Incremental Lower Bounds for Additive Cost Planning Problems

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ICAPS 2012

Australian Government
Department of Broadband, Communications and the Digital Economy
Australian Research Council

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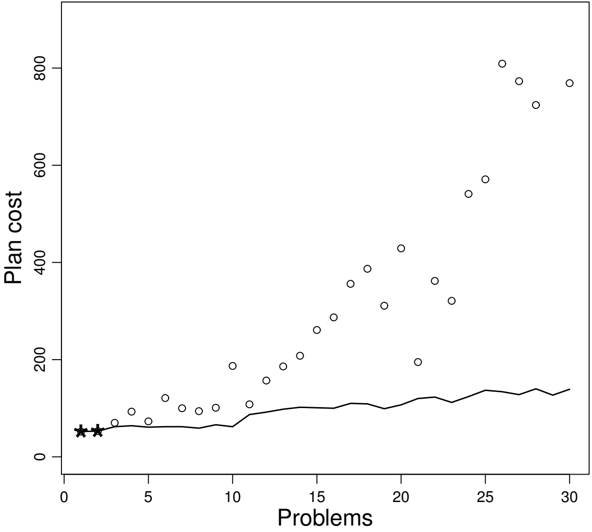
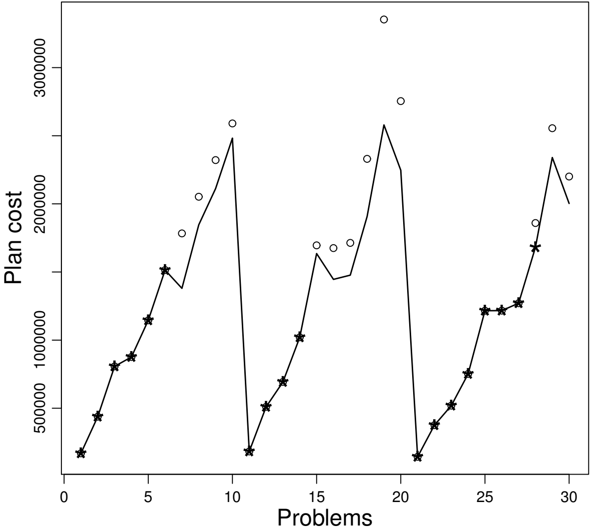
The Plan Quality Gap



Elevators domain, IPC 2008

The Plan Quality Gap



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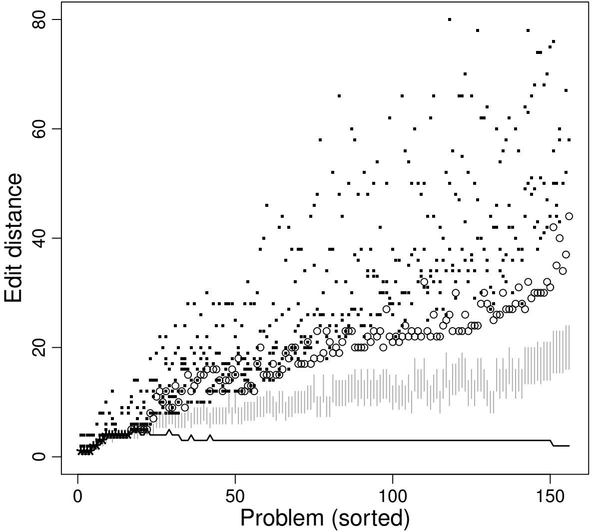
The Plan Quality Gap



Genome Edit Distance

The Plan Quality Gap

- Optimal planners do not scale.
- Non-optimal planners fall far short of achievable plan quality.
- Lack of sufficiently strong lower bounds.

Admissible Heuristics & Search

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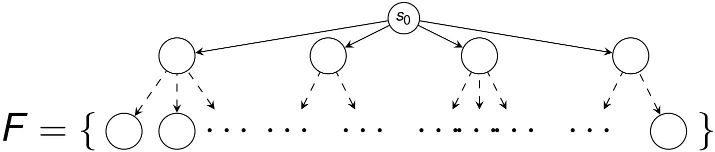
- If h is **admissible**, $h(s_0)$ is a lower bound.
- Strengthening via search (look-ahead):



- $f_{\min} = \min_{s \in F} (\text{cost}(s_0, s) + h(s))$ is also a lower bound.
- Many admissible heuristics for plan cost.

