

## Chapter: Plan Recognition in Hierarchical Planning

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(Based on slides by Héctor Geffner)



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### Overview:

- 1 Introduction
- 2 Plan Recognition in Non-Hierarchical Planning
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### So far: Automated Planning

Given:

- Model of behavior.
  - What characterizes the world (with respect to a task)?
  - How can we/an agent change the world?
- Initial state – How does the world look like in the current situation?
- Goal and initial task definition – Which properties of the world do we want to achieve (classical planning) and how should the plans look like (hierarchical planning)?

Task:

- Find a sequence of actions that transforms the world from the initial state to a state that has the desired goal properties.



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### Plan and Goal Recognition

Given:

- Model of behavior.
  - What characterizes the world (with respect to a task)?
  - How can an agent change the world?
  - **What are desirable goals?**
- Initial state – How does the world look like in the current situation?
- **Observations** – A sequence of actions some agent(s) has/have executed.

Task:

- Determine which of the goals the agent is pursuing.
- Determine what the agent is doing next.




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## Application Scenarios

- Robotics/software systems that interact with:
  - Humans and/or
  - other (autonomous) agents.
- Intrusion detection:
  - Classify behavior.
  - Detect unusual behavior.



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## What are we doing?

Automated planning:

- Based on an abstraction of the world, we generate a plan to reach some goal.
- When the model is sufficiently precise, generated solutions will transform the system as intended.

Plan and goal recognition:

- What must be fulfilled to classify some activity (e.g. some movement) as intentional action?
- We make assumptions about reasons of behavior (the agent *wants to realize* something).
- We presume objectives of an agent and judge the helpfulness of actions regarding the objectives.




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## So, What *are* we Doing?

- We solve a combinatorial problem.
  - Decision problem: Is there a plan in line with the observations (this is a generalization of planning).
  - Practical: Find a plan that is in line with observations (and output the corresponding goal).
  - More practical: Return a probability distribution over possible goals/plans.




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## Assumptions

### Agent

- Is the agent behaving rational?
- What does this mean?
  - Is *purchasing* a goal.
  - Is purchasing a goal *optimally*.
- Often assumed: “keyhole” observations (no contact to agent).
- Problematic: what is if the agent wants to confuse the observer (adversarial behavior, intrusion detection)?
- Integration of PGR and Planning: cooperative behavior.
- Is the model correct/complete?



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## Assumptions

### Environment

- What is the input for the PGR system?
  - Usually: actions (→ Activity Recognition).
  - Sometimes: changes in the environment.
- Does the observer see all actions (missed observations)?
- Can we be wrong (False observations)?

### Goals

- Single/multiple goal?
- Plans interleaved?
- Static/dynamic?




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## Approaches

### Based on

- plan libraries
- Parsing
- Probabilistic models
- ...
- Most recent approach: Plan Recognition as Planning




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## Plan Recognition as Planning

- Benefit from research in planning.
- Well-established formalisms.
- Use the efficient solvers that are available in planning.
- We will have a look at tree approaches:
  - Next: Two approaches based on STRIPS (slides by Héctor Geffner).
  - Afterwards: Based on Hierarchical Task Network (HTN) planning.




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## Plan Recognition

A			B			C
			↑			
			↑			
J			S			D
H			F			E

- Agent can move one unit in the four directions.
- Possible targets are A, B, C, ...
- Starting in S, he is observed to move up twice.
- Where is he going?



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### Standard Plan Recognition over Libraries (Abstract View)

- A plan recognition problem defined by triple  $T = (\mathcal{G}, \Pi, O)$ , where
  - $\mathcal{G}$  is the set of possible goals  $G$ .
  - $\Pi(G)$  is the set of possible plans  $\pi$  for  $G$ ,  $G \subseteq \mathcal{G}$ .
  - $O$  is an observation sequence  $a_1, \dots, a_n$  where each  $a_i$  is an action.
- A possible goal  $G \in \mathcal{G}$  is plausible if  $\exists$  plan  $\pi$  in  $\Pi(G)$  that satisfies  $O$ .
- An action sequence  $\pi$  satisfies  $O$  if  $O$  is a subsequence of  $\pi$ .



