Cutting Planes in SCIP

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Outline

General cutting planes

- Complemented mixed integer rounding cuts
- Gomory mixed integer cuts
- Strong Chvátal-Gomory cuts
- Implied bound cuts

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- 0-1 single node flow problem
- Stable set problem

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I want to solve general MIPs!
Why do I care about cutting planes for special problems?

$$\min\{c^T x : x \in X^{MIP}\} \qquad X^{MIP} := \{x \in \mathbb{Z}^n \times \mathbb{R}^m : Ax \leq b\}$$
$$\min\{c^T x : x \in X^{LP}\} \qquad X^{LP} := \{x \in \mathbb{R}^n \times \mathbb{R}^m : Ax \leq b\}$$

General Cutting Plane Method

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Observation

- If the data are rational, then
  - $\text{conv}(X^{MIP})$ is a rational polyhedron
  - we can formulate the MIP as $\underbrace{\min\{c^T x : x \in \text{conv}(X^{MIP})\}}_{\text{LP}}$

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Problem (in general)

- Complete linear description of $\text{conv}(X^{MIP})$?
- Number of constraints needed to describe $\text{conv}(X^{MIP})$ is extremely large

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Idea

- Construct a polyhedron Q with
  - $\text{conv}(X^{MIP}) \subseteq Q \subseteq X^{LP}$
  - $\min\{c^T x : x \in \text{conv}(X^{MIP})\} = \min\{c^T x : x \in Q\}$

$\rightsquigarrow$ Start with X^{LP} and add inequalities which are valid for X^{MIP} (but violated by the current LP solution) to X^{LP}

Valid Inequalities for X^{MIP}

- Inequalities valid for a relaxation of X^{MIP} are valid for X^{MIP}
- Generating valid inequalities for a relaxation is often easier
- The intersection of the relaxations should be a good approximation of X^{MIP}

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Relaxations of X^{MIP}

1. Linear combinations of constraints defining X^{MIP}
   (row of the simplex tab., single constraint)
2. Other information
   - Logical implications between binary variables
     (conflict graph)
   - Logical implications between a binary and a real variable

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- Implied bound cuts (Logical impl.)

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Cutting planes for special problems

- 0-1 knapsack problem (Single constraint)
- 0-1 single node flow problem (Linear comb. and bounds)
- Stable set problem (Conflict graph)

0-1 Knapsack Polytope

$\text{conv}(X^{BK})$ $$X^{BK} := \{x \in \{0,1\}^n : \sum_{j \in N} a_j x_j \leq a_0\}$$

- $N = \{1, \ldots, n\}$
- a_0 and a_j are integers for all $j \in N$

- $a_j > 0$ for all $j \in N$
  (since binary variables can be complemented)
- $a_j \leq a_0$ for all $j \in N$
  (since $a_j > a_0$ implies $x_j = 0$)

Definition (Cover)

$C \subseteq N$ ▷ $\sum_{j \in C} a_j > a_0$

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Theorem

*If $C \subseteq N$ is a cover for X^{BK}, then the **cover inequality***

$$\sum_{j \in C} x_j \leq |C| - 1$$

is valid for X^{BK}.

Let $x^* \in [0,1]^n \setminus \{0,1\}^n$ be a fractional vector with $\sum_{j \in N} a_j x_j^* \leq a_0$.

Find $C \subseteq N$ with $\sum_{j \in C} a_j > a_0$ such that

$$\sum_{j \in C} x_j^* > |C| - 1,$$

or show that no inequality in the **class of cover inequalities** is violated by x^*.

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or show that no inequality in the **class of cover inequalities** is violated by x^*.

The separation problem can be formulated as a 0-1 KP.

Separation Problem as 0-1 KP

For $C \subseteq N$, we introduce the characteristic vector $z \in \{0, 1\}^n$.

