Hierarchical Planning and Reasoning about Partially Ordered Plans – From Theory to Practice

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College of Engineering and Computer Science
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Australian
National
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Introduction

About the Speaker

Who am I? Why am I here?

- Did my PhD in Ulm, at the Institute of Artificial Intelligence
  - Under the supervision of Prof. Biundo
  - In the context of Hierarchical Planning, applied to Companion Technology (cognitive systems), specifically to provide planning-based user assistance
- Worked closely with Prof. Glimm (13 publications! – and counting)
- Bio:
  - 2002–2009: Studied Computer Science in Freiburg im Breisgau
  - 2009–2017: Doctoral Studies in Ulm
  - 2017–2019: Post-Doc – still in Ulm
  - 2019–2021: Lecturer (Assistant/Junior Professor) at the ANU
  - 2022–. . . : Senior Lecturer (Associate/W2 Professor) at the ANU

Talk/Expertise Overview: Main Research Interests

Problem classes:

- (Non-hierarchical) Partial Order Causal Link (POCL) Planning
- Hierarchical Task Network (HTN) Planning

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- Complexity investigations
  (of various interesting problems)
- Heuristic search
  (algorithms, heuristics, etc.)
- Practical applications
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} from theory to practice!

Planning in a Nutshell: Planning in a Nutshell

We consider *classical planning problems*, which consist of:

- An initial state s_I – all "world properties" true in the beginning.
- A set of available actions – how world states can be changed.
- A goal description g – all properties we'd like to hold.

What do we want?

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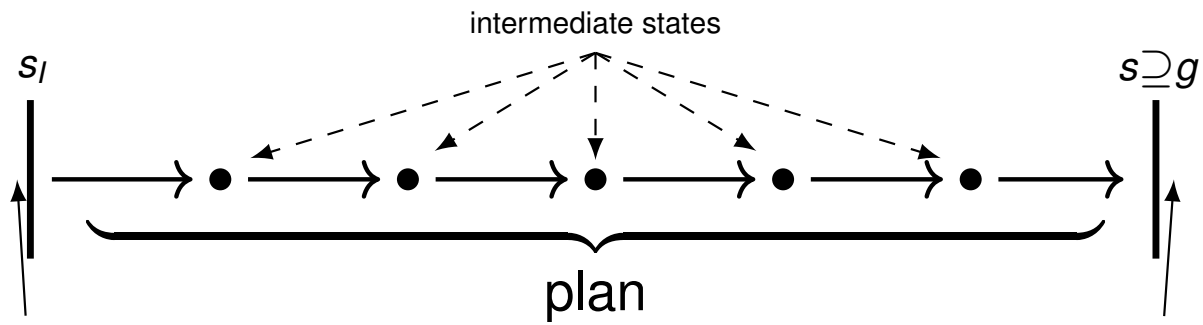
What do we want?

→ Find a *plan* that transforms s_I into g.



Planning in a Nutshell: Example: Home Theater Assembly Assistant

Sink devices:

- Television (requires video)
- Amplifier (requires audio)

Source devices:

- Blu-ray player
- Satellite receiver
  (both produce audio & video)

Planning in a Nutshell: Definitions, Examples

- Planning problems are usually defined in terms of a description language based on a first-order predicate logic.
  - Predicates, like $HasPort(?device, ?port)$, express relationships between variables representing objects.
  - Constants, like *AMPLIFIER* and *CABLE_HDMI*, represent objects.
- States are sets of (ground) propositions, e.g.,
  $s \supseteq \{HasPort(AMPLIFIER, HDMI),$
  $HasPort(AMPLIFIER, CINCH),$
  $HasPort(CABLE\_HDMI, HDMI),$
  $IsConnected(AMPLIFIER, CABLE\_HDMI, HDMI)\}$

(connected to each other)

Planning in a Nutshell: Definitions, Examples

- Actions are defined by preconditions and effects, e.g.,

  plugIn(?*cable*, ?*device*, ?*port***)**

  precondition: $HasPort(?device, ?port) \wedge$
  $HasPort(?cable, ?port) \wedge$
  $\nexists ?cable' : IsConnected(?device, ?cable', ?port)$
  $\nexists ?device' : IsConnected(?device', ?cable, ?port)$

  effect: $IsConnected(?device, ?cable, ?port)$

  (Signal flow not shown for the sake of simplicity)

Planning in a Nutshell: Planning Problem Definition in the Home Theater Domain

Initial state:

- HasPort(. . . , . . .) // which device has which ports?
- IsConnected(. . . , . . . , . . .) // how are the connections initially?
- HasSignal(. . . , . . . , . . .) // which device has which signals?