### (Classical) Plan Recognition over Action Theories

- PR over classical planning domains is similar but with set of plans  $\Pi(G)$  defined implicitly:
- A plan recognition problem is a triplet  $T = (P, \mathcal{G}, O)$ , where
  - $P = (F, A, I)$  is planning domain: fluents  $F$ , actions  $A$ , init  $I$ , no goal.
  - $\mathcal{G}$  is a set of possible goals  $G$ ,  $G \subseteq F$ .
  - $O$  is the observation sequence  $a_1, \dots, a_n$ , with  $a_i \in A$ .
- If  $\Pi(G)$  stands for “good plans” for  $G$  in  $P$  (to be defined), then as before:
  - A possible goal  $G \in \mathcal{G}$  is plausible if there is a plan  $\pi$  in  $\Pi(G)$  that satisfies  $O$ .
  - An action sequence  $\pi$  satisfies  $O$  if  $O$  is a subsequence of  $\pi$ .
- Our goal: define the good plans and solve the problem with a classical planner.



### Plan Recognition as Planning: First Formulation

Define the set  $\Pi(G)$  of “good plans” for  $G$  in  $P$ , as the optimal plans for  $G$  in  $P$ .

- Then  $G \in \mathcal{G}$  is a plausible goal given observations  $O$ :
  - iff there is an optimal plan  $\pi$  for  $G$  in  $P$  that satisfies  $O$ ;
  - iff there is an optimal plan  $\pi$  for  $G$  in  $P$  that is a plan for  $G + O$  in  $P'$ ;
  - iff cost of  $G$  in  $P$  equal to cost of  $G + O$  in  $P'$  abbreviated

$$c_{P'}(G + O) = c_P(G)$$

- Given that we can create a “new” planning problem solving  $G + O$ ,
- it follows that plausibility of  $G$  can be computed exactly by calling an optimal planner twice: one for computing  $c_{P'}(G + O)$ , one for computing  $c_P(G)$ .



### Compiling Observations Away

We get rid of observations  $O$  by transforming  $P = (F, I, A)$  into  $P' = (F', I', A')$  so that

- $\pi$  is a plan for  $G$  in  $P$  that satisfies  $O$  iff  $\pi$  is a plan for  $G + O$  in  $P'$ .

and

- $\pi$  is a plan for  $G$  in  $P$  that doesn't satisfy  $O$  iff  $\pi$  is a plan for  $G + \bar{O}$  in  $P'$ .

The transformation from  $P$  into  $P'$  is quite simple.



### Compiling Observations Away

- Given  $P = (F, I, A)$ , the transformed problem is  $P' = (F', I', A')$ :
  - $F' = F \cup \{p_a \mid a \in O\}$ , where  $p_a$  is new fluent for the observed action  $a$ .
  - $I' = I$ .
  - $A' = A$ .
- The actions  $a \in O$  have an extra effect in  $A'$ :
  - $p_a$ , if  $a$  is the first observation in  $O$ , and
  - $p_b \rightarrow p_a$ , if  $b$  is the action that immediately precedes  $a$  in  $O$ .
- The “goals”  $O$  and  $\bar{O}$  in  $P'$  are  $p_a$  and  $\neg p_a$  for the last action  $a$  in  $O$ .
- The plans  $\pi$  for  $G$  in  $P$  that satisfy/don't satisfy  $O$  are the plans in  $P'$  for  $G + O/G + \bar{O}$  respectively.



