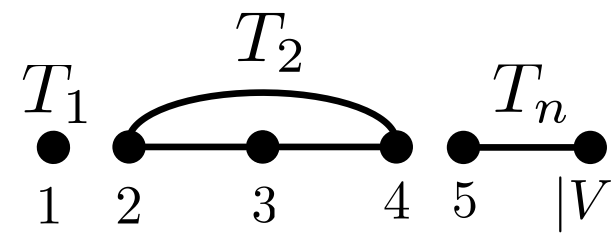


Bounds on Relaxation Complexity

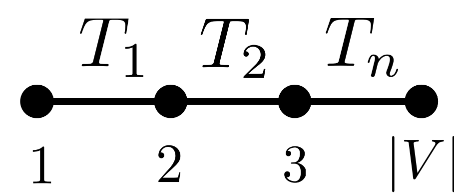
- Disjoint Case : $T_i \cap T_j = \emptyset$

$$\mathrm{rc}_G\left(\mathcal{P}\right) = 2$$

$$2 \leq \mathrm{rc}\left(\mathcal{P}\right) \leq 2 + |V| + n$$



- SOS2 constraints : $T_i = \{i, i+1\}$

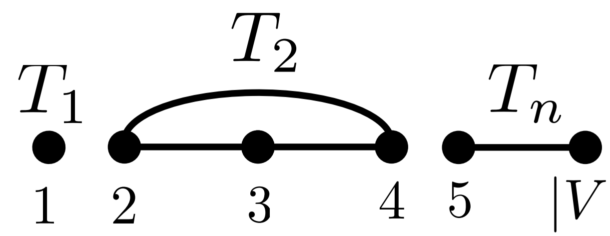


Bounds on Relaxation Complexity

- Disjoint Case : $T_i \cap T_j = \emptyset$

$$\mathrm{rc}_G(\mathcal{P}) = 2$$

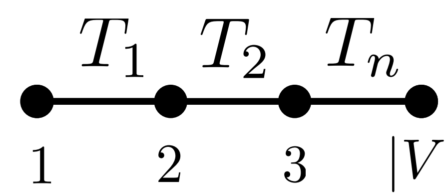
$$2 \leq \mathrm{rc}(\mathcal{P}) \leq 2 + |V| + n$$



- SOS2 constraints : $T_i = \{i, i+1\}$

$$2 \leq \mathrm{rc}_G(\mathcal{P}) \leq 4$$

$$2 \leq \mathrm{rc}(\mathcal{P}) \leq 5 + 2n$$

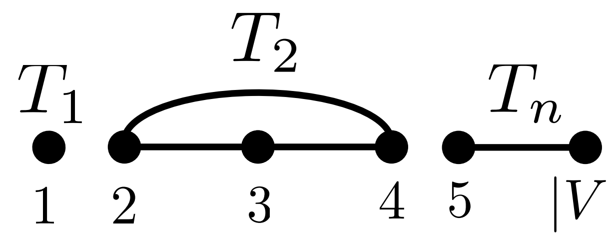


Bounds on Relaxation Complexity

- Disjoint Case : $T_i \cap T_j = \emptyset$

  $$\mathrm{rc}_G(\mathcal{P}) = 2$$

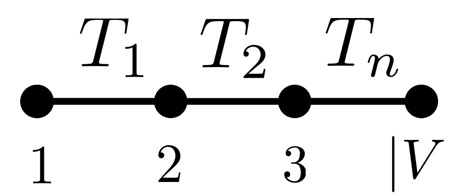
  $$2 \leq \mathrm{rc}(\mathcal{P}) \leq 2 + |V| + n$$



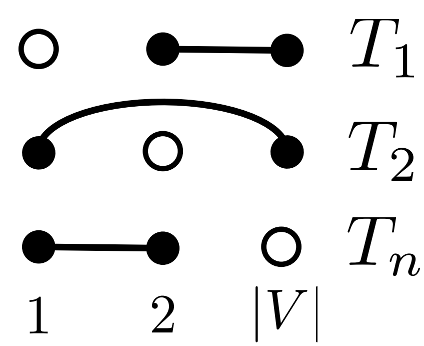
- SOS2 constraints : $T_i = \{i, i+1\}$

  $$2 \leq \mathrm{rc}_G(\mathcal{P}) \leq 4$$

  $$2 \leq \mathrm{rc}(\mathcal{P}) \leq 5 + 2n$$



- SOS(-1) constraints : $T_i = V \setminus \{i\}$

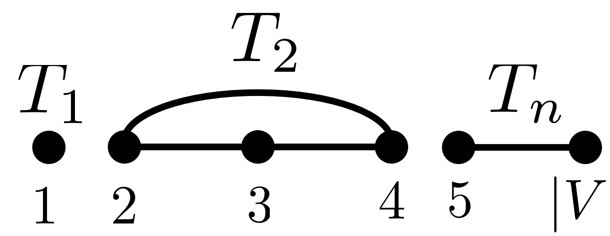


Bounds on Relaxation Complexity

- Disjoint Case : $T_i \cap T_j = \emptyset$

$$\mathrm{rc}_G\,(\mathcal{P}) = 2$$

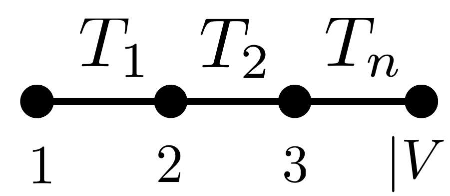
$$2 \leq \mathrm{rc}\,(\mathcal{P}) \;\; \leq 2 + |V| + n$$