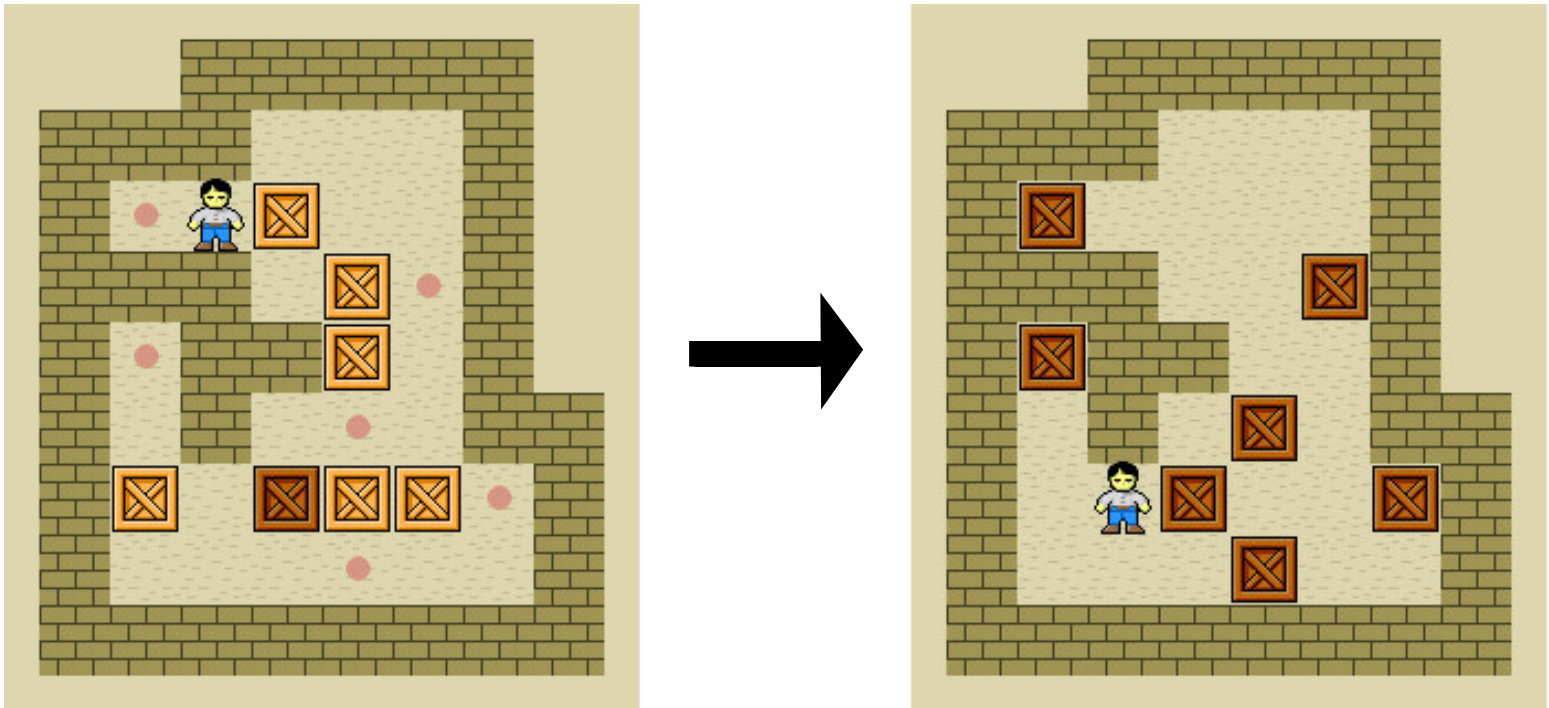
Action portfolio:

- ***plugIn(****?cable*, ?*device*, ?*port****)*** // plugging in a cable
- ***plugOut(****?cable*, ?*device*, ?*port****)*** // in case plugging out is allowed

Goal description:

- HasSignal(. . . , . . . , . . .) // e.g., HasSignal(TV, VIDEO, BR) denoting
- . . . that the TV has the video signal of the blu-ray player

Examples of Planning Problems: Computer Games Sokoban



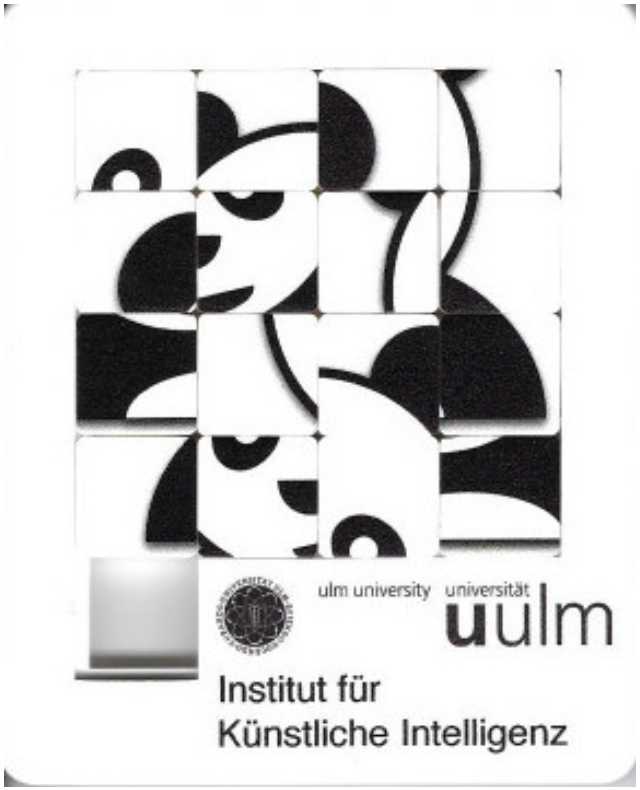
Title: A Sokoban puzzle and its solution

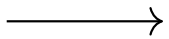
Source: `https://en.wikipedia.org/wiki/Sokoban`

Puzzle Author: Carlos Montiers Aguilera

Graphics Author: Borgar Þorsteinsson and Pascal Bercher.
The graphic has been modified multiple times (e.g., conversion from animated gif into this one.)