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Cover

$$\sum_{j \in C} a_j > a_0 \iff \sum_{j \in N} a_j z_j > a_0$$

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$$\begin{aligned}\sum_{j \in C} a_j > a_0 \quad &\Leftrightarrow \sum_{j \in N} a_j z_j > a_0 \\ &\Leftrightarrow \sum_{j \in N} a_j z_j \geq a_0 + 1\end{aligned}$$

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Violated cover inequality

$$\sum_{j \in C} x_j^* > |C| - 1 \quad \Leftrightarrow \quad \sum_{j \in N} x_j^* z_j > \sum_{j \in N} z_j - 1$$
$$\Leftrightarrow \quad \sum_{j \in N} (1 - x_j^*) z_j < 1$$

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x^* satisfies all cover inequalities

$$\Leftrightarrow \ \forall \ z \in \{0,1\}^n \ \text{with} \ \sum_{j \in N} a_j z_j \geq a_0 + 1 : \sum_{j \in N} (1 - x_j^*) z_j \geq 1$$

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$$\Leftrightarrow \ \min\{\sum_{j \in N} (1 - x_j^*) z_j : \sum_{j \in N} a_j z_j \geq a_0 + 1, \quad z \in \{0,1\}^n \ \} \geq 1$$

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$$\Leftrightarrow \min\{\sum_{j \in N} (1 - x_j^*) z_j : \sum_{j \in N} a_j z_j \geq a_0 + 1, \; z \in \{0,1\}^n \} \geq 1$$

$$\Leftrightarrow \max\{\sum_{j \in N} (1 - x_j^*) \bar{z}_j : \sum_{j \in N} a_j \bar{z}_j \leq \sum_{j \in N} a_j - (a_0 + 1), \; \bar{z} \in \{0,1\}^n \} \geq 1 - \sum (1 - x_j^*)$$

Heuristic for the 0-1 KP

Input : $c \in \mathbb{Q}_+^n$, $a \in \mathbb{Q}_+^n \setminus \{0\}$, and $b \in \mathbb{Q}_+$

Output: Feasible solution of $\max\{c^T x : a^T x \leq b, x \in \{0,1\}^n\}$

```
Sort the indices such that c_1/a_1 ≥ ... ≥ c_n/a_n
ā ← 0
for j ← 1 to n do
    if ā + a_j ≤ b then
        x_j ← 1
        ā ← ā + a_j
    else
        while j ≤ n do
            x_j ← 0
            j ← j + 1
return x
```

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Sort the indices such that $\frac{c_1}{a_1} \geq \ldots \geq \frac{c_n}{a_n}$
$\bar{a} \leftarrow 0$
for $j \leftarrow 1$ **to** n **do**
  if $\bar{a} + a_j \leq b$ **then**
    $x_j \leftarrow 1$
    $\bar{a} \leftarrow \bar{a} + a_j$
  else
    while $j \leq n$ **do**
      $x_j \leftarrow 0$
      $j \leftarrow j + 1$
return x

Solves the LP relaxation and rounds down the solution.

Heuristic for the 0-1 KP

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$\bar{a} \leftarrow 0$

for $j \leftarrow 1$ **to** n **do**

    if $\bar{a} + a_j \leq b$ **then**

        $x_j \leftarrow 1$

        $\bar{a} \leftarrow \bar{a} + a_j$

    else

        while $j \leq n$ **do**

            $x_j \leftarrow 0$

            $j \leftarrow j + 1$

return x

Time complexity: $O(n \log n)$

Input : $c \in \mathbb{Q}_+^n$, $a \in \mathbb{Z}_+^n \setminus \{0\}$, and $b \in \mathbb{Z}_+$
Output: Optimal solution of $\max\{c^T x : a^T x \leq b, x \in \{0,1\}^n\}$

Algorithm uses dynamic programming

Input : $c \in \mathbb{Q}^n_+$, $a \in \mathbb{Z}^n_+ \setminus \{0\}$, and $b \in \mathbb{Z}_+$
Output: Optimal solution of $\max\{c^T x : a^T x \leq b, x \in \{0,1\}^n\}$

Algorithm uses dynamic programming

Time complexity: $O(nb)$

- A separator for cover cuts has only a limited effect on the overall performance of SCIP
- It seems to be important to separate strong cutting planes (facets or at least faces of reasonably high dimension)

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- It seems to be important to separate strong cutting planes (facets or at least faces of reasonably high dimension)

Can we strengthen the cover inequalities?