- SOS2 constraints : $T_i = \{i, i+1\}$

$$2 \leq \mathrm{rc}_G\,(\mathcal{P}) \leq 4$$

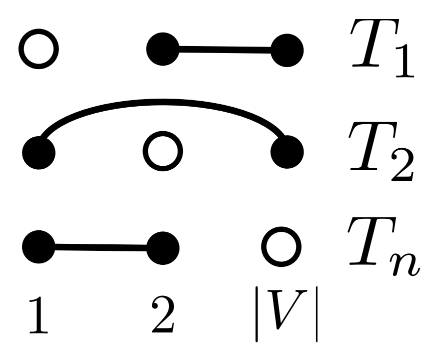
$$2 \leq \mathrm{rc}\,(\mathcal{P}) \;\; \leq 5 + 2n$$



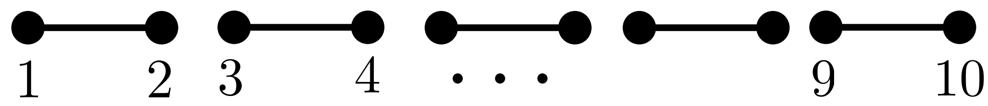
- SOS(-1) constraints : $T_i = V \setminus \{i\}$

$$\mathrm{mc}_G\,(\mathcal{P}) = \mathrm{rc}_G\,(\mathcal{P}) = n$$

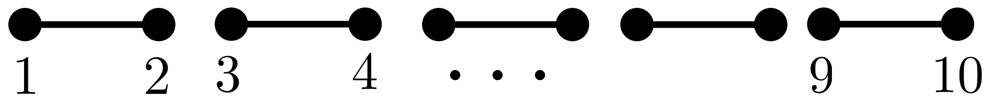
$$n \leq \mathrm{rc}\,(\mathcal{P}) \;\; \leq \mathrm{mc}\,(\mathcal{P}) \leq 3n$$



Formulation for Disjoint Case



Formulation for Disjoint Case

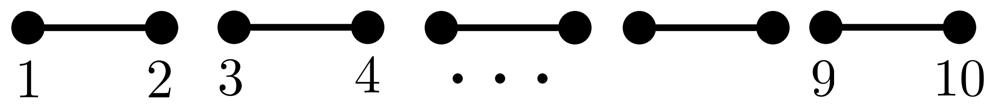


$$\sum_{i=1}^{n} p^i \left(\lambda_{2i-1} + \lambda_{2i}\right) \leq \sum_{i=1}^{n} p^i y_i$$

$$\sum_{i=1}^{2n} \lambda_i = 1, \quad \lambda \in \mathbb{R}_+^{2n}$$

$$\sum_{i=1}^{n} y_i = 1, \quad y \in \mathbb{R}_+^{n}$$

Formulation for Disjoint Case

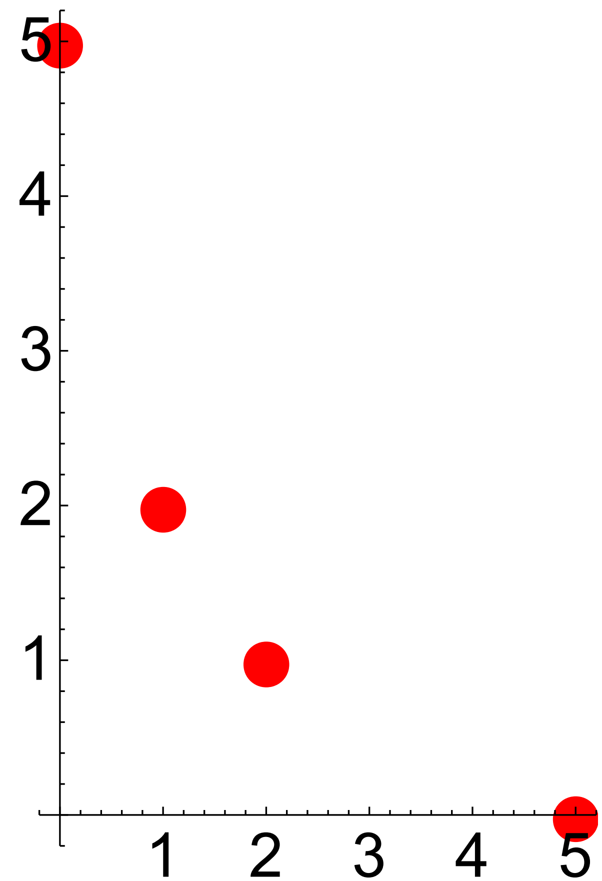


$$\sum_{i=1}^{n} p^i \left(\lambda_{2i-1} + \lambda_{2i}\right) \leq \sum_{i=1}^{n} p^i y_i$$