Examples of Planning Problems: Puzzle Games (here: Sliding Tile Puzzle)





Initial State

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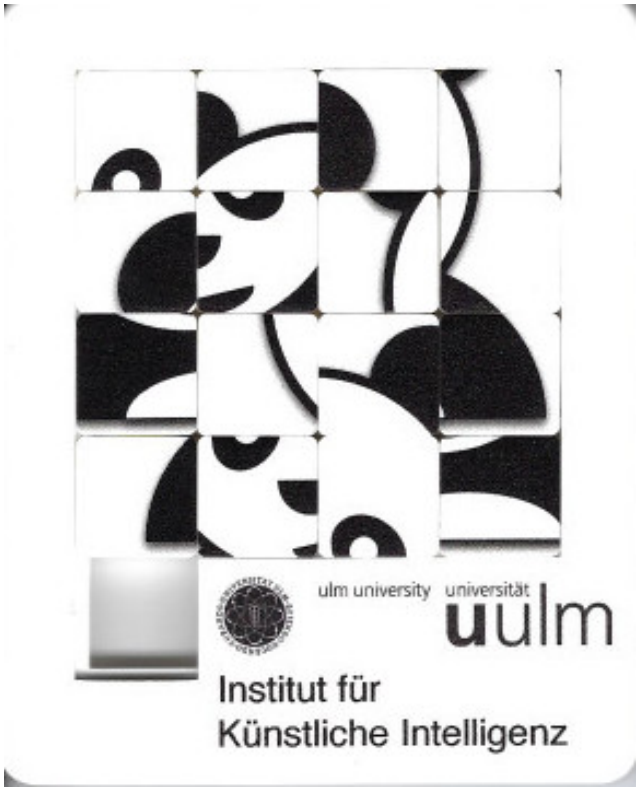
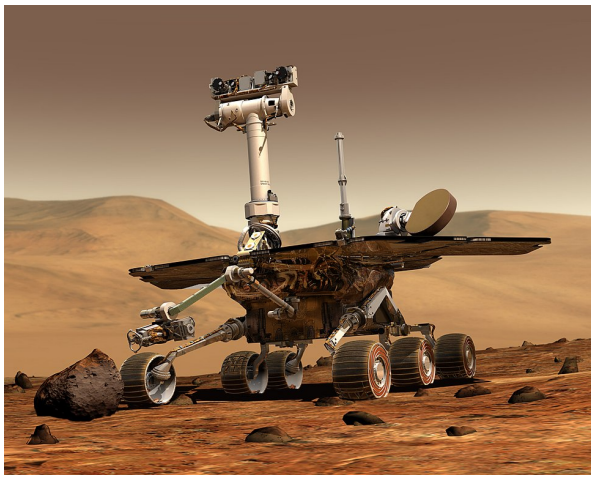


Initial State

Goal State

Examples of Planning Problems: Mars Rovers

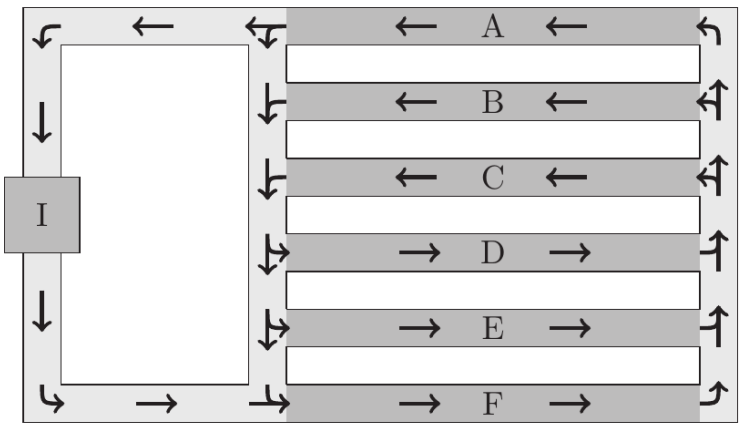




- MAPGEN (Mixed Initiative Activity Planning Generator) is a ground-based decision support system for Mars Exploration Rover mission operations and science teams that begins to give content to the notion of autonomous planetary exploration.
- The paradigm is to enable the person using the software to critique a plan that the system automatically produces and ensure that resulting plans are viable within mission and flight rules.

from *https://www.nasa.gov/*

Examples of Planning Problems: Automated Factories (here: a Greenhouse)