### Plan Recognition as Planning: A More General Formulation

- So far we filter goals  $G$  as plausible or implausible.
- Rather rank them with a probability distribution  $P(G|O)$ ,  $G \in \mathcal{G}$ .
- From Bayes Rule  $P(G|O) = \alpha P(O|G)P(G)$ , where
  - $\alpha$  is a normalizing constant.
  - $P(G)$  is assumed to be given in problem specification.
  - $P(O|G)$  is defined in terms of extra cost to pay for not complying with the observations  $O$ :

$$P(O|G) = \text{function}(c(G + \bar{O}) - c(G + O))$$



### Example: Navigation in a Grid Revisited

A				B			C
				↑			
				↑			
J			S				D
H			F				E

- If  $\Delta(G, O)$  defined as  $c(G + \bar{O}) - c(G + O)$ :
- For  $G = B$ ,  $c(B + O) = c(B) = 4$ ;  $c(B + \bar{O}) = 6$ ; thus  $\Delta(B, O) = 2$ .
  - For  $G = C$  or  $A$ ,  $c(C + O) = c(C + \bar{O}) = c(C) = 8$ ; thus  $\Delta(C, O) = 0$ .
  - For all other  $G$ ,  $c(G + O) = 8$ ;  $c(G + \bar{O}) = c(G) = 4$ ; thus  $\Delta(G, O) = -4$ .
- If  $P(O|G)$  is a monotonic function of  $\Delta(G, O)$ , then
- $$P(O|B) > [P(O|C) = P(O|A)] > P(O|G), \text{ for } G \notin \{A, B, C\}.$$



### Defining the Likelihoods $P(O|G)$

- Assuming Boltzmann distribution and writing  $\exp\{x\}$  for  $e^x$ , likelihoods become

$$P(O|G) = \alpha \exp\{-\beta c(G + O)\}$$

$$P(\bar{O}|G) = \alpha \exp\{-\beta c(G + \bar{O})\}$$

where  $\alpha$  is a normalizing constant, and  $\beta$  is a positive constant.

- Taking ratio of two equations, it follows that

$$P(O|G)/P(\bar{O}|G) = \exp\{\beta \Delta(G, O)\}$$

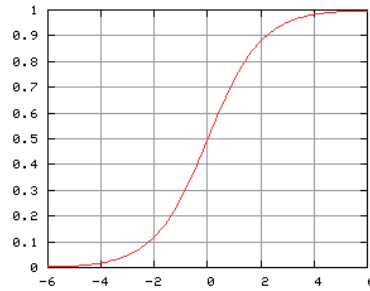
and hence

$$P(O|G) = 1/(1 + \exp\{-\beta \Delta(G, O)\}) = \text{sigmoid}(\beta \Delta(G, O))$$

(whiteboard)



