The LAMA Planner

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1. Overview

2. Landmarks - Generation & Usage

3. Further Characteristics of LAMA
   - Multi-heuristic Search
   - Preferred Operators
   - Anytime Search

4. IPC-2008 Results
Outline

1. Overview

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4. IPC-2008 Results
LAMA is a state-of-the-art heuristic search planner.

Won the satisficing track of the 6th International Planning Competition (IPC-2008).

Based on Fast Downward (Helmert & Richter), winner of the satisficing track at IPC-2004.

Core components we will discuss:

- **Landmarks** to direct search
- **Multi-heuristic search**
- **Preferred Operators** as further source of heuristic information
- **Anytime search** to try to make best use of given time
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Landmarks

- Facts that **must** be true in every plan
  (Porteous & Cresswell 2002; Hoffmann et al. 2004)
- Intuitively helpful to direct search
- Automatically found, incl. orderings

Next: how to find landmarks, and how to use them
Landmark Generation I

Find landmarks by backchaining (Hoffmann et al. 2004)

- Every goal is a landmark
- If B is landmark and all actions that achieve B have A as precondition, then A is a landmark
- Useful restriction: consider only the case where B is achieved for the first time → find more landmarks. (Why?)
- NP-hard to find all first achievers → over-approximation by building RPG without actions that add B. Any action applicable in this RPG can possibly be executed before B first becomes true.
Landmark Generation I

Disjunctive landmarks also possible, e.g., \( (o-in-p_1 \lor o-in-p_2) \):

- If \( B \) is landmark and all actions that (first) achieve \( B \) have either \( A \) or \( C \) as precondition, then \( A \lor C \) is a landmark.
- Generalises to any number of disjuncts, though usually restricted in practice.
- Large number of possible disjunctive landmarks in practice, restrict set of facts, e.g. such that all facts must be instantiations of the same predicate.
Domain Transition Graphs (DTGs)

Find landmarks through DTGs (Richter et al. 2008)

The domain transition graph of $v \in \mathcal{V}$ (DTG$_v$) represents how the value of $v$ can change.

Given: a SAS$^+$ task $\langle \mathcal{V}, A, s_0, s_\ast \rangle$

DTG$_v$ is a directed graph with nodes $\mathcal{D}_v$ that has arc $\langle d, d' \rangle$ iff

- $d \neq d'$, and
- $\exists$ action with $v \mapsto d'$ as effect, and either
  - $v \mapsto d$ as precondition, or
  - no precondition on $v$

$\sim$ DTG$_v$ is the same as the graph of an atomic abstraction
DTG Example

DTG for $v_o$: 

![Diagram showing DTG example with nodes B, D, A, C, and E connected by arrows and labels t and p.]
DTG Example
DTG Example

DTG for $v_o$:

B → t → A → C → P → E

load-o-t-B

p

o
t
Find landmarks through DTGs: if

- $s_0(v) = d_0$,
- $v \mapsto d$ landmark, and
- every path from $d_0$ to $d$ passes through $d'$,

then $v \mapsto d'$ landmark
Find landmarks through DTGs: if

- $s_0(v) = d_0$,
- $v \mapsto d$ landmark, and
- every path from $d_0$ to $d$ passes through $d'$,

then $v \mapsto d'$ landmark
Landmark Generation II (ctd.)

DTG for $v_b$:

Graph:
- Nodes: B, C, D, A, E
- Edges: B→t→C→p→E

Additional landmarks:
- b-at-B
- t-at-B
- b-in-t
- t-at-C
- p-at-C
- b-at-C
- b-in-p
- b-at-E
Landmark Generation II (ctd.)

DTG for $v_b$:

```
B -> t -> C -> p -> E
```

Further Characteristics of LAMA

IPC-2008 Results

Landmarks - Generation & Usage
Landmark Generation II (ctd.)

DTG for $v_b$:

\[ o-at-B \quad t_1-at-B \]
\[ o-in-t_1 \quad t-at-C \]
\[ o-at-C \quad o-in-p_1 \lor b-in-p_2 \lor o-in-t_2 \]
\[ o-at-E \]
Landmark Generation II (ctd.)

DTG for $v_b$:

- Event $t_1$ leading to events $t_1$ and $b$.
- Event $t_1$ leading to event $t_2$.