Source: `https://www.lemnatec.com/`

Copyright: With kind permission from *LemnaTec GmbH*

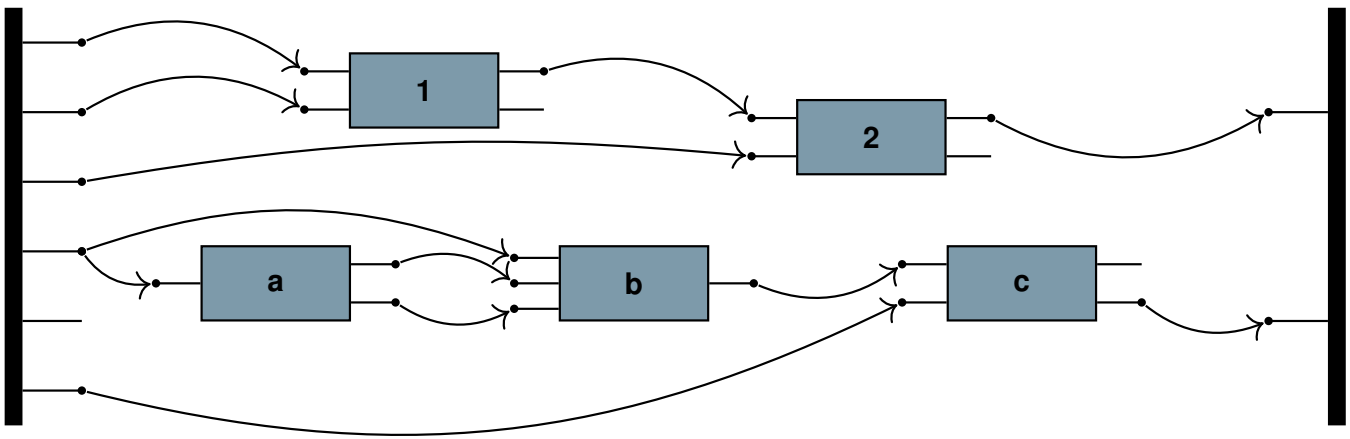
Further reading:

- M. Helmert and H. Lasinger. "The Scanalyzer Domain: Greenhouse Logistics as a Planning Problem". In: *Proceedings of the 20th International Conference on Automated Planning and Scheduling (ICAPS 2010)*
- The IPC Scanalyzer Domain in PDDL (see paper above).

POP and POCL Planning

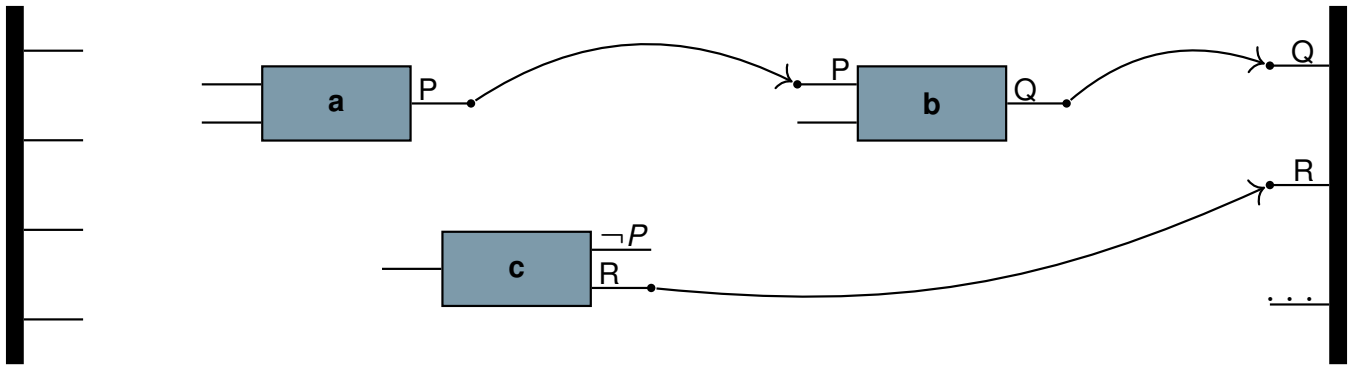
Introduction

- Most planning systems generate *action sequences* as solutions!
- But plans may be just *partially ordered* in general.



- Partial Order Causal Link (POCL) plans are partially ordered
- POCL plans are interesting for many tasks like plan optimization

(A Glance at the) Planning Procedure



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- Causal dependencies are represented using causal links

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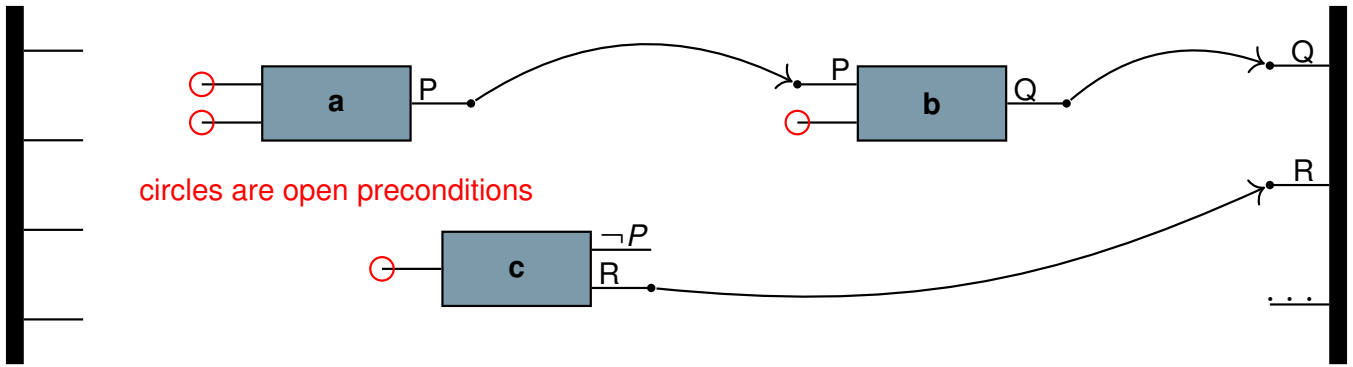