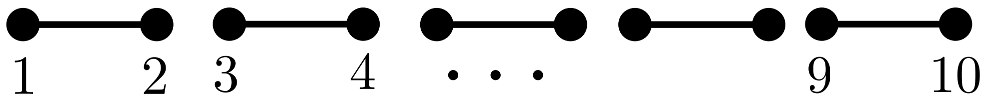
$$\sum_{i=1}^{2n} \lambda_i = 1, \quad \lambda \in \mathbb{R}_+^{2n}$$

$$\sum_{i=1}^{n} y_i = 1, \quad y \in \mathbb{R}_+^{n}$$

$$p^i \in \mathbb{R}_+^2, \quad \operatorname{conv}\left(\left\{p^j\right\}_{j \neq i}\right) \not\leq p^i$$



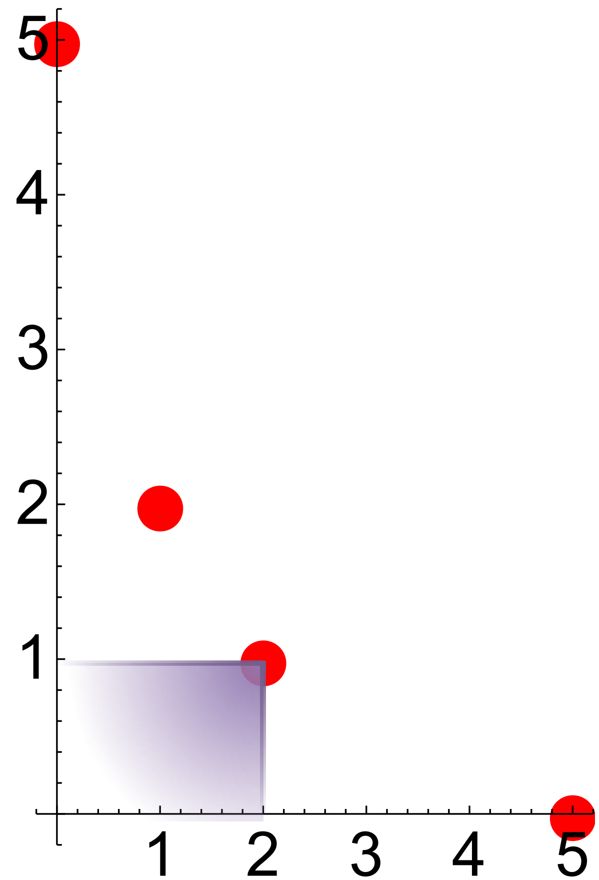
Formulation for Disjoint Case



$$\sum_{i=1}^{n} p^i \left(\lambda_{2i-1} + \lambda_{2i}\right) \leq \sum_{i=1}^{n} p^i y_i$$

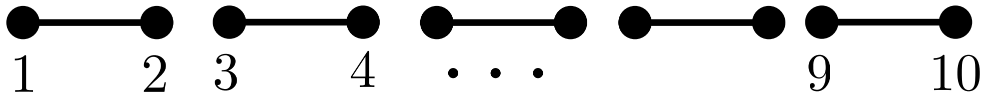
$$\sum_{i=1}^{2n} \lambda_i = 1, \quad \lambda \in \mathbb{R}_+^{2n}$$

$$\sum_{i=1}^{n} y_i = 1, \quad y \in \mathbb{R}_+^{n}$$



$$p^i \in \mathbb{R}_+^2, \qquad \operatorname{conv}\left(\left\{p^j\right\}_{j \neq i}\right) \not\leq p^i$$

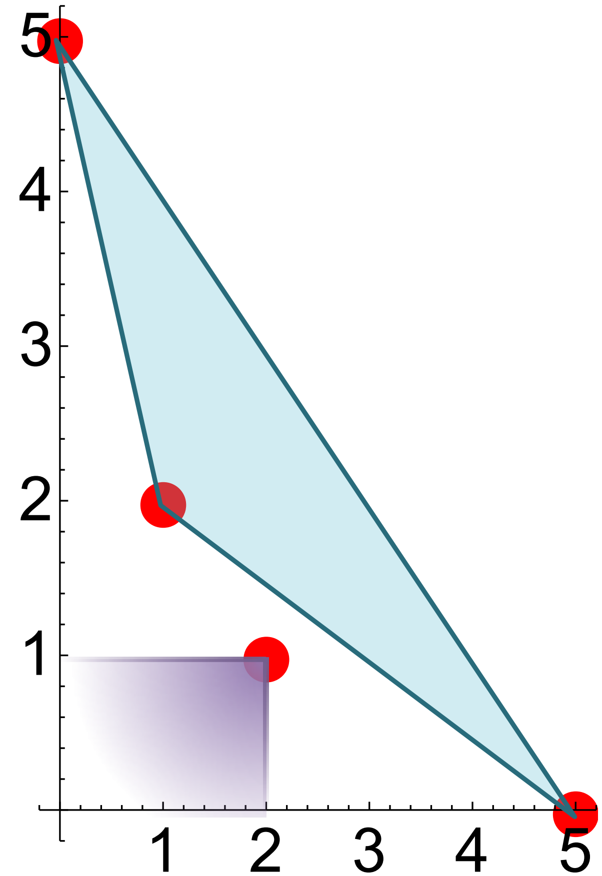
Formulation for Disjoint Case



$$\sum_{i=1}^{n} p^i(\lambda_{2i-1} + \lambda_{2i}) \leq \sum_{i=1}^{n} p^i y_i$$

