Sequencing Operator Counts

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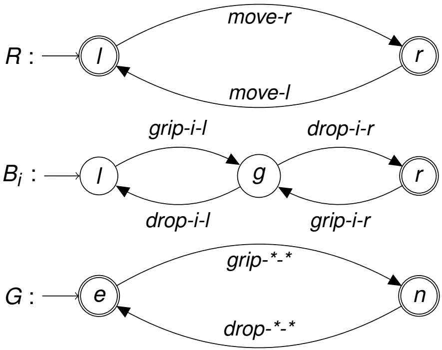
The Planning Problem

Find a sequence of operators which:

- Satisfies multiple Domain Transition Graphs (DTGs).
- Has minimum cost.



Algorithms for planning

- Forward (and backward) state-based search
- Planning-as-SAT
- Partial-order planning

Planning-as-SAT

- Encode a number of time-indexed “layers” as a SAT formula.

$$\neg\texttt{holding-b1@t1} \Rightarrow \neg\texttt{drop-b1-in-left@t1}$$

$$\neg\texttt{b1-in-left@t1} \wedge \texttt{b1-in-left@t2} \Rightarrow \texttt{drop-b1-in-left@t1}$$

- Incrementally extend the formula as needed.
- How do you prove optimality?

Heuristic Search

- A* with a relaxation (heuristic) gives a LB.
- By expanding minimum LB state, we can prove optimality.
- How do you handle side constraints?

Operator Counting Heuristics

$$\text{minimize} \sum_{o \in O} c(o) \cdot Y_o$$

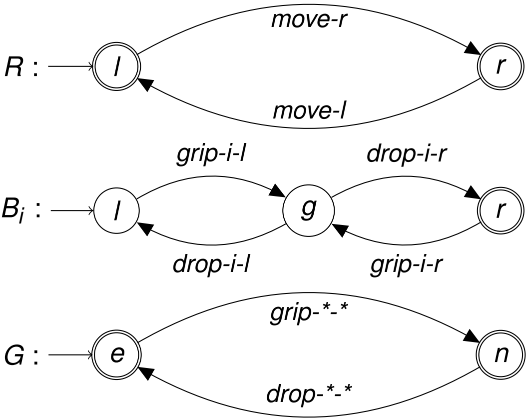
$$s.t.$$

$$\sum_{o \in LM} Y_o \geq 1 \qquad \forall LM$$

$$\sum_{o \in \text{prod}(p)} Y_o - \sum_{o \in \text{cons}(p)} Y_o = \Delta_p \qquad \forall p$$

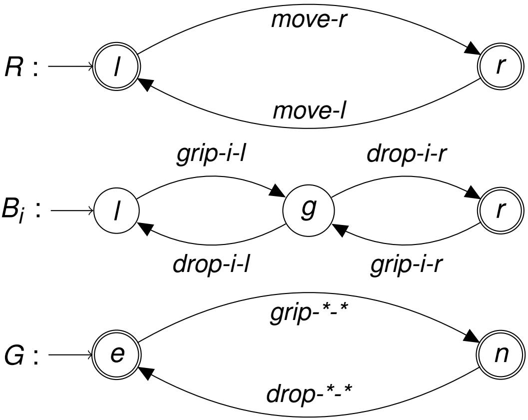
- Use a MIP with Y_o variables which count each operator o.
- Heuristics can be combined, often strictly dominating the components.
- The MIP solution gives a heuristic estimate; and
- **An assignment to the Y_o variables.**

Sequencing operator counts



- $\mathcal{C}(o)$ =
  grip-1-l: 1
  grip-2-l: 1
  move-l: 1
  move-r: 1
  drop-1-r: 1
  drop-2-r: 1
  otherwise: 0