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- For solution POCL plans,
  - all preconditions must be supported, and

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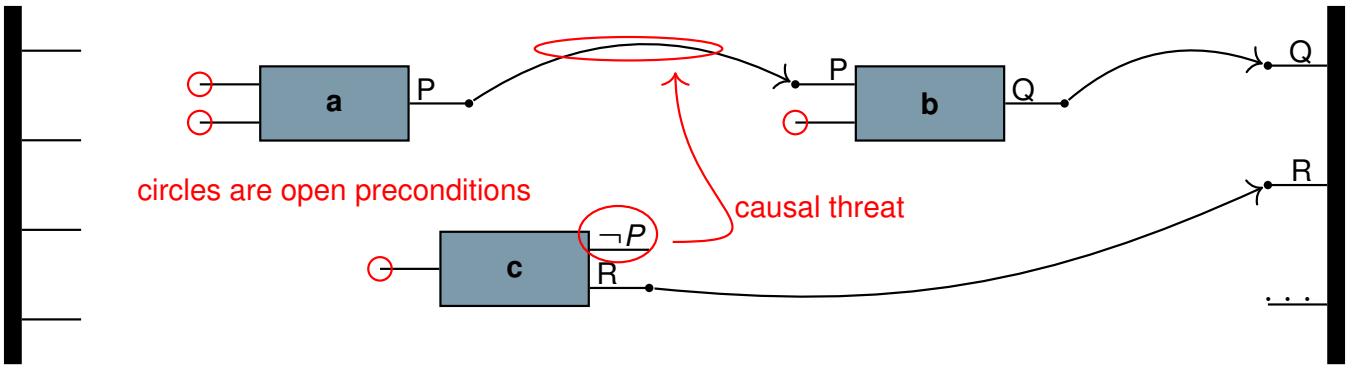

- Partial Order Causal Link (POCL) plans are partially ordered
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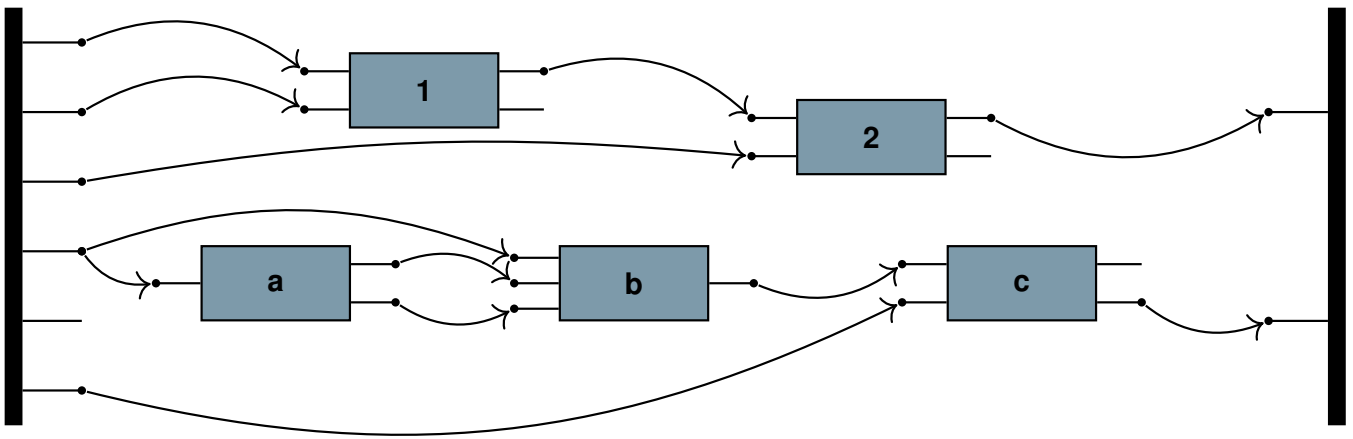
- For solution POCL plans,
  - all preconditions must be supported, and
  - all causal threats must be resolved

Solutions / Summary

- Once all preconditions have a causal link and there are no causal threats, we have a solution:



- In a solution, every linearization that's compatible with the given ordering constraints is an executable action sequence.
- Therefore, POCL plans can represent up to an exponential number of sequential solutions!

So What?

Why did I introduce this?