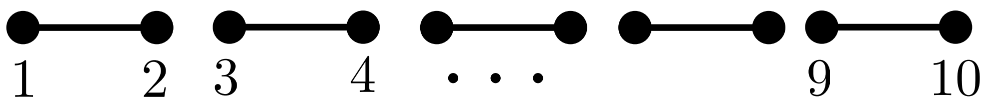
$$\sum_{i=1}^{2n} \lambda_i = 1, \quad \lambda \in \mathbb{R}^{2n}_+$$

$$\sum_{i=1}^{n} y_i = 1, \quad y \in \mathbb{R}^{n}_+$$



$$p^i \in \mathbb{R}^2_+, \quad \mathrm{conv}\left(\left\{p^j\right\}_{j\neq i}\right) \nleq p^i$$

Formulation for Disjoint Case

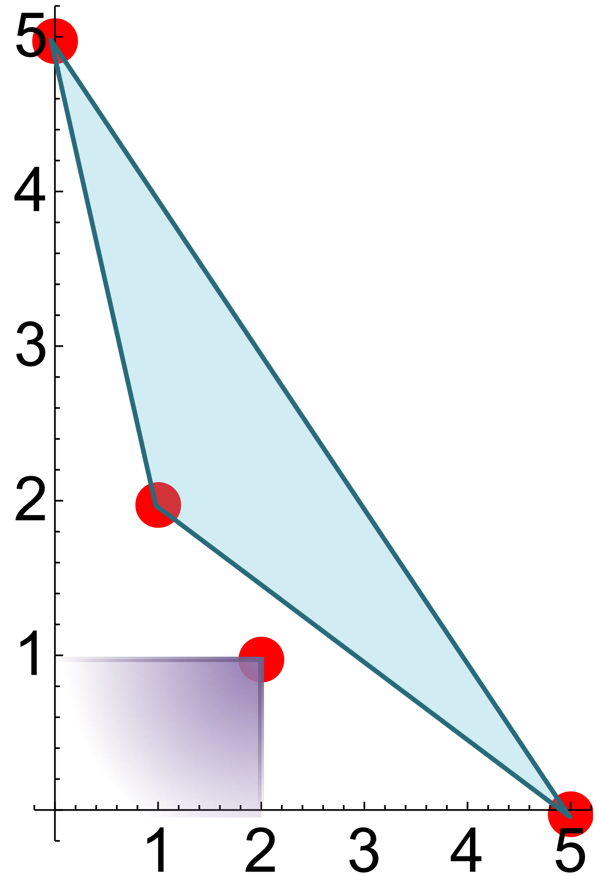


$$\sum_{i=1}^{n} p^i \left(\lambda_{2i-1} + \lambda_{2i}\right) \leq \sum_{i=1}^{n} p^i y_i$$

$$\sum_{i=1}^{2n} \lambda_i = 1, \quad \lambda \in \mathbb{R}^{2n}_{+}$$

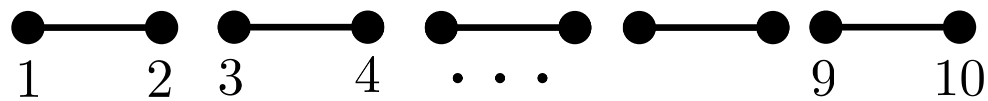
$$\sum_{i=1}^{n} y_i = 1, \quad y \in \mathbb{R}^{n}_{+}$$

$$p^i \in \mathbb{R}^2_+, \quad \operatorname{conv}\left(\left\{p^j\right\}_{j \neq i}\right) \not\leq p^i$$



- Polynomial sized coefficients:
  - $p^i \in \mathbb{Z}^2_+, \quad \left\|p^i\right\|_\infty \leq 5^{\lceil (n-2)/2 \rceil}$

