Extended Goal Recognition Design with First-Order Computation Tree Logic

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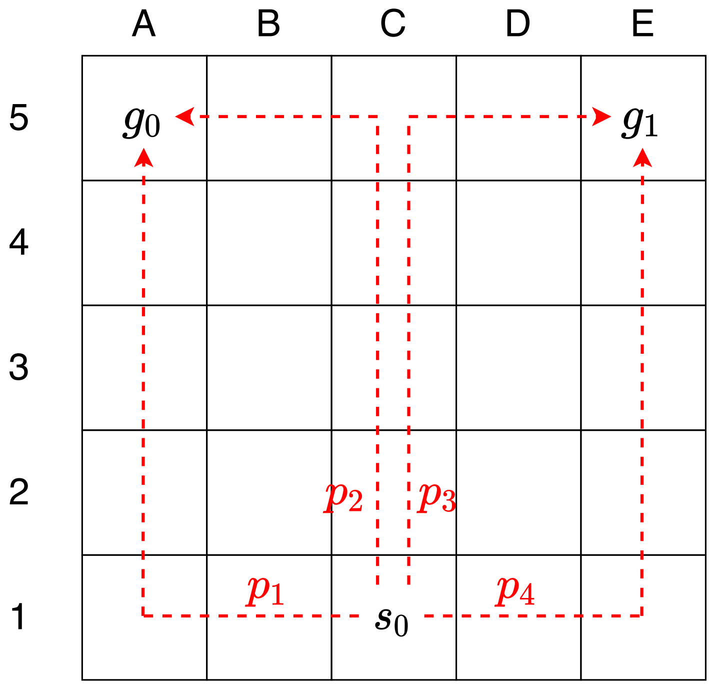
Goal Recognition Design (GRD)

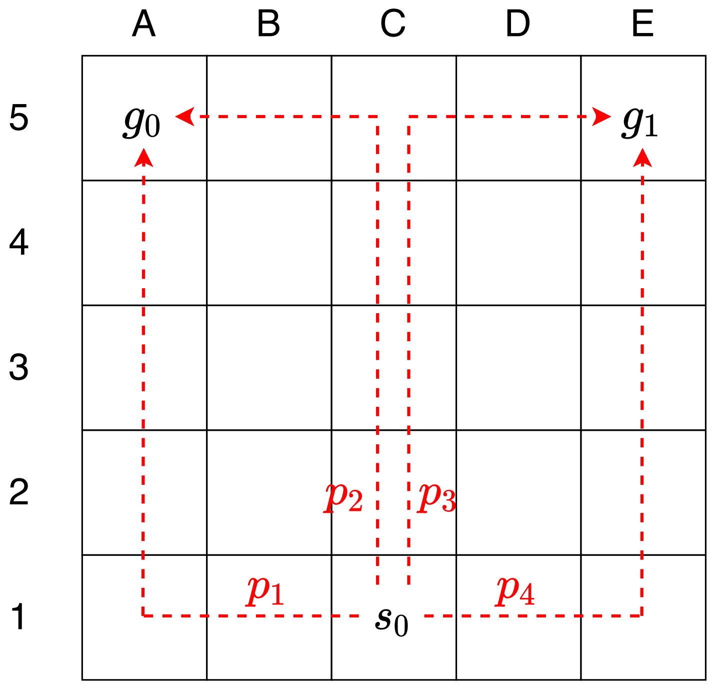
- **Goal recognition** – an observer infers the goal of an agent from a sequence of observations of agents' actions.
- **Goal recognition design**[1] – modify an environment to help observers to recognize the goal of an agent.