- Because I'm interested in it! :) I'm an expert for POCL plans, notably complexity analyses. For example I studied, among others, how hard it is to decide whether:
  - a solution can be optimized by removing an action?
  - the makespan (parallel execution time) can be optimized by removing ordering constraints?
  - a given partial plan can be turned into a solution by ignoring certain information (like causal links)?

  (most problems are NP-complete)

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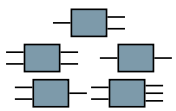
  (most problems are NP-complete)
- Because it was used in the assembly assistant, notably for plan explanations (explaining why a specific action is in a plan)

HTN Planning

Introduction: Introduction to HTN Planning

primitive tasks



compound tasks

$$\mathcal{P} = (F, P, \delta, C, M, s_I, c_I, g)$$

- F a set of facts
- P a set of primitive task names
- $\delta : P \rightarrow (2^F)^3$ the task name mapping
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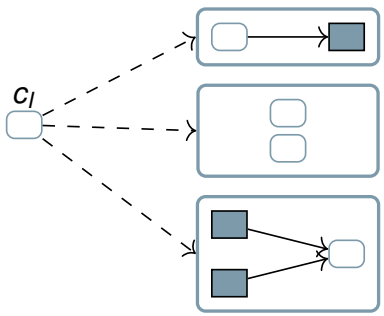

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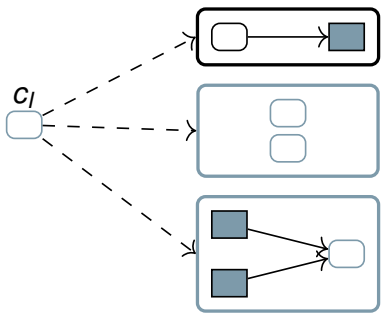

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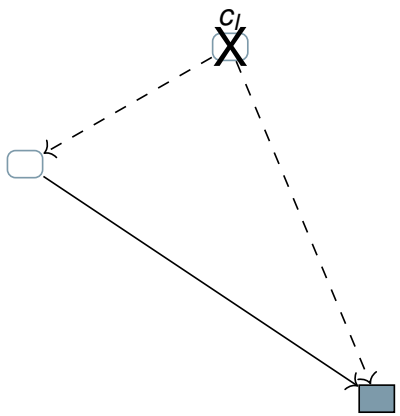

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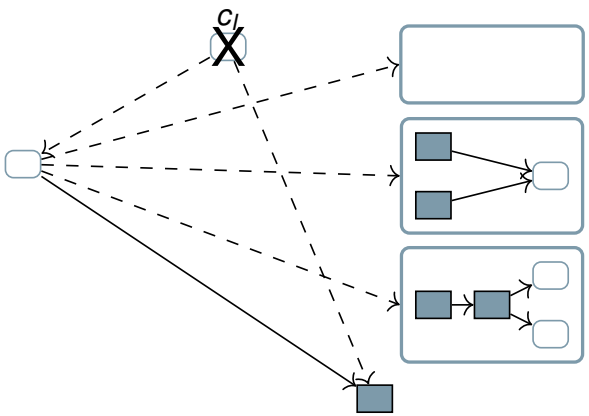

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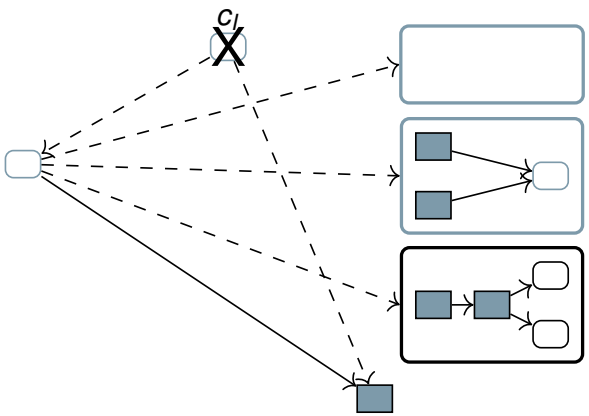

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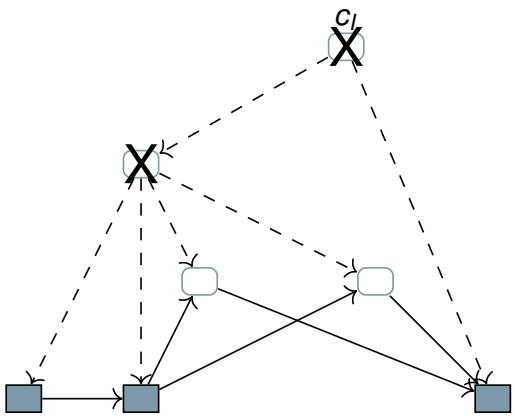

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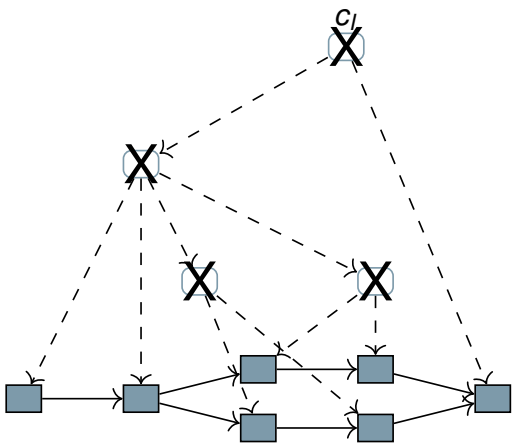