Formulation for Disjoint Case

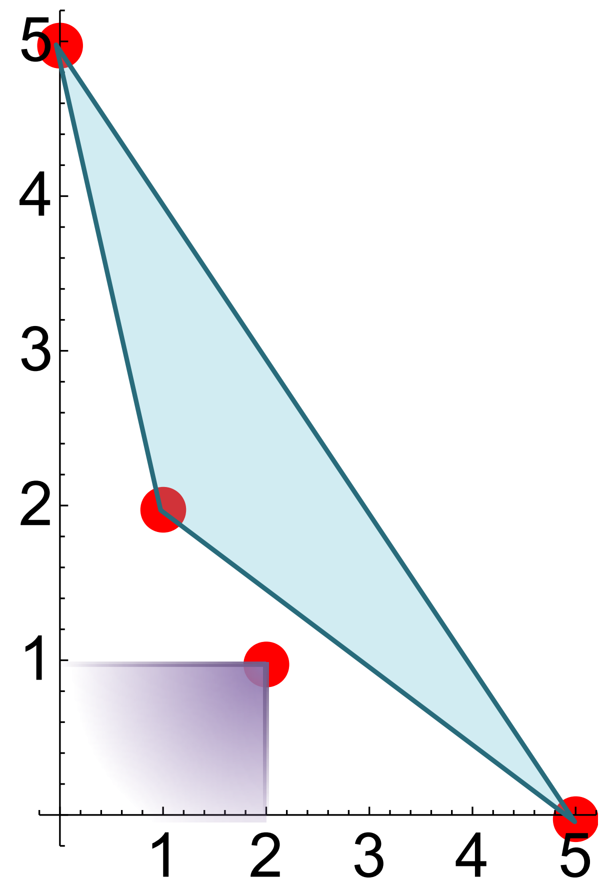


$$\sum_{i=1}^{n} p^i (\lambda_{2i-1} + \lambda_{2i}) \leq \sum_{i=1}^{n} p^i y_i$$

$$\sum_{i=1}^{2n} \lambda_i = 1, \quad \lambda \in \mathbb{R}_+^{2n}$$

$$\sum_{i=1}^{n} y_i = 1, \quad y \in \mathbb{R}_+^{n}$$

$$p^i \in \mathbb{R}_+^2, \quad \operatorname{conv}\left(\{p^j\}_{j \neq i}\right) \not\ni p^i$$



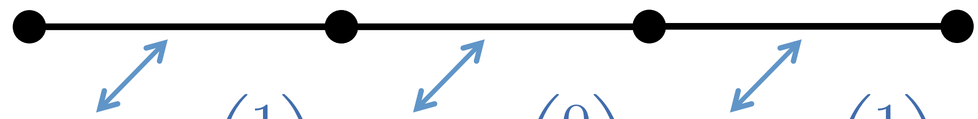
- Polynomial sized coefficients:
  - $p^i \in \mathbb{Z}_+^2, \quad \|p^i\|_\infty \leq 5^{\lceil (n-2)/2 \rceil}$
- 80 fractional extreme points for n = 5

Embedding Complexity: $\mathrm{size}\left(Q\left(H\right)\right)$ for SOS2

Embedding Formulation for SOS2: Part 1

- From encodings to hyperplanes:

$$\{h^i\}_{i=1}^{n}$$



$$h^1 = \begin{pmatrix} 1 \\ 1 \end{pmatrix}, \; h^2 = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \; h^3 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

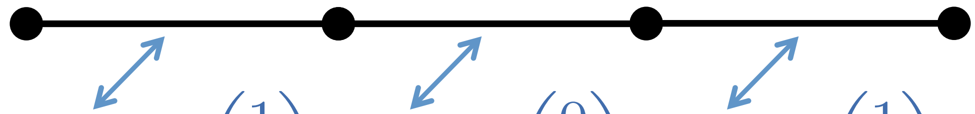
Embedding Formulation for SOS2: Part 1

- From encodings to hyperplanes:

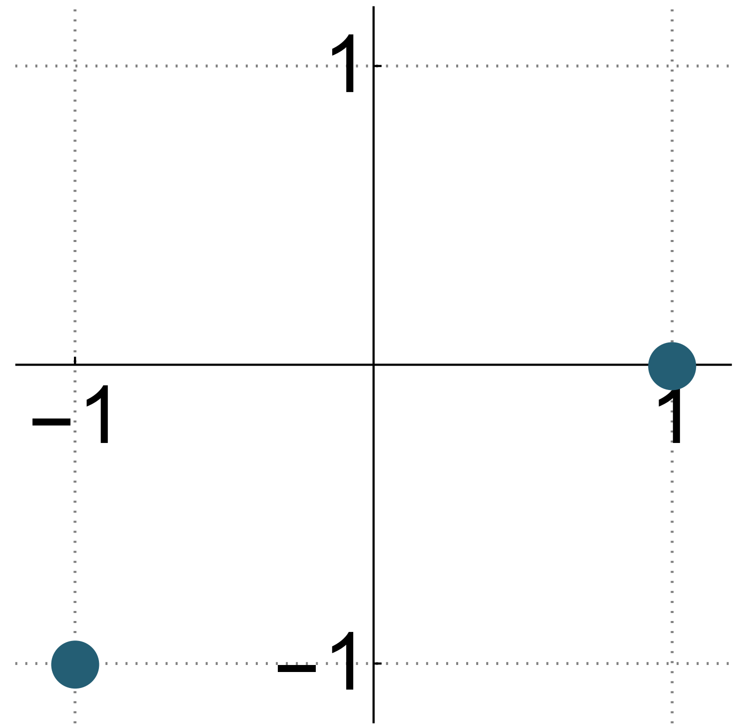
$$\left\{h^i\right\}_{i=1}^{n}$$

$$c^i = h^{i+1} - h^i$$

$$\left\{c^i\right\}_{i=1}^{n-1}$$



$$h^1 = \begin{pmatrix}1\\1\end{pmatrix},\ h^2 = \begin{pmatrix}0\\0\end{pmatrix},\ h^3 = \begin{pmatrix}1\\0\end{pmatrix}$$