[1] Keren et al. Goal Recognition Design. AAAI 2014

Worst Case Distinctiveness (WCD)

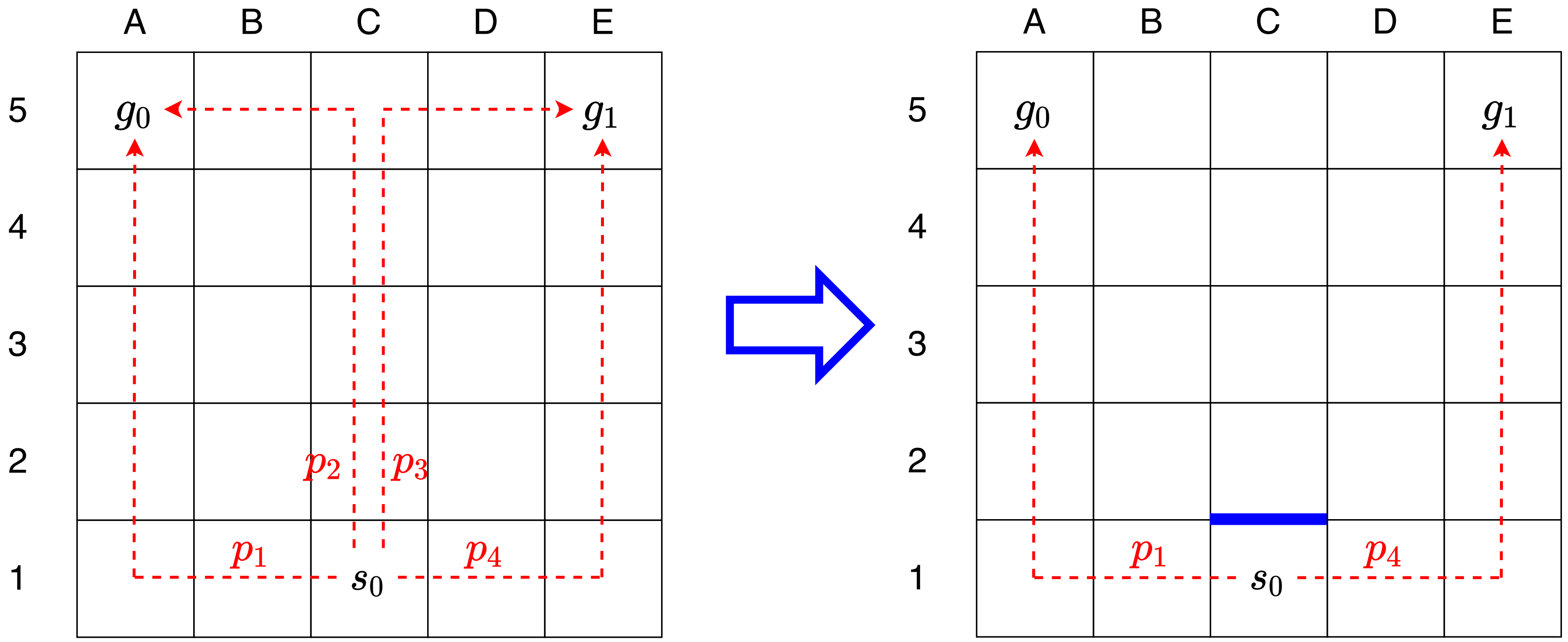
- **Worst case distinctiveness** – a popular objective function for GRD
  - The highest number of observations that an observer needs to observe *before* it can be certain of the agent's goal in the worst case.



Before redesign, WCD = 4

Minimizing WCD

- GRD aims to find a sequence of modifications to an environment in order to minimize the WCD.

