Accurately Determining Intermediate and Terminal Plan States Using Bayesian Goal Recognition

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Overview

1. Recognition without Libraries
2. Results
3. Conclusions and Future Possibilities
The *de facto* (and defined) standard

- Traditional GR/PR makes use of libraries
  - Collection of known goals/plans
  - Hand coded or generated
  - Plans through state space
  - Specialised to one subject
  - Represented as HTNs

- Recognition
  - Probabilistic/Bayesian
  - Weights hand coded or automated
  - Observe actions and map to X plans from library which match with varying probabilities
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- Recognition
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- But what if there is nothing to map to?
Recognition without Libraries

- Goal Recognition as Planning
  - “Planning” in the sense of not doing any planning
- Planning and Recognition mirror one-another
  - Goal Recognition also uses Propositions, Actions, States and Goals
    - So why not try to link the two?
- Recognition systems have no common language, but Planning has PDDL
  - By working with PDDL, any problem can be constructed quickly
  - Use recent Planning advances in solving the GR problem
    - heuristic convergence
- No plan/goal library
  - Try to automatically detect lost information
Problem Formulation

- No libraries
- Any domain
- No pre-compilation
- Any (valid) fact conjunctions can be goal
- Use Planning representation for goal space
  - Cannot hope to enumerate the true goal space
  - Goal Space $\mathcal{H}$ = domain’s reachable facts
  - Assume independence between facts
    - No explicit conjunctions (yet)
    - Standard mutex detection
- Also analogous to Particle Filtering and Fault Diagnosis
Plan movement through state-space
Plan movement through state-space
Plan movement through state-space
Plan movement through state-space
Plan movement through state-space
Assumptions and Relaxations

- Plan is totally-ordered
  - Can be taken from anywhere- created or parsed in from known results
    - We use IPC3/IPC5 results
- Fully observable
  - No hidden actions
- No assumption about “intelligence” of plan
- No knowledge of plan steps remaining
- **Anything** can be a goal, and a goal can be made up of anything
  - Conjunctions are common in Planning, but uncommon in Recognition
Step 1 – Putting the Vitamins back in

- Cue strange orange juice analogy...
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- But once instantiated, structure is rich, albeit hard to find
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- Cue strange orange juice analogy...
- PDDL domain inputs are flat and dull
- But once instantiated, structure is rich, albeit hard to find
- Domain Transition Graphs, Causal Graphs, Static Facts, Relaxed Plans, Heuristic Estimates, Sampling
Domain Analysis

- Predicate Partitioning
  - Grounding process produces all goals
  - So try and categorise them to find those which are very likely and those which are less likely
- Causal Graph Leaf-Nodes
  - Exist only to be altered, so adjust probabilities of facts containing them appropriately
- Produce initial probability distribution over $\mathcal{H}$
- But of course a manual distribution is still possible
Step 2 – Plan Observation

- Action is fed into recogniser
- Get *heuristic estimate* to all $f \in \mathcal{H}$
  - Further actions needed to achieve $f$
  - If decreasing, fact is possibly goal
  - If increasing, fact is probably not goal
- Use heuristic results to increase/decrease probability if $f$ being a goal w.r.t. mutually-exclusive facts
- Over time, some facts will become highly likely to be goals
  - ... or at least be in final state
- Heuristic estimates used to update goal probabilities using Bayes’
Heuristic Bayesian Updates

- After each observation, a subset of the search-space will be closer.
- The amount of work performed by an action w.r.t \( G \) is

\[
W(G | O) = \begin{cases} 
\frac{1}{| \bar{G}_{\text{mutex}}^{\text{nearer}} |} & \text{if } h_t(G) < h_{t-1}(G), \\
\frac{1}{| \bar{G}_{\text{mutex}}^{\text{nearer}} |} & \text{if } h_t(G) = h_{t-1}(G) = 0, \\
0 & \text{otherwise} 
\end{cases} 
\]

- Give a *bonus* to facts which remain true.
Example of $W(G)$ with and without bonus

- **Goal:** Passenger 1 and Passenger 2 at City 1
- **$W(G)$** associated with Passenger 2

### Table: Without bonus

<table>
<thead>
<tr>
<th></th>
<th>at p2 c1</th>
<th>at p2 c2</th>
<th>at p2 c3</th>
<th>in plane p2</th>
</tr>
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Is O relevant if G is goal