Embedding Formulation for SOS2: Part 1

- From encodings to hyperplanes:

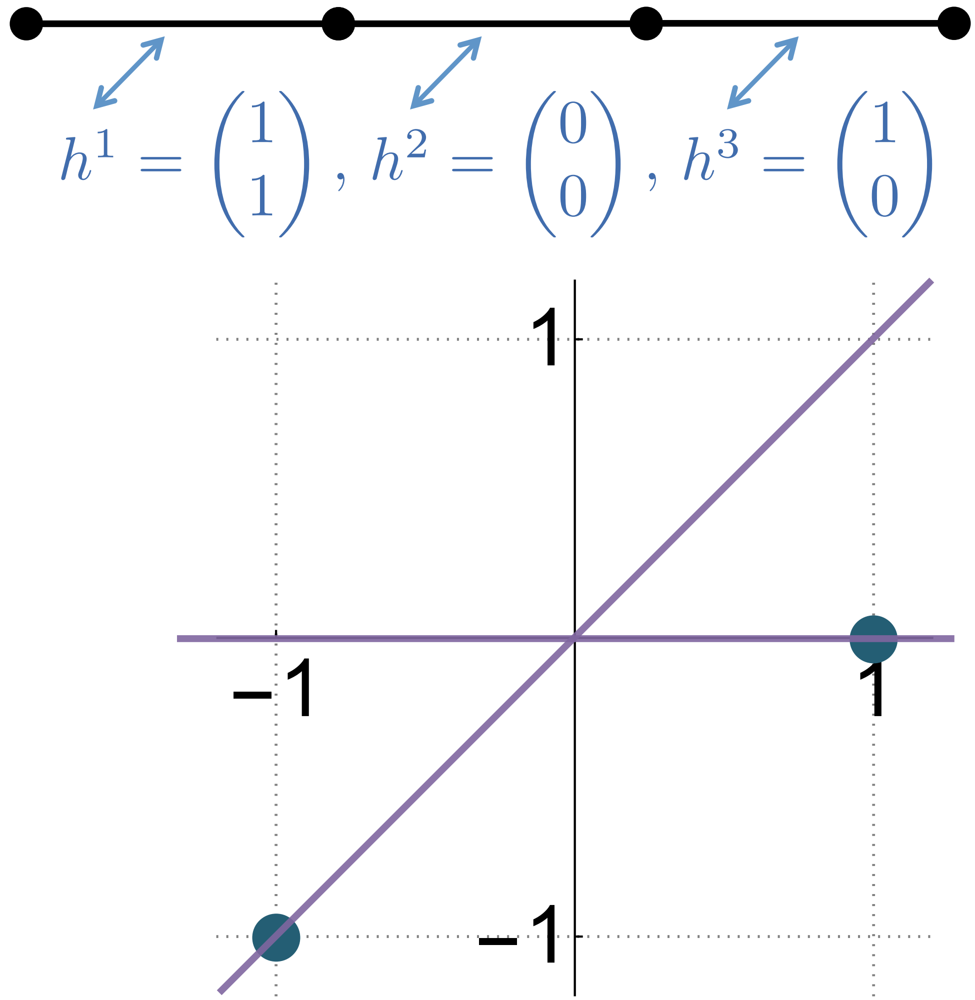
$$\{h^i\}_{i=1}^{n}$$

$$c^i = h^{i+1} - h^i$$

$$\{c^i\}_{i=1}^{n-1}$$

Hyperplanes spanned by

$$\{b^i \cdot y = 0\}_{j=1}^{L}$$



Embedding Formulation for SOS2: Part 2

$$\left\{b^i \cdot y = 0\right\}_{j=1}^{L}$$

$$L\left(H\right) := \text{aff}\left(H\right) - h^1$$

$$Q(H) =$$

$$\left(b^j \cdot h^1\right)\lambda_1 + \sum_{i=2}^{n} \min\left\{b^j \cdot h^i, b^j \cdot h^{i-1}\right\}\lambda_i + \left(b^j \cdot h^n\right)\lambda_{n+1} \leq \quad b^j \cdot y \quad \forall j$$

$$-\left(b^j \cdot h^1\right)\lambda_1 - \sum_{i=2}^{n} \max\left\{b^j \cdot h^i, b^j \cdot h^{i-1}\right\}\lambda_i - \left(b^j \cdot h^n\right)\lambda_{n+1} \leq -b^j \cdot y \quad \forall j$$

$$\sum_{i=1}^{n+1} \lambda_i = 1, \quad \lambda \in \mathbb{R}_+^{n+1}$$

$$y \in L(H)$$

- # general inequalities = 2 × # of hyperplanes

Embedding Complexity for SOS2

Embedding Complexity for SOS2

- Unary encoding (Padberg / Lee and Wilson, early 00's):

$$\text{size}_G\left(Q\left(H\right)\right) = 2(n-1), \quad \text{size}\left(Q\left(H\right)\right) = 2n$$