Strengthening via De-Relaxation

- A general idea...

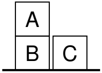
1. Solve a relaxation of the problem, optimally.
2. If the relaxed solution is also a real solution, it is optimal.
3. Else, use hints from the failure of the relaxed solution to strengthen the relaxation, and repeat from 1.

- ...with many instances:
  - Incremental generation of valid cuts in MIP.
  - Counterexample-guided abtraction refinement.
  - **Here:** Delete relaxation of planning problem.

The Delete Relaxation

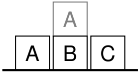
- The delete relaxation, P^+, of a planning problem P is exactly like P except del(a) $= \emptyset$ for each a.
- Relaxation: any plan for P is also valid for P^+.
  - Actions (and goal) require atoms to be *true*.
  - $h^+(s) = h^\star(P^+, s) \leq h^\star(P, s)$.
- Cost-optimal delete relaxed planning is "only" NP-hard (and often feasible in practice).
- No negative interactions in P^+:
  - Combining plans for separate goals always yields a valid plan for their conjunction.
  - This is not true in P.

The Delete Relaxation (example)



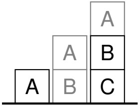
(on-table A)
(on-table B)
(on-table C)
(on A B)
(on A C)
(on B A)
(on B C)
(on C A)
(on C B)
(clear A)
(clear B)
(clear C)

(MoveToT$^+$ A B)
pre: (on A B),
(clear A)
add: (on-table A),
(clear B)



(on-table A)
(on-table B)
(on-table C)
(on A B)
(on A C)
(on B A)
(on B C)
(on C A)
(on C B)
(clear A)
(clear B)
(clear C)

(MoveFromT$^+$ B C)
pre: (on-table B),
(clear B), (clear C)
add: (on B C)



(on-table A)
(on-table B)
(on-table C)
(on A B)
(on A C)
(on B A)
(on B C)
(on C A)
(on C B)
(clear A)
(clear B)
(clear C)

Goal: (on A B),
(on B C)

Strengthening the Relaxation

- The P^C construction:
  - Represent $c = \{p_1, \ldots, p_k\}$ with a new atom π_c
  - Modify problem so π_c is true iff c.
- **Theorem**: $h^\star(P^C) = h^\star(P)$.
- **Theorem**: Let S be an optimal plan for P^+. If S is not valid for P, there is an (efficiently findable) $C = \{c_1, \ldots, c_n\}$ such that S is not valid for $(P^C)^+$.
- **Corollary**: $h^+(P^C) = h^\star(P)$ for large enough C.

The P^C Construction

- Let C be a set of sets of atoms (conjunctions).
- Atoms in P^C: atoms in P and $\{\pi_c \mid c \in C\}$.
- Notation:

$$x^C = x \cup \{\pi_c \mid c \subseteq x\}.$$
$$C^t(a) = \{c \in C \mid c \subseteq (\text{add}(a) \cup \text{pre}(a)) - \text{del}(a)\};$$
$$C^f(a) = \{c \in C \mid c \cap \text{del}(a) \neq \emptyset\};$$
$$C^p(a) = \{c \in C - C^t(a) \mid c \cap \text{add}(a) \neq \emptyset, c \cap \text{del}(a) = \emptyset\};$$
$$C^n(a) = \text{the rest.}$$

- Initial state: s_0^C
- Goal: G^C

The P^C Construction (cont'd)

- Actions in P^C: $\alpha_{a,X}$ with

$$\begin{aligned}
\text{pre}(\alpha_{a,X}) &= \Big(\text{pre}(a) \cup \bigcup_{c \in X} (c - \text{add}(a))\Big)^C \\
\text{add}(\alpha_{a,X}) &= \text{add}(a) \cup \{\pi_c \mid c \in C^t(a) \cup X\} \\
\text{del}(\alpha_{a,X}) &= \text{del}(a) \cup \{\pi_c \mid c \in C^f(a)\} \\
\text{cost}(\alpha_{a,X}) &= \text{cost}(a)
\end{aligned}$$

  for each action a and each $X \subseteq C^p(a)$ (downward closed).
- $|P^C|$ can be exponential in $|C|$.