- Feed into *conditional probability*

\[
P(O|G) = \lambda \times W(G|O) \times S(G) + (1 - \lambda) \times \frac{1}{1 + |\text{mutex}(g)|} \tag{2}
\]

- Stability \( S'(G) \) indicates how often a fact flicks from true to false

\[
S_t(G) = \begin{cases} 
1 
& \text{if } G \text{ unachieved in } P, \\
\frac{|\text{Obs}| - G^\text{true}_t}{\sum G^\text{true}_i} 
& \text{otherwise}
\end{cases} \tag{3}
\]
Example of $P(G | A)$ with and without bonus

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Step 3 – Hypotheses

- Now have a new probability distribution over $\mathcal{H}$
- Pull out highest probability facts to form *terminal goal hypothesis*
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<table>
<thead>
<tr>
<th>Domain</th>
<th>$P = 0%$</th>
<th>$P = 25%$</th>
<th>$P = 50%$</th>
<th>$P = 75%$</th>
<th>$P = 100%$</th>
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</thead>
<tbody>
<tr>
<td>Driverlog</td>
<td>0.22/0.3</td>
<td>0.33/0.45</td>
<td>0.46/0.6</td>
<td>0.55/0.69</td>
<td>0.66/0.84</td>
</tr>
<tr>
<td>Rovers</td>
<td>0.28/1</td>
<td>0.28/1</td>
<td>0.28/1</td>
<td>0.28/1</td>
<td>0.32/1</td>
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<tr>
<td>Zenotravel</td>
<td>0.28/0.46</td>
<td>0.23/0.39</td>
<td>0.25/0.43</td>
<td>0.36/0.63</td>
<td>0.4/0.68</td>
</tr>
<tr>
<td>Average</td>
<td>0.26/0.59</td>
<td>0.28/0.61</td>
<td>0.33/0.68</td>
<td>0.4/0.77</td>
<td>0.46/0.84</td>
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A Step Further

- But we would also like to have hypotheses for non-goal intermediate states
- So *estimate* the number of steps remaining based on what the final goal is expected to be
- Can then generate a hypothesis for $n$ further observations
Estimating Intermediate Goals

- Estimate whether $G$ will be true in $n$ steps
- Clearly linked to whether action which achieves it will be observed

\[
P^n(A) = \begin{cases} 
0 & \text{if } h(A_{pre}) > n, \\
\max P(f) & \forall f \in A_{add} \text{ otherwise} 
\end{cases} \quad (4)
\]

\[
P^n(G) = \max P^n(A) \quad \forall A \in achievers(G) \quad (5)
\]
Intermediate Results - Driverlog

Density of Bounded Intermediate Hypothesis P/R in Driverlog 1-10
Intermediate Results- Rovers

Density of Bounded Intermediate Hypothesis in Rovers 1-10
Intermediate Results- Zenotravel

Density of Bounded Intermediate Hypothesis in Zenotravel 1-10
Conclusions

- Presented a new formulation of Goal Recognition as a Planning task, which does not rely on libraries
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- How well are Plan Libraries replaced?
Conclusions

- Presented a new formulation of Goal Recognition as a Planning task, which does not rely on libraries
- How well are Plan Libraries replaced?
  1. Structure- largely done
  2. Prediction- Good results for both intermediate and terminal results
  3. Abstraction- None really. Could be learned from domains, or probable conjunctions generated at runtime
  4. Termination- Intermediate state estimates are pretty good, but the estimation itself is too short
    - Probably heavily linked to heuristic choice
- Backwards compatibility not broken at any point
  - Known goal conjunctions can still be added
  - Known plans still applicable
  - Probability weightings still applicable
Extensions

- The move into PR seems natural
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- Bringing Planning and PR closer together
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- Convergence
Extensions

• The move into PR seems natural
• Bringing Planning and PR closer together
• Convergence
  • Instead of storing plans in a library, generate them at runtime
  • Use of landmarks, inference, deduction in next action-prediction
  • “Heuristic learning” from previous plan observations
  • Macro-Actions ⇒ high-level concepts?
  • Domain-learning/extension
  • Conjunction learning- genetic techniques
Thank you for your attention

• Questions/comments?
Coffee Break

- Resume at 11.00