Embedding Complexity for SOS2

- Unary encoding (Padberg / Lee and Wilson, early 00's):

$$\text{size}_G\left(Q\left(H\right)\right) = 2(n-1), \quad \text{size}\left(Q\left(H\right)\right) = 2n$$

- **Smallest Binary** encoding (V. and Nemhauser '08, Muldoon '12):

$$\text{size}_G\left(Q\left(H\right)\right) = 2\left\lceil \log_2 n \right\rceil,$$

$$2 + 2\left\lceil \log_2 n \right\rceil \leq \text{size}\left(Q\left(H\right)\right) \leq n + 1 + 2\left\lceil \log_2 n \right\rceil$$

Embedding Complexity for SOS2

- Unary encoding (Padberg / Lee and Wilson, early 00's):

$$\text{size}_G(Q(H)) = 2(n-1), \quad \text{size}(Q(H)) = 2n$$

- **Smallest Binary** encoding (V. and Nemhauser '08, Muldoon '12):

$$\text{size}_G(Q(H)) = 2\lceil \log_2 n \rceil,$$

$$2 + 2\lceil \log_2 n \rceil \leq \text{size}(Q(H)) \leq n + 1 + 2\lceil \log_2 n \rceil$$

- Adding lower bounds (# hyperplanes ≥ dimension):

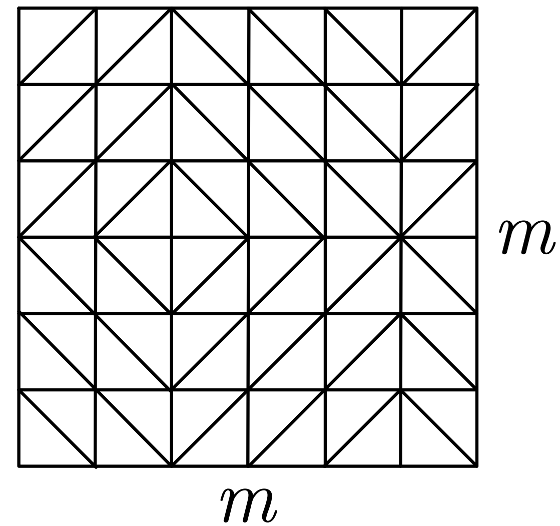
$$\text{mc}_G(\mathcal{P}) = 2\lceil \log_2 n \rceil,$$

$$n + 1 \leq \text{xc}(\mathcal{P}) \leq \text{mc}(\mathcal{P}) \leq n + 1 + 2\lceil \log_2 n \rceil$$

Practical Constructions for Multivariate Piecewise Linear Functions

Formulations and Complexity for Triangulations

$$n = 2m^2$$

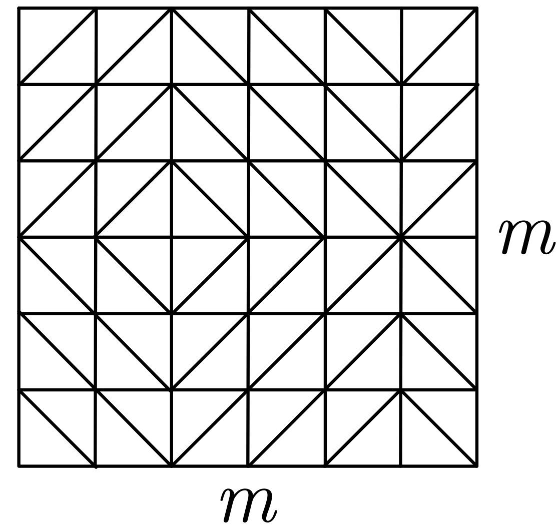


Formulations and Complexity for Triangulations

- Lower bound:

$$\left(\sqrt{n/2}+1\right)^2 \leq \mathrm{mc}\left(\mathcal{P}\right)$$

$$n = 2m^2$$



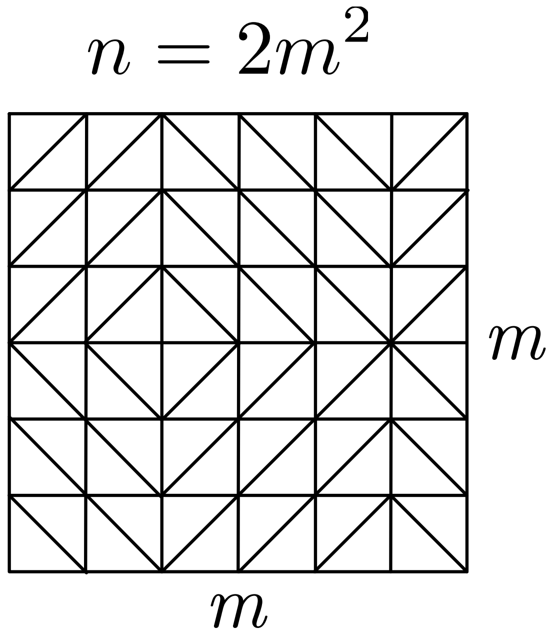
Formulations and Complexity for Triangulations