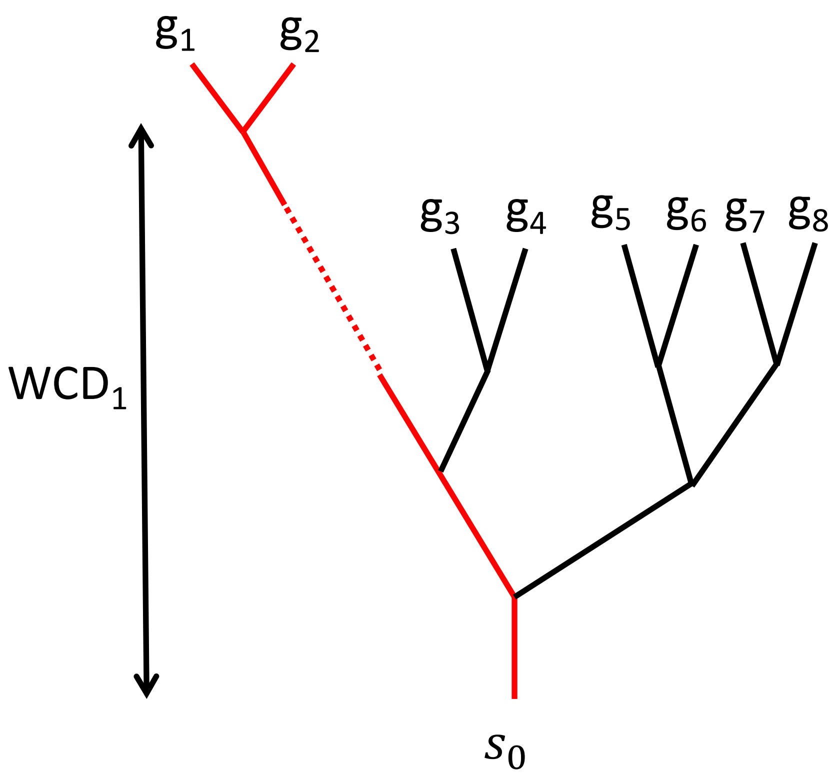


Before redesign, WCD = 4

After redesign, WCD = 0

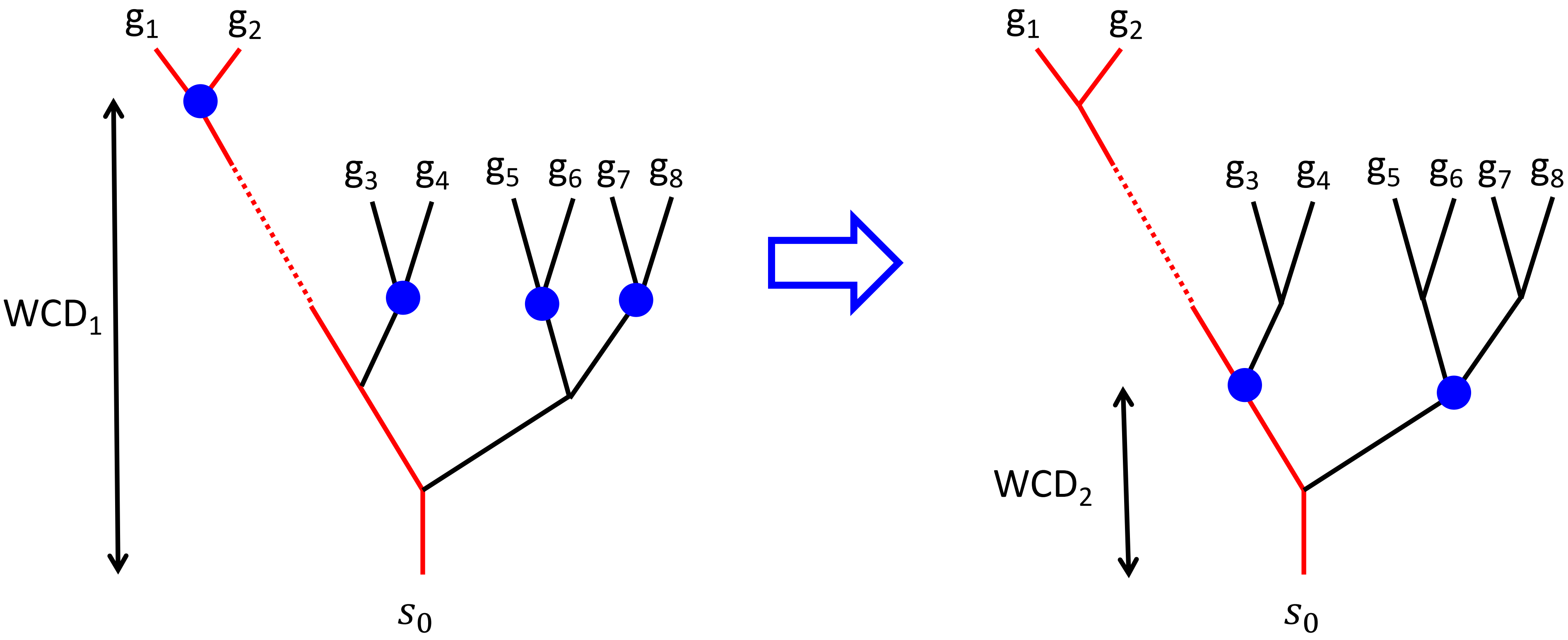
Weakness of WCD

- When there exist two paths to two different goals but share a long common prefix, it is difficult to reduce the WCD even if other goals can be recognized easily.