The P^C Construction (example)

- $c_1 = \{(\text{on A B}), (\text{on B C})\}$, $c_2 = \{(\text{clear B}), (\text{on B C})\}$
- $C = \{c_1, c_2\}$
- $\alpha_{(\text{MoveFromT A B}),\emptyset} \equiv (\text{MoveFromT A B}) + \text{del: } \pi_{c_2}$
- $\alpha_{(\text{MoveFromT A B}),\{c_1\}}$:
  - pre: (on-table A), (clear A), (clear B),
    (on B C), π_{c_2}
  - add: (on A B), π_{c_1}
  - del: (on-table A), (clear B), π_{c_2}

Conflict Extraction: What C?

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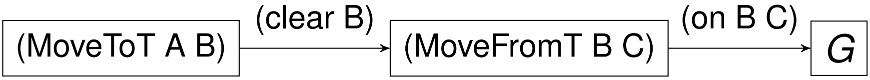
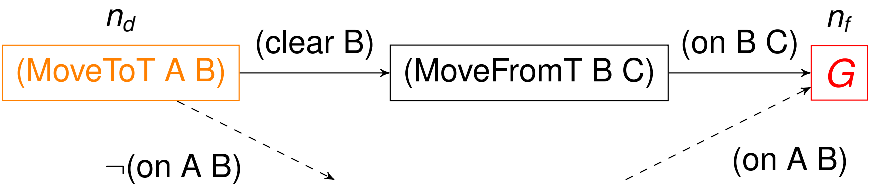
- S is a valid plan for P^+.
- RPDG(S):
  - Graph over $\{n_a \mid a \in S\} \cup \{n_G\}$;
  - $n_a \xrightarrow{l} n'$ iff $l = \text{pre}(n') - R^+(S - \{a\}) \neq \emptyset$.
  - Transitively reduced.
- Example:



Conflict Extraction: What C?

- S is not a valid plan for P:
  - Some $p \in \text{pre}(n_f)$ fails to hold for some n_f.
  - p must have been deleted by some action (associated with n_d) before n_f.
- Example:



Conflict Extraction: What C?

- A **simple dependency path** from n to n' in RPDG(S) is a path with one (arbitrarily chosen) atom p from each edge label.
- A **dependency closure** D from n to n' in RPDG(S) is a minimal (w.r.t. $\subset$) union of paths such that:
  - D contains a simple dependency path from n to n'.
  - For all $n_a \xrightarrow{q} \in D$ and $b \in S$ such that $b \neq a$ and $q \in \text{add}(b)$, D contains a simple dependency path from n to n_b.

Conflict Extraction: What C?

- Case 1: Path in RPDG(S) from n_d to n_f.
  - Let D be a dependency closure from n_d to n_f.
  - $C = \{\{p, q\} \mid q$ labels an edge in $D\}$.
- Case 2: No path in RPDG(S) from n_d to n_f.
  - Let n_c be the first-in-S common descendant of n_d and n_f.
  - Let D_{n_d}, D_{n_f} be dependency closures from n_d to n_c and n_f to n_c.
  - $C = \{\{q, q'\} \mid q$ labels an edge in D_{n_d}, $q' = p$ or q' labels an edge in $D_{n_f}\}$.