### Defining the Likelihoods $P(O|G)$



$$P(O|G) = \text{sigmoid}(\beta\Delta(G, O))$$

$$\Delta(G, O) = c(G + \bar{O}) - c(G + O)$$

E.g.,

$$P(O|G) < P(\bar{O}|G) \text{ if } c(G + \bar{O}) < c(G + O)$$

$$P(O|G) = 1 \text{ if } c(G + O) < c(G + \bar{O}) = \infty$$

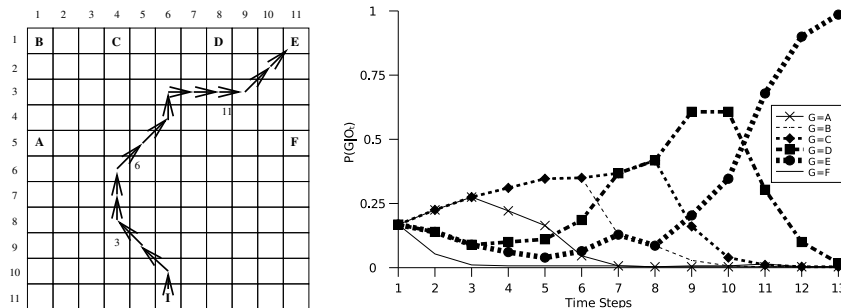


### Probabilistic Plan Recognition as Planning: Summary

- A plan recognition problem is a tuple  $T = (P, \mathcal{G}, O, Prob)$  where
  - $P$  is a planning domain  $P = (F, I, A)$ .
  - $\mathcal{G}$  is a set of possible goals  $G, G \subseteq F$ .
  - $O$  is the observation sequence  $a_1, \dots, a_n, a_i \in O$ .
  - $Prob$  is prior distribution over  $\mathcal{G}$ .
- Posterior distribution  $P(G|O)$  obtained from:
  - Bayes Rule  $P(G|O) = \alpha P(O|G) Prob(G)$  and
  - Likelihood  $P(O|G) = \text{sigmoid}\{\beta[c(G + \bar{O}) - c(G + O)]\}$ .
- Distribution  $P(G|O)$  computed exactly or approximately:
  - exactly using optimal planner for determining  $c(G + O)$  and  $c(G + \bar{O})$  and
  - approximately using suboptimal planner for  $c(G + O)$  and  $c(G + \bar{O})$ .
- In either case,  $2 \times |G|$  planner calls are needed.



### Example: Noisy Walk

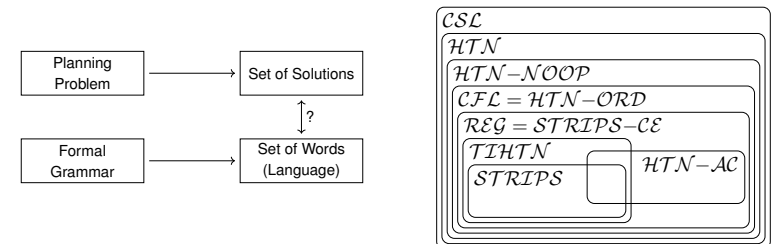


Graph on the left shows “noisy walk” and possible targets; curves on the right show posterior  $P(G|O)$  of each possible target  $G$  as a function of time.



### Plan and Goal Recognition as HTN Planning

- STRIPS: specifies what has to be in a plan.
- HTN: also excludes other elements from being in the plan.
  - No actions apart from hierarchy.
  - Enables to plan only once, regardless how many goals there are.
  - Interesting to rule out non-fitting plans/goals.
- Formalism much more expressive than STRIPS planning.



### Problem Definition

Let  $\mathcal{D} = (V, P, \delta, C, M)$  be an HTN planning domain.

#### Definition (Plan and Goal Recognition Problem)

A PGR problem  $(\mathcal{D}, s_1, O, \mathcal{G})$  extends the model by:

- $s_0$  the initial state.
- $O = \langle o_1, o_2, \dots, o_m \rangle$  the sequence of observations.
- $\mathcal{G} = \{G_1, G_2, \dots, G_r\}$  a set of possible goal (task) networks.

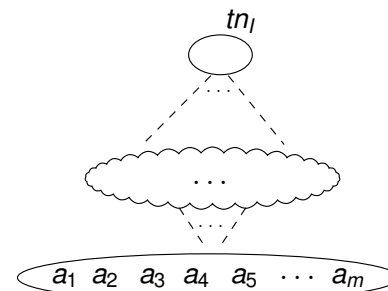
#### Definition (Recognized Plan and Goal)

Given a PGR problem, a goal  $G_i \in \mathcal{G}$  explains the observations  $\langle o_1, o_2, \dots, o_m \rangle$  iff there is a solution  $s \in Sol(\mathcal{D}, s_0, G_i)$  with an executable linearization  $\langle a_1, a_2, \dots, a_n \rangle$  of its tasks with:

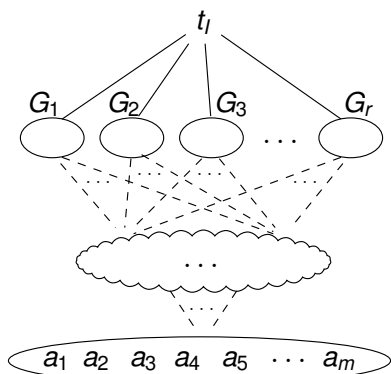
- $n \geq m$  and  $o_i = a_i$  for  $1 \leq i \leq m$ .
- $\langle a_1, a_2, \dots, a_n \rangle$  is the recognized plan.