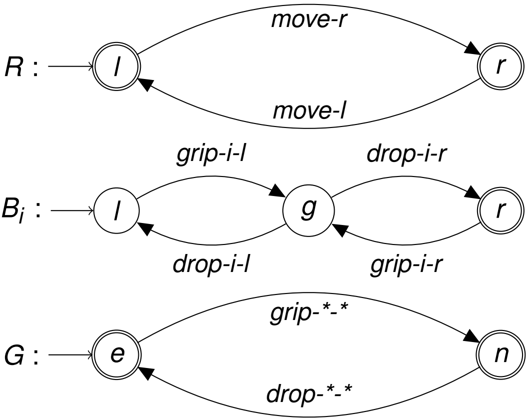
Sequencing operator counts



✗ $\mathcal{C}(o)$ =

grip-1-l: 1
grip-2-l: 1
move-l: 1
move-r: 1
drop-1-r: 1
drop-2-r: 1
otherwise: 0

Sequencing operator counts



✓ $\mathcal{C}(o)$ =
grip-1-l: 1
grip-2-l: 1
move-l: 1
move-r: 2
drop-1-r: 1
drop-2-r: 1
otherwise: 0

Landmarks

A (Disjunctive Action) Landmark is a necessary condition on the set of operators in a plan.

$$Y_1 + \cdots + Y_n \geq 1$$

or

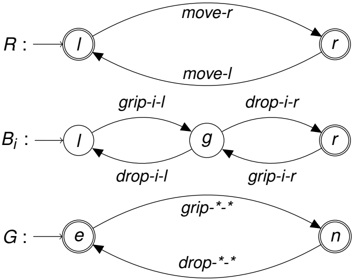
$$[Y_1 \geq 1] \vee \cdots \vee [Y_n \geq 1]$$

"at least one of these operators occurs at least one time"

Generalized Landmarks (GLMs)

We generalize this to:

$$[Y_1 \geq k_1] \vee \cdots \vee [Y_n \geq k_n]$$



The flaw we identified earlier:

$$[Y_{move\text{–}r} \geq 2]$$

Domain Constraints

Bounds literals ($[Y_o \geq k]$) are not built in to MIPs,
To define their relationship with the Y_o variables, we add:

$$[Y_o \geq k] \leq [Y_o \geq k-1]$$

$$Y_o \geq \sum_{i=1}^{\infty} [Y_o \geq i]$$

$$Y_o \leq M[Y_o \geq k] + k - 1$$

- $[Y_o \geq k] \Rightarrow [Y_o \geq k-1]$
- n bounds literals are set, then $Y_o \geq n$;
- if k or more operators occur, $[Y_o \geq k]$ must be set.

We then lazily create the bounds literals when they are mentioned in a GLM.

Theorem

There exists a set of generalized landmark constraints such that solving a MIP with these constraints will compute $h^*(s_0)$.

Proof.

With optimal operator count $\mathcal{C}$, either:

- We have found a plan projection; or
- We can add

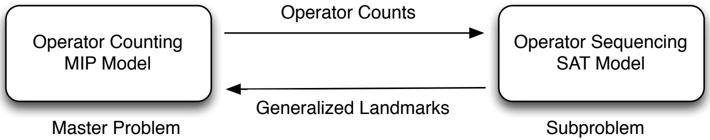
$$\sum_{o \in O} [Y_o \geq \mathcal{C}(o) + 1] \geq 1$$

  and re-optimise to get a new count.

□

Logic-Based Benders Decomposition

$$\mathcal{C} : O \rightarrow \mathbb{N}$$



$$\sum_{o \in L} [Y_o \geq \mathcal{C}(o) + 1] \geq 1$$

Using SAT to get better cuts

We use the at-most-k constraint $\leq_k$ encoded into SAT.
Add **assumptions** to SAT-planning model for each upper-bound $Y_o \leq \mathcal{C}(o)$:

$$\neg[Y_o \geq \mathcal{C}(o) + 1]$$

When UNSAT is proved, the solver identifies a subset of the assumptions responsible for failure.