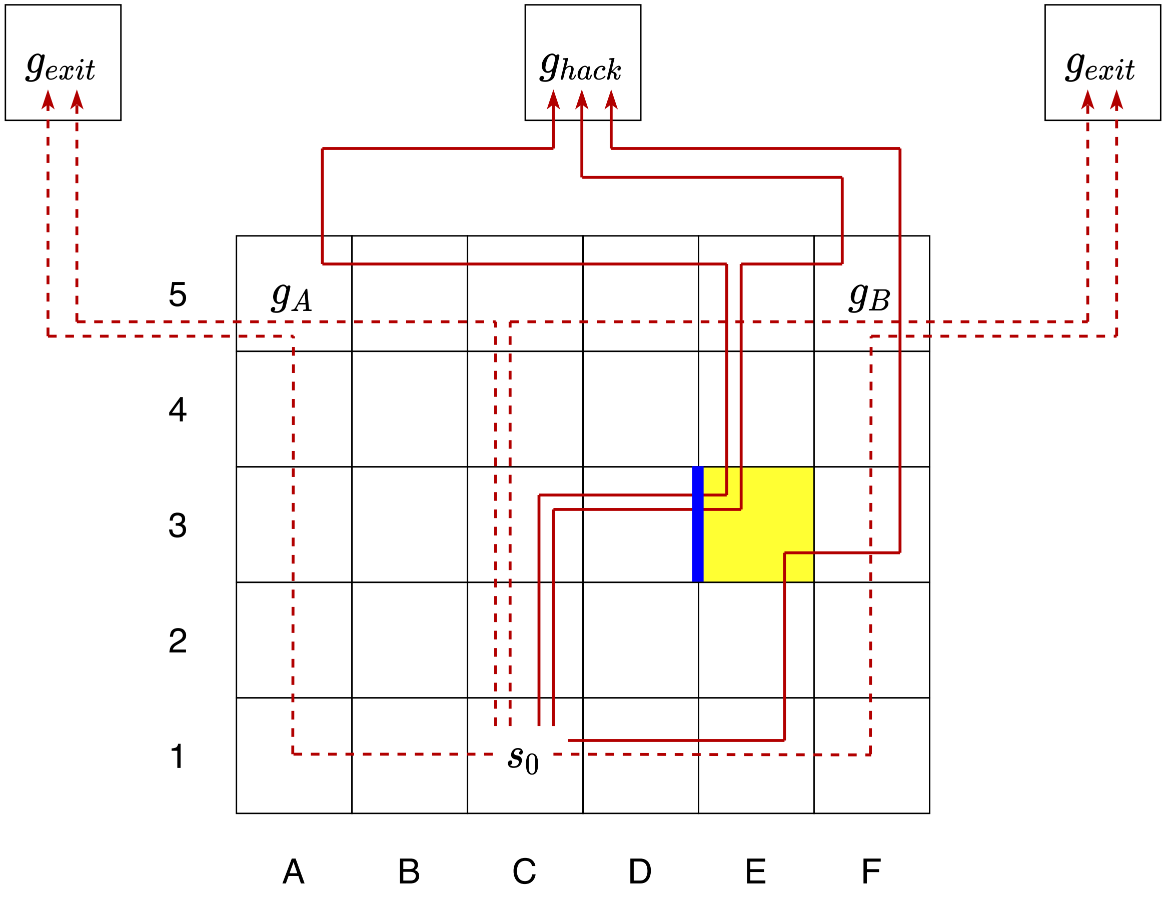
Goal Condition

- Instead of asking exactly which goal an agent aims for, an observer asks whether the agent aims for a **goal condition**
  - e.g., one of any two goals but not any other goals
  - It is weaker than recognizing a goal exactly, but still useful.



Extended Goal Recognition Design (EGRD)

- **Goal sequence** – an agent can aim for more than one goal.



Our Contributions

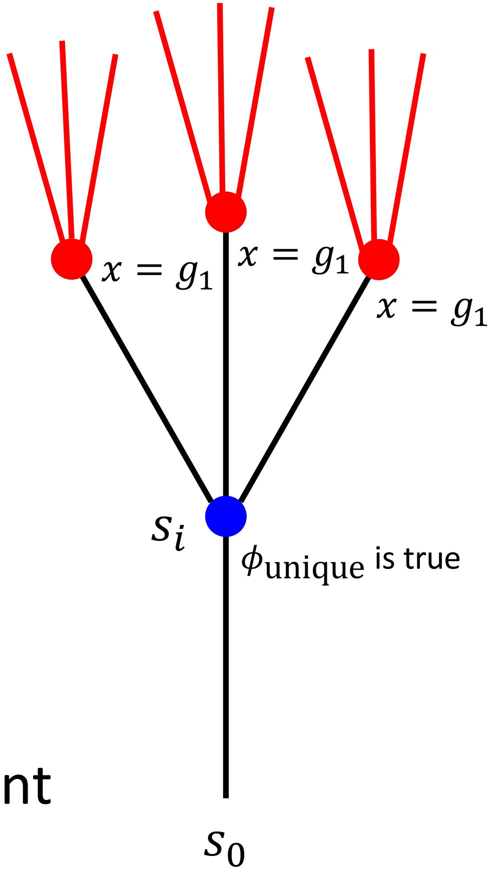
- **A framework of extended goal recognition design**
  - » Use first-order computation tree logic (FO-CTL) to express goal conditions
  - » The definition of WCD based on goal conditions.
  - » Finding WCD by model checking
- **A graphical representation of FO-CTL sentences for extended goal recognition**
  - » A translation algorithm from goal query graphs to FO-CTL sentences
- **The EGRD search algorithm**
  - » A caching mechanism for speeding up the search algorithm

First-Order Computation Tree Logic (FO-CTL)

- FO-CTL = first-order logic with path quantifiers (**A** and **E**) and temporal operators (**F**, **G**, **X**, and **U**)
  - » **A** ψ means ψ holds on all paths
    E ψ means ψ holds on at least one path
    where ψ **is either**
    - **F** ϕ means ϕ eventually has to hold
      G ϕ means ϕ always holds
      X ϕ means ϕ holds at the next state
      (ϕ_1 **U** ϕ_2) means ϕ_1 has to hold at least until ϕ_2 holds
  - » We assume no function symbol, and there is only one predicate symbol Goal(g)
    - The predicate symbol Goal will be omitted.
- For example,

$$\phi_{\text{unique}} = \exists x\{\mathbf{AF}\ (x \wedge \forall x'[(x' \neq x) \Rightarrow \mathbf{AG}\ \neg x'])\}$$

which checks whether a goal g exists such that an agent must eventually achieve g while the agent will not achieve any other goal after achieving g.