Definition (Minimal cover)

$C \subseteq N$

- $\sum_{j \in C} a_j > a_0$
- $\sum_{j \in C \setminus \{i\}} a_j \leq a_0$ for all $i \in C$

Class of Minimal Cover Inequalities

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Theorem

If $C \subseteq N$ is a minimal cover for X^{BK}, then the ***minimal cover inequality***

$$\sum_{j \in C} x_j \leq |C| - 1$$

defines a facet of

$$conv(\ X^{BK} \bigcap \{x \in \{0,1\}^n \ :\ x_j = 0 \ \ for\ all\ \ j \in N \setminus C\}\ ).$$

Sequential Up-Lifting

- $(j_1, \ldots, j_t)$ lifting sequence of the variables in $N \backslash C$
- $X^i := X^{BK} \bigcap \{x \in \{0,1\}^n : x_{j_{i+1}} = \ldots = x_{j_t} = 0\}$

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- $X^i := X^{BK} \bigcap \{x \in \{0,1\}^n : x_{j_{i+1}} = \ldots = x_{j_t} = 0\}$

$$
\begin{aligned}
\sum_{j \in C} x_j &\leq |C| - 1 \quad \text{valid for } X^0 \\
\sum_{j \in C} x_j + \alpha_{j_1} x_{j_1} &\leq |C| - 1 \quad \text{valid for } X^1 \\
&\vdots \\
\sum_{j \in C} x_j + \sum_{k=1}^{t} \alpha_{j_k} x_{j_k} &\leq |C| - 1 \quad \text{valid for } X^t = X^{BK}
\end{aligned}
$$

- $(j_1, \ldots, j_t)$ lifting sequence of the variables in $N \setminus C$
- $X^i := X^{BK} \bigcap \{x \in \{0,1\}^n : x_{j_{i+1}} = \ldots = x_{j_t} = 0\}$

Theorem

For each $i = 1, \ldots, t$, consider the 0-1 knapsack problem

$$z_{j_i} = \max\{\sum_{j \in C} x_j + \sum_{k=1}^{i-1} \alpha_{j_k} x_{j_k} \ : \ \sum_{j \in C} a_j x_j + \sum_{k=1}^{i-1} a_{j_k} x_{j_k} \leq a_0 - a_{j_i}, \ x \in \{0,1\}^{|C|+(i-1)}\}$$

and let $\alpha_{j_i} = (|C| - 1) - z_{j_i}$. Then for each $i = 1, \ldots, t$,

$$\sum_{j \in C} x_j + \sum_{k=1}^{i} \alpha_{j_k} x_{j_k} \leq |C| - 1$$

defines a facet of conv(X^i).

- $(j_1, \ldots, j_t)$ lifting sequence of the variables in $N \setminus C$
- $X^i := X^{BK} \bigcap \{x \in \{0,1\}^n : x_{j_{i+1}} = \ldots = x_{j_t} = 0\}$

Different lifting sequences may lead to different inequalities!

Computing the Lifting Coefficients

- For each $i = 1, \ldots, t$, solve the 0-1 KP
  - approximately ($O(n \log n)$)
  - exactly ($O(nb)$)
- Zemel: Exact algo to calculate all lifting coefficients ($O(n^2)$)
  - Uses dynamic programming to solve a reformulation of the 0-1 KPs
    (role of the objective function and the constraint is reversed)

- Using sequential up-lifting to strengthen minimal cover cuts improves the performance of SCIP

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But, a separator which uses up- and down-lifting performs even better!

Theorem

If $C \subseteq N$ is a minimal cover for X^{BK}, then the ***minimal cover inequality***

$$\sum_{j \in C} x_j \leq |C| - 1$$

defines a facet of

$$conv(\ X^{BK} \bigcap \{x \in \{0,1\}^n \ : \ x_j = 0 \ \ for\ all\ \ j \in N \backslash C\}\ ).$$

$\rightsquigarrow$ Up-lifting: variables in $N \backslash C$

Class of Minimal Cover Inequalities

Theorem

If $C \subseteq N$ is a minimal cover for X^{BK} and (C_1, C_2) is any partition of C with $C_1 \neq \emptyset$, then inequality

$$\sum_{j \in C_1} x_j \leq |C_1| - 1$$

defines a facet of

$$conv(X^{BK} \bigcap \{x \in \{0,1\}^n \ : \ x_j = 0 \ \ for\ all\ \ j \in N \backslash C, \\ x_j = 1 \ \ for\ all\ \ j \in C_2\} \ ).$$

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If $C \subseteq N$ is a minimal cover for X^{BK} and (C_1, C_2) is any partition of C with $C_1 \neq \emptyset$, then inequality

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defines a facet of

$$\begin{aligned} conv(\ X^{BK} \bigcap \{x \in \{0,1\}^n \ :\ & x_j = 0 \ \text{ for all } \ j \in N \backslash C, \\ & x_j = 1 \ \text{ for all } \ j \in C_2\} \ ). \end{aligned}$$