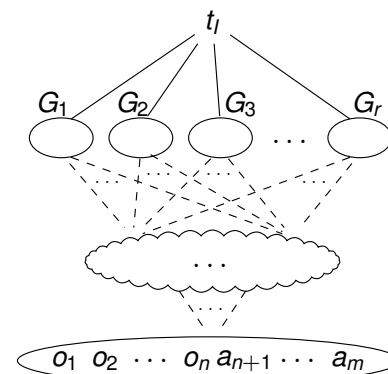
### Approach



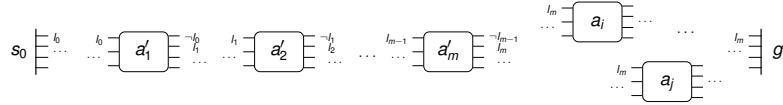
### Approach – Make Goals Reachable



### Approach – Enforce a Prefix



## Approach – Enforce a Prefix



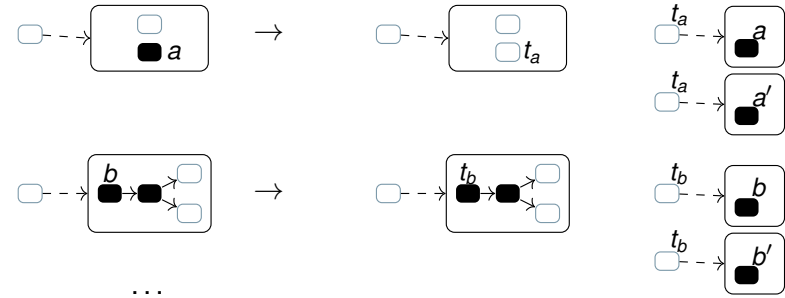
- Copy observed actions:  $a \rightarrow a, a'$
- $a'$  gets new preconditions and effects, it can only be placed at the position where it has been observed
- $a$  is modified such that they can only be placed after the prefix
- Observed actions have to be in the plan



## Approach – Enforce a Prefix

Observations:  $ab$

Set of methods:



## Approach

- Off-the-shelf HTN planners solve the PGR problem.
- Needing a single run of the planner, regardless how many goals there are.

Example: Simple cooking domain.

- There is a short plan for making noodles.
- There is a long plan for making tiramisù (needing eggs).
- Observation: an egg was broken.

HTN planning behavior:

- HTN planner is forced to generate the long plan.
- Planner will tend to find a short/cheap plan.

Consider a similar (goal) encoding in STRIPS:

- Planner might start with “open egg” and make noodles afterwards.
- This might even be cheaper when planning optimally.



## Plan and Goal Recognition (as Planning)

- We studied the *Plan and Goal Recognition* problem.
- Assumptions are more problematic than in planning.
- Less “converged” problem definition:
  - type of behavior model,
  - what is computed,
  - what is an observation,
  - ...
- One way to solve it: “Plan Recognition as Planning”.
- Compilation to planning, we have seen:
  - 1st transformation into classical planning: Miquel Ramrez and Hctor Geffner. “Plan Recognition as Planning”. In: *Proc. of the 21st Int. Joint Conf. on Artificial Intelligence (IJCAI 2009)*. AAAI Press, 2009, pp. 1778–1783
  - 2nd transformation, enabling the computation of probability distributions: Miquel Ramrez and Hector Geffner. “Probabilistic Plan Recognition Using Off-the-Shelf Classical Planners”. In: *Proc. of the 24th AAAI Conf. on Artificial Intelligence (AAAI 2010)*. AAAI Press, 2010
  - Transformation into the more expressive HTN formalism.