Graph with nodes $B$, $C$, $D$, $E$, $F$ and edges $t_1$, $p_1$, $p_2$, $o-in-t$ and $o-at-B$. The graph illustrates the temporal logic representation and the relationships between events and propositions in the context of Landmark Generation.
DTG for $v_b$:

$$B \xrightarrow{t_1} C \xrightarrow{t_2}$$

Landmarks - Generation & Usage

Further Characteristics of LAMA

IPC-2008 Results

Landmark Generation II (ctd.)

$$o\text{-at-B} \quad t_1\text{-at-B}$$

$$o\text{-in-}t_1$$

$$t\text{-at-C}$$

$$o\text{-at-C}$$

$$o\text{-in-}p_1 \lor b\text{-in-}p_2 \lor o\text{-in-}t_2$$

$$o\text{-at-E}$$
Find orderings: given two landmarks A and B,

- if A was found by backchaining from B, then A can be ordered before B.
- if it is not possible to reach B before A in an RPG, then A can be ordered before B.
- Reasonable orderings: if we have to make B false in order to achieve A, then it “makes sense” to achieve A before B. These orderings may not always be correct, but can help in practise!
Using landmarks in localised search approach

- Make the landmarks subgoals, then simply concatenate plans of subtasks (Hoffmann et al. 2004)
- Greatly speeds up search in many domains
- Any base planner possible for subtasks
- But: Incomplete (dead ends), and bad-quality plans
Using landmarks in global search approach

- Heuristic = \#landmarks that still need to be achieved (Richter et al. 2008)
- Takes landmark orderings into account: some landmarks may have to be achieved more than once if they are preconditions for other landmarks
- **Pseudo-Heuristic** because depends on path to state
- Can be combined with other heuristics through multi-heuristic BFS (more details later)
Backchaining and DTGs to find landmarks
Also disjunctive landmarks
Landmark heuristic with action costs incorporated: rather than counting the number of missing landmarks, sum over lower bounds on their costs
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Multi-heuristic Search

Several heuristics can be combined for better performance (Helmert 2006):

- In a heuristic search using open lists (e.g. BFS, A*, ...) use a separate open list for each heuristic
- Evaluate states with all heuristic functions and put in all corresponding open lists
- Select next state **alternatingly** from the various open lists

(Why should we not use a single open list?)

LAMA: combines landmark heuristic with cost-sensitive variant of FF-heuristic
Second source of heuristic information

Idea: prefer actions that are likely to improve heuristic value, and try these actions before others $\Rightarrow$ one-step look-ahead

E.g., actions which are part of plan for simplified problem (Helmert 2006, Hoffmann & Nebel 2001)

Often substantial performance improvement
Preferred Operators (ctd.)

- FF heuristic: preferred operators = “helpful actions”: actions that are part of plan for relaxed task
- Landmark heuristic: preferred operators = landmark-achieving operators or operators in relaxed plan to nearest landmark
- LAMA: uses preferred operators for both FF heuristic and landmarks heuristic
Anytime Search

IPC-2008 requirement: find best possible plan within 30 minutes. This suggests an anytime approach:

- Find a solution as quickly as possible (any solution is better than none).
  LAMA: greedy BFS.
- While there is still time, try to improve the solution.
  LAMA: series of weighted A* searches with decreasing weights.
- Interesting finding: a series of independent runs of weighted A* is better than one continued search (restarts overcome early mistakes)
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4. IPC-2008 Results
The IPC 2008 tracks

Three track categories:

- **sequential:**
  - STRIPS + action costs
  - objective: minimize total cost (sum of action costs)

- **temporal:**
  - STRIPS + durative actions (+ numeric fluents)
  - objective: minimize total time (makespan)

- **net benefit:**
  - STRIPS + action costs + soft goals (+ numeric fluents)
  - objective: maximize net benefit
    - (utility of achieved goals minus total cost)

Six tracks:

- for each category, a **satisficing track** and an **optimization track**
- awards given to winner and runner-up of each track
- one additional **jury award**
Sequential Satisficing Track

Number of competitors: 23 registered, 9 submitted

Competition setting for all satisficing tracks:
- 6–9 domains per track, 30 tasks each
- planners get score 0.0-1.0 for each solved task
- score is 1.00 for optimal or best known solutions
- otherwise score is
  $\frac{\text{cost of best known plan}}{\text{cost of generated plan}}$
- highest aggregate score wins
- score only depends on plan quality
- runtime does not affect score
- limits per task: 30 minutes, 2 GB RAM
Participants in the sequential satisficing track

- **C³** (Miguel Ramírez, Nir Lipovetzky, Héctor Geffner): forward state space search with powerful structural pruning scheme based on inference along possible causal chains
- **Divide-and-Evolve 1/2** (Jacques Bibai, Pierre Savéant, Marc Schoenauer, Vincent Vidal): subgoal decomposition, evolutionary algorithms + CPT
- **DTGPlan** (Ruoyun Huang, Yixin Chen, Weixiong Zhang): A* search in hierarchically extended abstract search space, subplans generated from DTGs via causal analysis
- **FF(hᵃ)** and **FF(hˢᵃ)** (Emil Keyder, Héctor Geffner): FF made cost-sensitive by using best supports of atoms (hᵃ) or propagating action sets rather than cost values (hˢᵃ).
Participants in the sequential satisficing track (ctd.)