$\rightsquigarrow$ Up-lifting: variables in $N \backslash C$

$\rightsquigarrow$ Down-lifting: variables in C_2

Sequential Up- and Down-Lifting

- Similar theorem as for sequential up-lifting
- Extension of Zemel's up-lifting procedure can be used
- In SCIP, the separation problem for the **class of lifted minimal cover inequalities using sequential up- and down-lifting** is solved heuristically

Outline of the Separation Algorithm

Step 1 (Cover)

- Determine a cover C for X^{BK}
  (separation problem for the class of cover inequalities)

Step 2 (Minimal cover and partition)

- Make the cover minimal by removing vars from C
- Find a partition (C_1, C_2) of C with $C_1 \neq \emptyset$

Step 3 (Lifting)

- Determine a lifting sequence of the variables in $N \setminus C_1$
- Lift the inequality $\sum_{j \in C_1} x_j \leq |C_1| - 1$ using sequential up- and down-lifting

Step 1 (Cover)

- Which algorithm do we use to find the cover?
  - Fixing of variables
  - Modification of the separation problem (Gu et al. (1998))
  - Solving the separation problem exactly or approximately

Step 2 (Minimal cover and partition)

- In which order do we remove the variables?
- Which partition of the minimal cover do we use?

Step 3 (Lifting)

- Which lifting sequence do we use?
- Which algorithm do we use to solve the knapsack problems that occur in the sequential lifting procedure?

Step 1 (Cover)

- Fix all vars with $x_j^* = 0$ to zero and all vars with $x_j^* = 1$ to one
- Use the modification of the separation problem
- Solve the modified separation problem approximately

Step 2 (Minimal cover and partition)

- Nondecreasing order of x_j^* and nondecreasing order of a_j
- $C_2 := \{j \in C : x_j^* = 1\}$ ($|C_1| = 1$: change the partition)

Step 3 (Lifting)

- $\{j \in N \backslash C : x_j^* > 0\}$, C_2, and then $\{j \in N \backslash C : x_j^* = 0\}$ (nonincreasing order of a_j)
- Use an extension of Zemel's procedure

	Gap Closed % (Geom. Mean)		Sepa Time sec (Total)	
	Value	△	Value	△
Default algorithm	16.31	0.00	1355.9	0.0
Resulting algorithm	16.36	0.05	7.4	-1348.5

	Gap Closed % (Geom. Mean)		Sepa Time sec (Total)	
	Value	△	Value	△
Default algorithm	16.31	0.00	1355.9	0.0
Cover – 1. modification	15.61	-0.70	7.6	-1348.3
Resulting algorithm	16.36	0.05	7.4	-1348.5

- Determination of the cover
  - Solve the separation problem approximately

	Gap Closed % (Geom. Mean)		Sepa Time sec (Total)	
	Value	△	Value	△
Default algorithm	16.31	0.00	1355.9	0.0
Cover – 1. modification	15.61	-0.70	7.6	-1348.3
Cover – 2. modification	16.42	0.11	7.1	-1348.8
Resulting algorithm	16.36	0.05	7.4	-1348.5

- Determination of the cover
  - Solve the separation problem approximately
  - Modification of the separation problem

Comparison with other MIP solvers

- Are the cutting plane separators implemented in SCIP competitive to the ones included in other MIP solvers?

MIP solvers

- SCIP (CPLEX as LP solver)
- CPLEX
- COIN-OR Branch and Cut solver (COIN-OR LP solver)

Computational Study

MIP solvers

- SCIP (CPLEX as LP solver)
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Settings

- One cutting plane separator
- Isolated application
- Presolving disabled (used presolved instances obtained by the presolving routines of CPLEX)