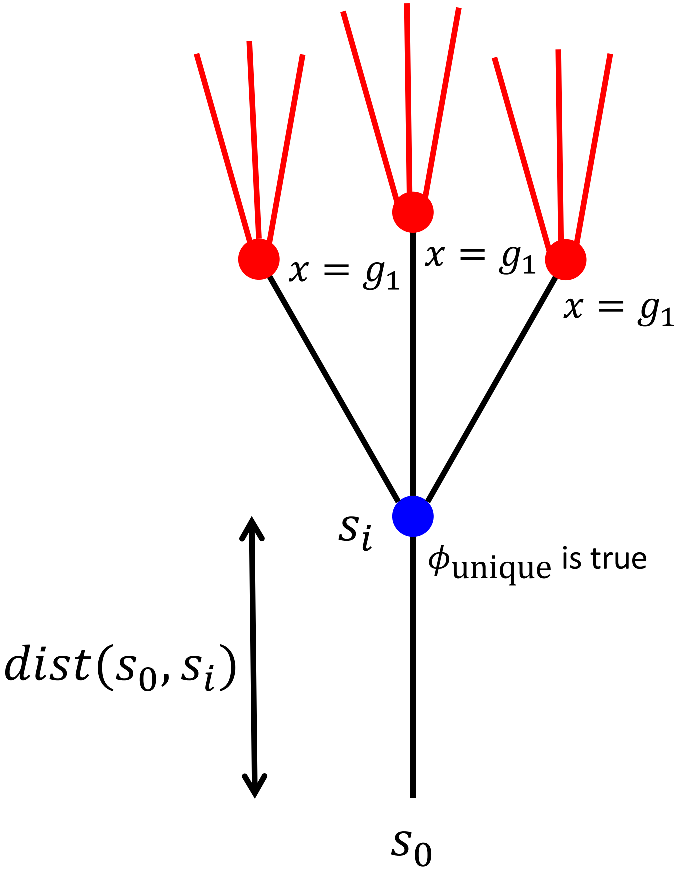
The WCD of a Goal Condition

- The WCD of a goal condition ϕ is

$$\left\{ \max_{p \in P^{leg}} \min_{s_i \in S_\phi(p)} [dist(s_0, s_i)] \right\} - 1$$

where

- P^{leg} is the set of all *legal paths*
- $S_\phi(p)$ is the set of states on a legal path $p \in P^{leg}$ such that ϕ is true in these states
- $dist(s_0, s_i)$ is the distance between s_i and the initial state s_0