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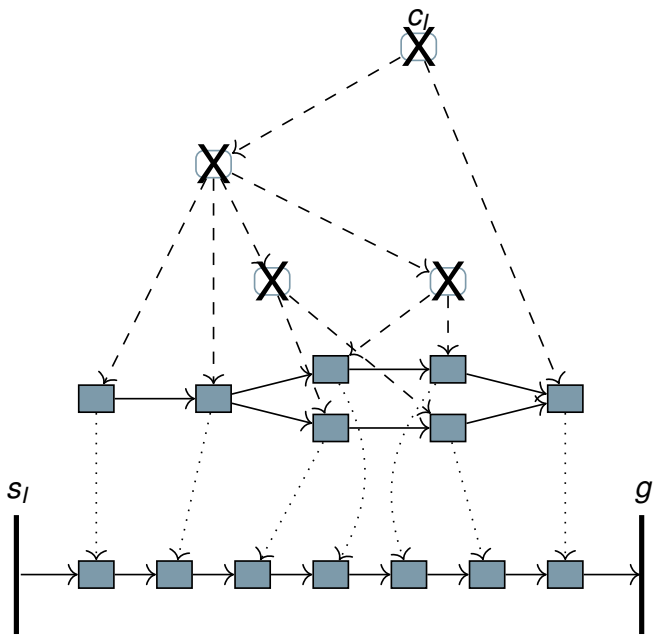

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- $s_I \in 2^F$ the initial state
- $g \subseteq F$ the (optional) goal description

A solution task network *tn* must:

- be a refinement of c_I,
- only contain primitive tasks, and
- have an executable linearization.

Introduction: Motivation

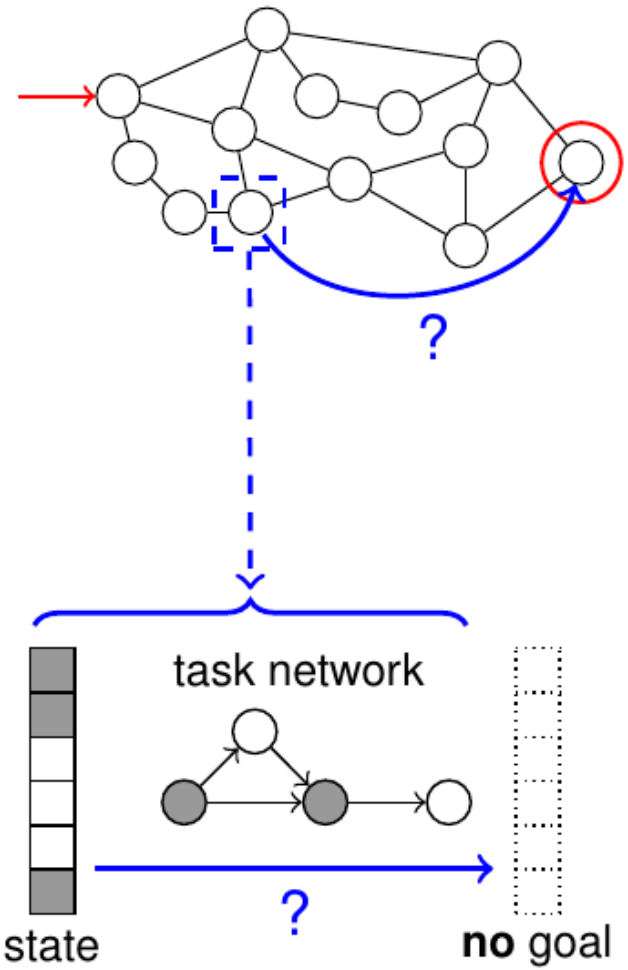
Why defining/solving a *Hierarchical Problem*?

- In many real-world applications, knowledge is given in form of control rules: we know the steps required to perform some task.
- More control on the generated plans, since all the “rules” need to be obeyed. We can *exclude* undesired plans!
- Plans can be presented *more abstract* by relying on task hierarchies.
- And many more!