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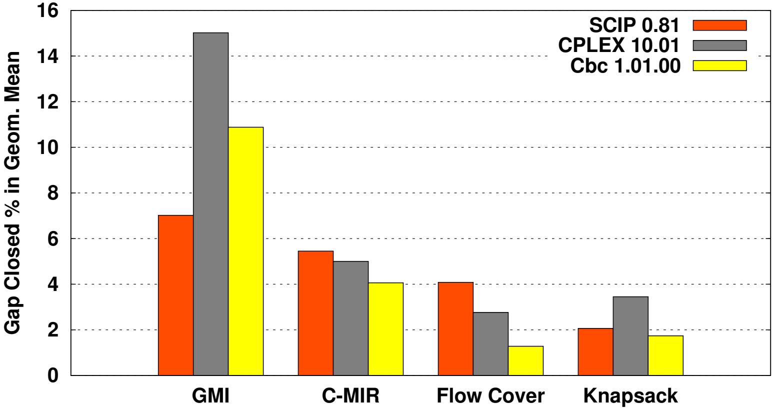
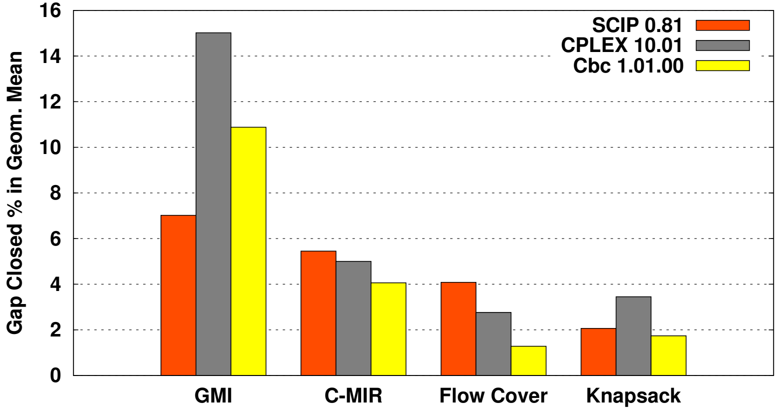
Test set

- 134 instances (MIPLIB 2003, MIPLIB 3.0, and MIP collection of Mittelmann)



Performance measure   Gap Closed % $\left(100 \cdot \frac{db - z_{LP}}{z_{MIP} - z_{LP}}\right)$

Computational Results



Knapsack

CPLEX: Time in total $\approx 9,400$ sec

SCIP and CBC: Time in total ≈ 600 sec

Impact on the overall performance of SCIP

- How strong is the impact of the individual cutting plane separators on the overall performance of SCIP?

Two Types of Tests

Impact of the individual cutting plane separators when they are used

as the only separators in SCIP

1. Started with running SCIP without any separators
2. Compared the performance with the one of SCIP when we enabled one separator

in connection with all other separators of SCIP

1. Started with running SCIP with all separators
2. Compared the performance with the one of SCIP when we disabled one separator

Enabling – Computational Study

Performance measures

- Nodes
- Time
- Gap %

Enabling – Computational Study

Performance measures

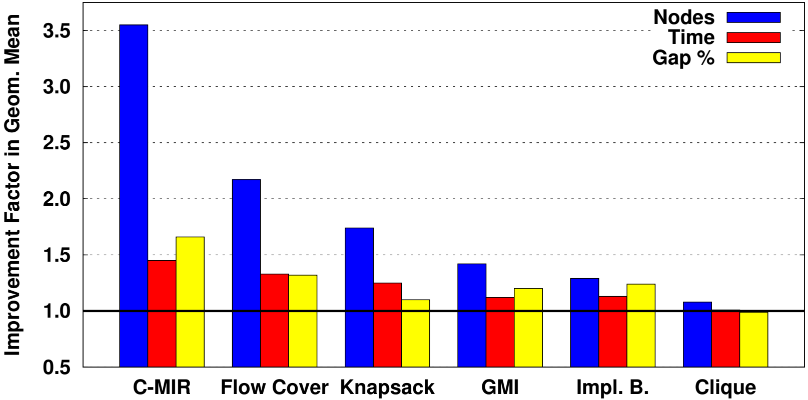
- Nodes
- Time
- Gap %

Improvement factor for each performance measure

$$\frac{\text{Value for SCIP run without any separators}}{\text{Value for SCIP run with one separator enabled}}$$

$\rightsquigarrow$ Factor by which enabling the separator improves the overall performance (Factor > 1?)

Enabling – Computational Results



Performance measures

- Nodes
- Time
- Gap %

Performance measures

- ▷ Nodes
- ▷ Time
- ▷ Gap %

Degradation factor for each performance measure

$$\frac{\text{Value for SCIP run with one separator disabled}}{\text{Value for SCIP run with all separators}}$$

⇝ Factor by which disabling the separator degrades the overall performance (Factor >1?)

Disabling – Computational Results