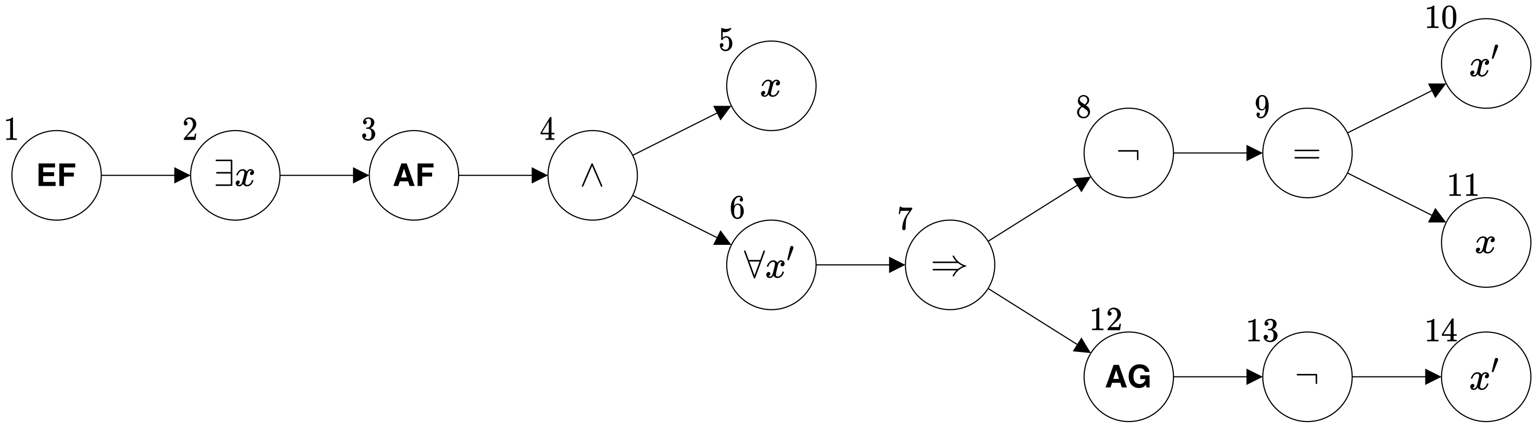


Finding WCD by Model Checking

- Given a goal condition ϕ, evaluate **EF** ϕ at the initial state s_0 by model checking.
- For example,

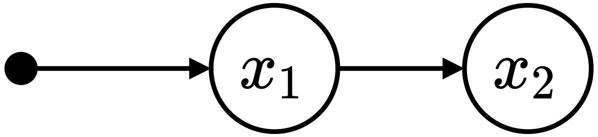
$$\textbf{EF}\ \phi_{\text{unique}} = \textbf{EF}\ \exists x\{\textbf{AF}\ (x \wedge \forall x'[(x' \neq x) \Rightarrow \textbf{AG}\ \neg x'])\}$$

- Attach a *cost function* to each node in a sentence.
  - » e.g, the cost function of Node 1 is max, and the cost function of Node 2 is $dist(s_0, s_i)$
- The costs, along with the truth values, are propagated to the root node during the execution of the model checking algorithm.

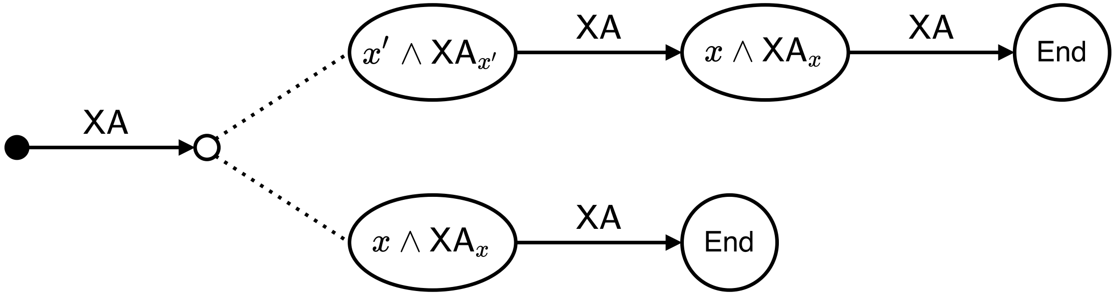


Goal Query Graph (GQG)

- **Goal query graph** – a graphical representation of goal conditions
- For example, the GQG of $\exists x_1 \exists x_2[\textbf{AF}\ [x_1] \wedge \textbf{AX AF}\ x_2]$ is



- Directed acyclic graph:
  - » 3 vertex types: state vertices, nil vertices, and choice vertices
  - » 5 edge types: **AP** edges, **EP** edges, **AX** edges, **EX** edges, and choice edges
- State vertices can have **state conditions** (e.g., $(x_2 \vee \neg x_1)$)
- AP edges and EP edges can have **edge conditions** (e.g., $\text{XA} = \forall x[\neg x]$)
- Choice vertices and choice edges:



Translating GQGs into FO-CTL Sentences

- A depth-first search in the goal query graph.
  - The FO-CTL sentence is constructed in a bottom-up fashion.
  - Each vertex/edge type has its own rule for translation.
  - Insert existential qualifiers for the free variables.
  - Optimization techniques for shortening the sentence.
- Running time: $O(|V| + |E|)$