Case 1:

$$n_d \xrightarrow[q_1]{} n_1 \xrightarrow[q_2]{} \cdots \xrightarrow[q_{m-1}]{} n_{m-1} \xrightarrow{q_m} n_f \xleftarrow{p}$$

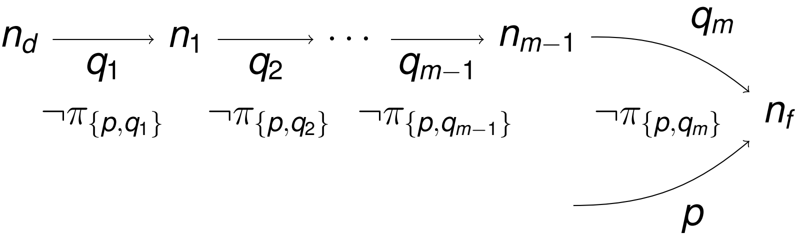
Case 2:

$$n_d \xrightarrow[q_1]{} n_1 \xrightarrow[q_2]{} \cdots \xrightarrow[q_{m-1}]{} n_{m-1} \xrightarrow{q_m} n_c$$

$$\xrightarrow[p]{} n_f \xrightarrow[q'_1]{} n'_1 \xrightarrow[q'_2]{} \cdots \longrightarrow n'_{l-1} \xrightarrow{q'_l} n_c$$

Why It Works

Case 1:



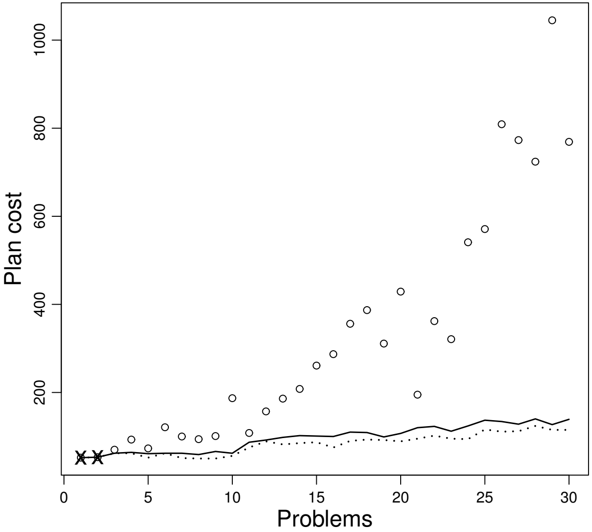
- No representative of a_d adds $\pi_{\{p,q_1\}}$ because $p \in \text{del}(a_d)$.
- Any representative of a_i that adds $\pi_{\{p,q_i\}}$ requires $\pi_{\{p,q_{i-1}\}}$.
- $\pi_{\{p,q_m\}} \in \text{pre}(n_f)$ cannot hold.

h^{++}

1. Compute an optimal plan S for P^+.
2. If S is valid for P, done (optimal plan).
3. If S is not valid for P, find C as above, set $P \coloneqq P^C$ and repeat from 1.

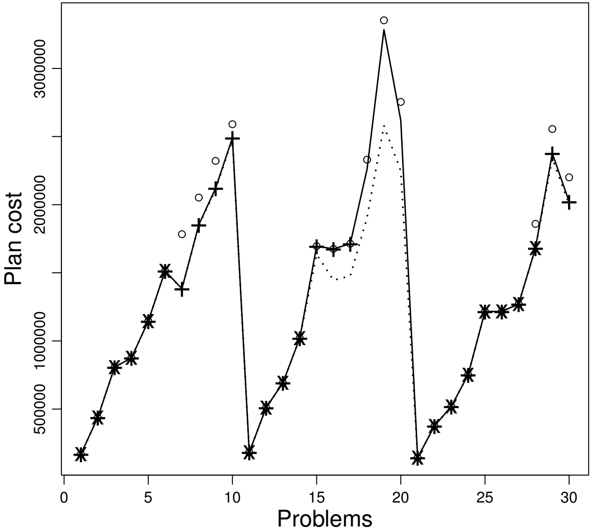
- How to compute S?
  - Iterative landmark-based algorithm.
    - Advantage: Anytime lower bound on h^+.
  - Reduction to weighted MaxSAT.
  - Specialisations of (heuristic) search.