Using SAT to get better cuts

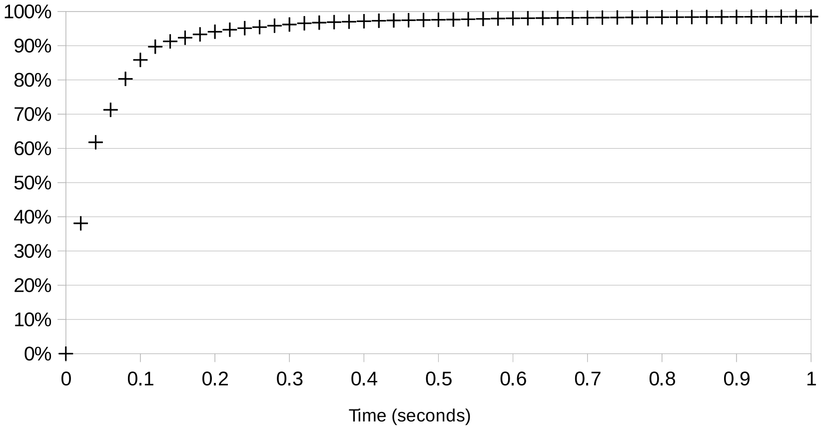
$$[Y_{grip-1-r} \geq 1] + [Y_{drop-1-l} \geq 1] + [Y_{grip-1-l} \geq 2] + [Y_{drop-1-r} \geq 2] +$$
$$[Y_{grip-2-l} \geq 2] + [Y_{drop-2-r} \geq 2] + [Y_{grip-2-r} \geq 1] + [Y_{drop-2-l} \geq 1] +$$
$$[Y_{move-l} \geq 2] + [Y_{move-r} \geq 2] \geq 1$$

vs

$$[Y_{grip-1-r} \geq 1] + [Y_{drop-1-l} \geq 1] + [Y_{move-r} \geq 2] + [Y_{drop-2-l} \geq 1] +$$
$$[Y_{grip-2-r} \geq 1] + [Y_{move-l} \geq 2] + [Y_T \geq 7] \geq 1$$

NB: Y_T is the count of a "fake" operator T: the total operator count.

Generating GLMs is surprisingly efficient



Benchmark	*OpSeq* C	*OpSeq* =	*OpSeq* Q	*Hpp* C	*Hpp* =	*Hpp* Q	*SymBA*-2* C	*SymBA*-2* =	*SymBA*-2* Q
barman	0	0	9.37	0	0	9.14	**11**	**20**	**20.00**
elevators	11	11	19.38	0	0	16.47	**19**	**20**	**20.00**
nomystery	5	10	18.33	5	8	8.00	**15**	**18**	**19.82**
openstacks	0	0	5.52	0	0	5.52	**20**	**20**	**20.00**
parcprinter	**20**	**20**	**20.00**	**20**	**20**	**20.00**	17	17	18.63
pegsol	2	5	15.97	0	0	12.43	**19**	**20**	**20.00**
scanalyzer	1	3	7.99	3	**14**	**18.93**	**9**	10	14.32
sokoban	0	2	10.70	1	2	11.27	**20**	**20**	**20.00**
transport	5	13	**19.47**	0	0	12.41	**11**	**14**	17.81
visitall	**14**	**20**	**20.00**	5	13	19.21	12	12	15.70
woodworking	**20**	**20**	**20.00**	18	18	19.95	19	19	19.74
Total	78	104	166.74	52	75	153.33	**172**	**189**	**206.02**

Coverage (C)

Number of best bounds (=)

Dual quality scores (Q)

Conclusion and Future Work

This is a fundamentally new approach to planning, splitting planning into an operator counting problem, and a sequencing problem.

Any **explaining** constraint or theory can be added to the sub-problem, and can be re-written into the assumptions

This has applications in:

- Temporal planning.
- Planning with resources.
- Hybrid planning/scheduling problems.