The EGRD Search Algorithm with Caches

- A depth-limited, best-first search
  - Store unexpanded transition systems in an open list.
  - Repeat the following steps until the open list is empty or the time limit
    - Remove a transition system M from an open list
    - Use a model checking algorithm to evaluate M and compute WCD.
    - If the evaluation is true and the WCD is lower than the best WCD
      - set this transition system as the best solution.
    - If the search depth of M is less than a threshold
      - apply modifications to M to insert the generated models into the open list.
  - Return the best solution

The Caching Mechanism

- **Caching mechanism** – store the evaluation results of the recursive calls in the model checking algorithm in a cache.
  - Reuse the results in subsequent runs of the model checking algorithm.
  - Need a succinct encoding of transition systems' states.

Empirical Evaluation

- The goal query graph:

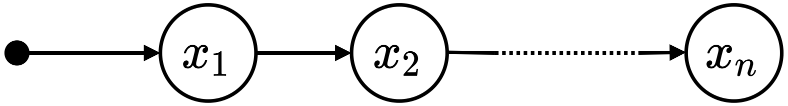
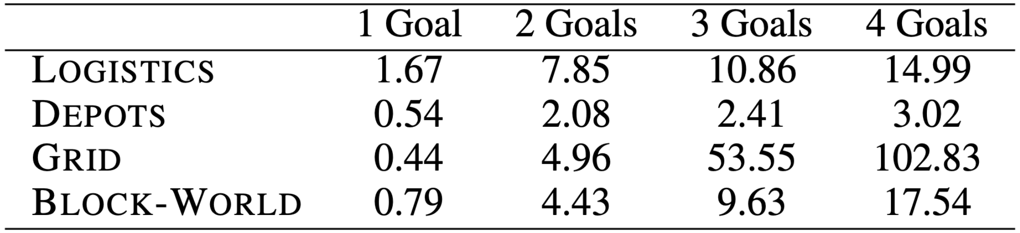
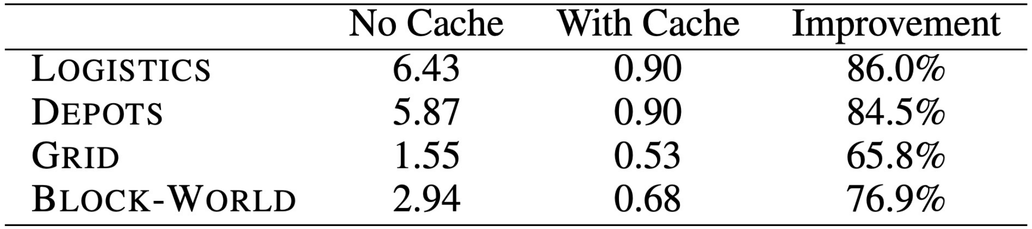


Table 1: Execution times (in sec.) vs. the number of goals.



	1 Goal	2 Goals	3 Goals	4 Goals
LOGISTICS	1.67	7.85	10.86	14.99
DEPOTS	0.54	2.08	2.41	3.02
GRID	0.44	4.96	53.55	102.83
BLOCK-WORLD	0.79	4.43	9.63	17.54

Table 2: Execution times (in sec.) with and without cache.



	No Cache	With Cache	Improvement
LOGISTICS	6.43	0.90	86.0%
DEPOTS	5.87	0.90	84.5%
GRID	1.55	0.53	65.8%
BLOCK-WORLD	2.94	0.68	76.9%

- The running times increase as the number of goals increases.
- The caching mechanism can greatly reduce the running time of the EGRD search algorithm.

Summary and Future Work

- Extended goal recognition design
  - Weaker goal conditions
  - Agents can aim for a sequence of goals
- Express goal conditions in FO-CTL
  - Finding WCDs by model checking
  - Goal query graphs
- Caching mechanism to speed up the EGRD search
- Future work: Partial observability
- The source code with additional examples:

  https://github.com/chiuau/AAAI22-egrd

Thank you!