Results



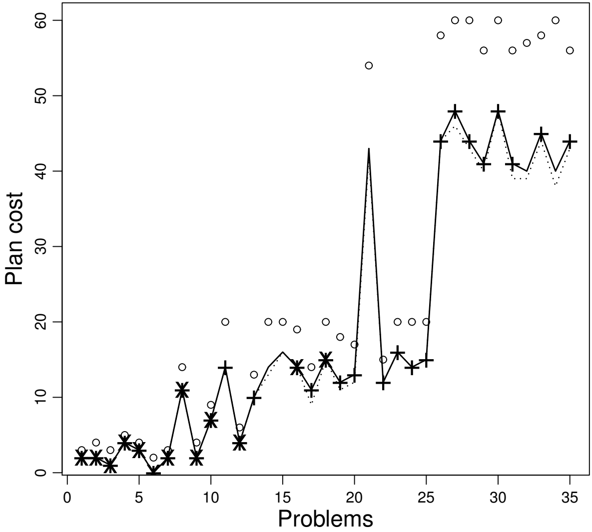
Elevators domain, IPC 2008

Results



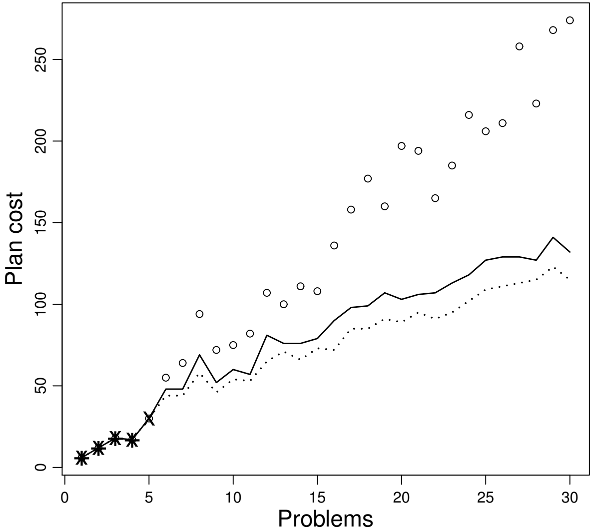
ParcPrinter domain, IPC 2008

Results



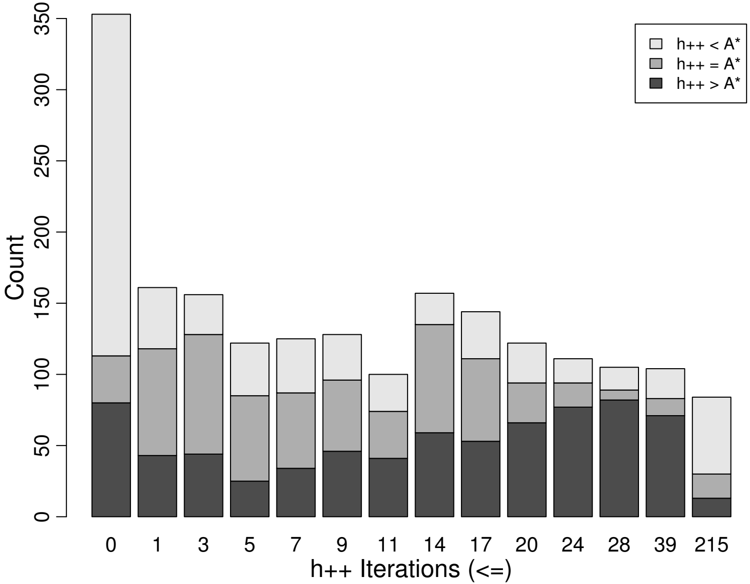
Power Network Alarm Processing domain

Results



Pathways Domain, IPC 2006

Results



h++ < A*
h++ = A*
h++ > A*
Count
0
50
100
150
200
250
300
350
0
1
3
5
7
9
11
14
17
20
24
28
39
215
h++ Iterations (<=)

Conclusions

- Finding good plans and proving good lower bounds are different problems – and should be attacked with different methods.
- The gap remains.
  - Current & future work: Finding better plans.
  - Apply iterative strengthening to abstractions.
- Planning can learn from other areas of optimisation.