- Lower bound:

$$\left(\sqrt{n/2}+1\right)^2 \leq \mathrm{mc}\left(\mathcal{P}\right)$$

- Size of unary formulation is:
  (Lee and Wilson '01)

$$\mathrm{mc}\left(\mathcal{P}\right) \leq \binom{2\sqrt{n/2}}{\sqrt{n/2}} + \left(\sqrt{n/2}+1\right)^2$$



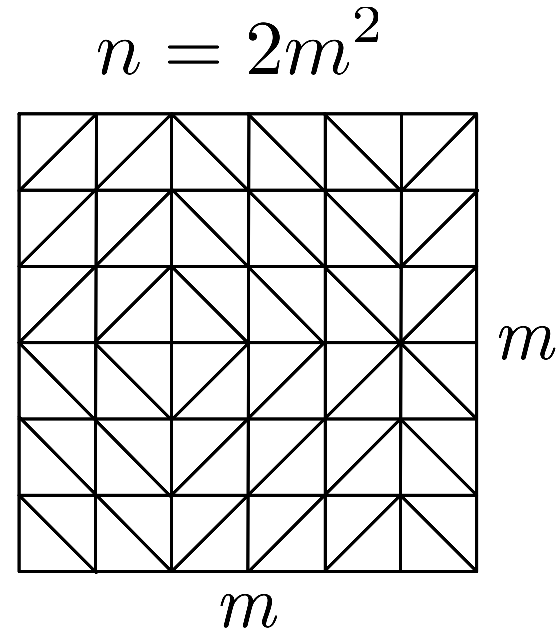
Formulations and Complexity for Triangulations

- Lower bound:

$$\left(\sqrt{n/2}+1\right)^2 \leq \mathrm{mc}\left(\mathcal{P}\right)$$

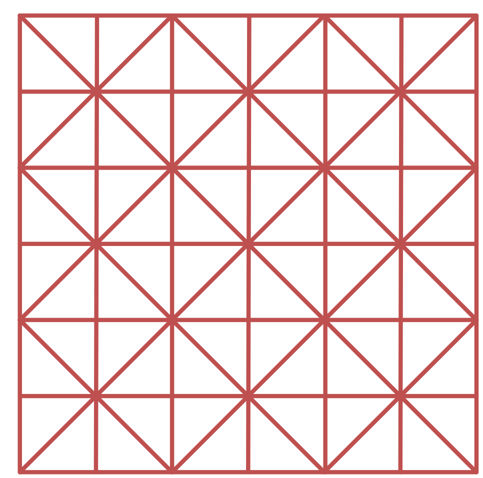
- Size of unary formulation is:
  (Lee and Wilson '01)

$$\mathrm{mc}\left(\mathcal{P}\right) \leq \binom{2\sqrt{n/2}}{\sqrt{n/2}} + \left(\sqrt{n/2}+1\right)^2$$



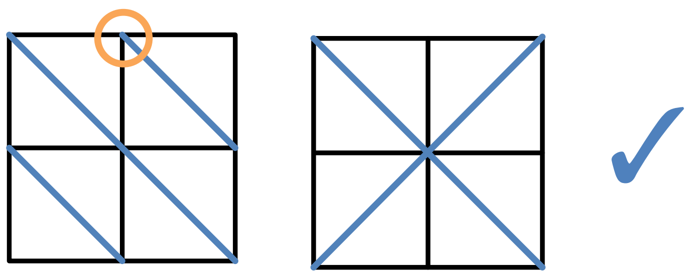
- Small binary formulation for union jack triangulation of size:
  (V. and Nemhauser '08)

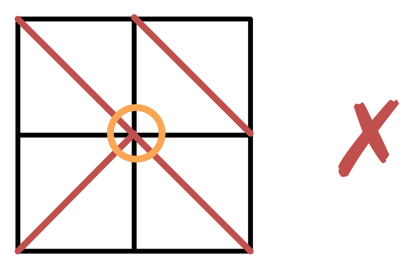
$$\mathrm{mc}\left(\mathcal{P}\right) \leq 4\log_2\sqrt{n/2}+2+\left(\sqrt{n/2}+1\right)^2$$



Beyond Union Jack: Exploit Redundancy

- **Embedding-like** formulation for triangulations with "even degree outside the boundary"





- Formulation size slightly larger than for union jack:

$$4\log_2\sqrt{n/2}+4+\left(\sqrt{n/2}+1\right)^2$$

- Formulation fits **independent branching** framework (V. and Nemhauser '08)

Summary

- Embedding Formulations = Systematic procedure
  - Encoding can significantly affect size
- Complexity of Union of Polyhedra beyond convex hull
  - Embedding Complexity (non-extended ideal formulation)
  - Relaxation Complexity (any non-extended formulation)
  - Still open questions on relations between complexity
- More details (practical formulation construction)
  - Embedding Formulations and Complexity for Unions of Polyhedra, arXiv:1506.01417
- Application to facility layout problem (Huchette, Dey, V. '14)
  - INFORMS 2015, Philadelphia, Nov 2nd
- Extension to unions of convex sets = representability (Soon ☺)