- **LAMA** (Silvia Richter, Matthias Westphal): Fast Downward with FF heuristic + landmark heuristic + iterated WA*
- **Plan-A** (Qiang Lv, Yixin Chen, Ruoyun Huang): DPLL-opt (DPLL with linear cost function optimization) + branch-and-bound pruning
- **SGPlan 6** (Chih-Wei Hsu, Benjamin Wah) subproblem partitioning + Metric-FF + conflict resolution with Extended Saddle Point Condition
- **baseline planner:** throw away action costs, run FF
Sequential satisficing track: Results

$C^3$
DAE-1
DAE-2
DTGPlan
FF($h_a$)
FF($h_{sa}$)
LAMA
Plan-A
SGPlan 6
(Upwards)
baseline
Sequential satisficing track: Results

Domain: Cyber security

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<th>Value</th>
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## Sequential satisficing track: Results

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## Sequential satisficing track: Results

### Domain: Elevators

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Sequential satisficing track: Results

- C³
- DAE-1
- DAE-2
- DTGPlan
- FF($h_a$)
- FF($h_{sa}$)
- LAMA
- Plan-A
- SGPlan 6
- (Upwards)
- baseline
### Sequential satisficing track: Results

**Domain:** Openstacks

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Sequential satisficing track: Results

- C³
- DAE-1
- DAE-2
- DTGPlan
- FF($h_a$)
- FF($h_{sa}$)
- LAMA
- Plan-A
- SGPlan 6
- (Upwards)
- baseline
Sequential satisficing track: Results

Domain: ParcPrinter

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Sequential satisficing track: Results

C³
DAE-1
DAE-2
DTGPlan
FF($h_a$)
FF($h_{sa}$)
LAMA
Plan-A
SGPlan 6
(Upwards)
baseline
## Sequential satisficing track: Results

**Domain: Peg Solitaire**

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Sequential satisficing track: Results

- C³
- DAE-1
- DAE-2
- DTGPlan
- FF(\(h_a\))
- FF(\(h_{sa}\))
- LAMA
- Plan-A
- SGPlan 6
- (Upwards)
- baseline
## Sequential satisficing track: Results

**Domain:** Scanalyzer-3D

<table>
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<th>Algorithm</th>
<th>Score</th>
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Sequential satisficing track: Results

- C³
- DAE-1
- DAE-2
- DTGPlan
- FF\(h_a\)
- FF\(h_{sa}\)
- LAMA
- Plan-A
- SGPlan 6
- (Upwards)
- baseline
Sequential satisficing track: Results

Domain: Sokoban

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<th>Algorithm</th>
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<td>SGPlan 6 (Upwards)</td>
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Sequential satisficing track: Results

- $C^3$
- DAE-1
- DAE-2
- DTGPlan
- $FF(h_a)$
- $FF(h_{sa})$
- LAMA
- Plan-A
- SGPlan 6
- (Upwards)
- baseline
Sequential satisficing track: Results

Domain: *Transport*

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<td>Plan-A</td>
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<tr>
<td>SGPlan 6</td>
<td>18.08</td>
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<tr>
<td>(Upwards)</td>
<td>5.84</td>
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<td>baseline</td>
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Sequential satisficing track: Results

- $C^3$
- DAE-1
- DAE-2
- DTGPlan
- $\text{FF}(h_a)$
- $\text{FF}(h_{sa})$
- LAMA
- Plan-A
- SGPlan 6
- (Upwards)
- baseline
### Domain: Woodworking

<table>
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<th>Runtime</th>
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<tr>
<td>C³</td>
<td>26.41</td>
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<td>DAE-1</td>
<td>15.06</td>
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<td>DAE-2</td>
<td>17.87</td>
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<td>DTGPlan</td>
<td>4.64</td>
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<tr>
<td>FF($h_a$)</td>
<td>23.67</td>
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<td>FF($h_{sa}$)</td>
<td>23.84</td>
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<td>26.49</td>
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<td>Plan-A</td>
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<td>SGPlan 6 (Upwards)</td>
<td>20.85</td>
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<tr>
<td>baseline</td>
<td>11.83</td>
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<td>15.45</td>
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Sequential satisficing track: Results

- C³
- DAE-1
- DAE-2
- DTGPlan
- FF($h_a$)
- FF($h_{sa}$)
- LAMA
- Plan-A
- SGPlan 6 (Upwards)
- baseline
Sequential satisficing track: Results

Total scores

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<th>Algorithm</th>
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## Sequential satisficing track: Awards

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<th>Category</th>
<th>Project</th>
<th>Authors</th>
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<tr>
<td><strong>Winner</strong></td>
<td><strong>LAMA</strong> by Silvia Richter and Matthias Westphal</td>
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<td><strong>Runner-up</strong></td>
<td><strong>FF($h_{sa}$)</strong> by Emil Keyder and Héctor Geffner</td>
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<td><strong>Jury Award</strong></td>
<td><strong>C³</strong> by Miguel Ramírez, Nir Lipovetzky and Héctor Geffner</td>
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</tbody>
</table>
References


Silvia Richter, Malte Helmert and Matthias Westphal. Landmarks revisited. 
Describes DTG method for finding landmarks and the landmark heuristic.

Malte Helmert.
The Fast Downward planning system.
Describes the architecture of Fast Downward and LAMA.

Describes the FF heuristic of which LAMA uses a cost-sensitive variant.