Heuristic Search: Introduction

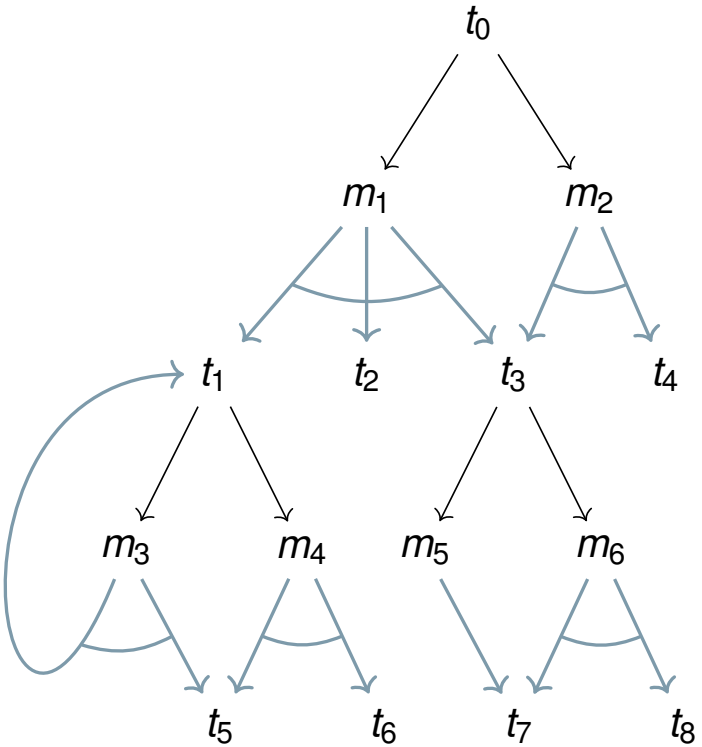
How does search work?

- We systematically “search” through the search space, i.e., we explore all “options” from an initial search node.
- In *heuristic* search, we explore search nodes according to their heuristic value.
- Heuristics estimate the distance from the current search node to the nearest goal.
- They do so by solving a simplified problem and using its cost as heuristic value. (Example: straight line distance!)



Heuristic Search: TDG-based Heuristics

A Task Decomposition Graph (TDG) represents the task hierarchy:



A TDG is a (possibly cyclic) bipartite graph $\mathcal{G} = \langle N_T, N_M, E_{(T,M)}, E_{(M,T)} \rangle$ with

- N_T, the task nodes,
- N_M, the method nodes,
- $E_{(T,M)}$, the task edges,
- $E_{(M,T)}$, the method edges.

P. Bercher et al. "An Admissible HTN Planning Heuristic". In: ***IJCAI 2017***

P. Bercher, S. Keen, and S. Biundo. "Hybrid Planning Heuristics Based on Task Decomposition Graphs". In: ***SoCS 2014***

(Partially) based on the TDG as well: *Landmarks*

M. Elkawkagy, **P. Bercher**, B. Schattenberg, and S. Biundo. "Improving Hierarchical Planning Performance by the Use of Landmarks". In: ***AAAI 2012***

D. Höller and **P. Bercher**. "Landmark Generation in HTN Planning". In: ***AAAI 2021***

Heuristic Search: TDG-based Heuristics

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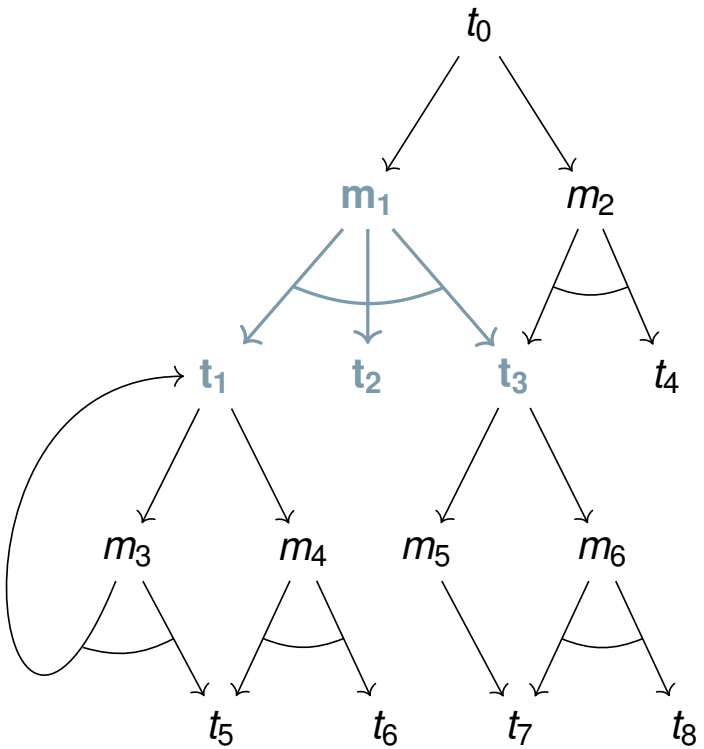
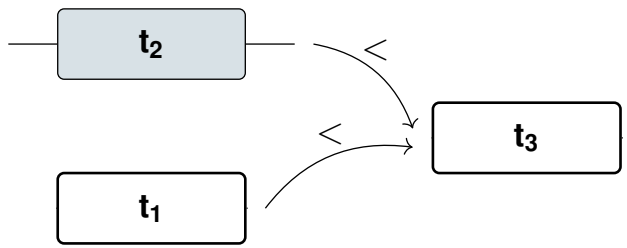


What to do?

- Minimize over all methods,
- add tasks within a method



$$h_M(m_1) = \sum_{t_i \in \{t_1, t_2, t_3\}} h_T(t_i)$$
$$= h_T(t_1) + cost(t_2) + h_T(t_3)$$

P. Bercher et al. "An Admissible HTN Planning Heuristic". In: ***IJCAI 2017***

P. Bercher, S. Keen, and S. Biundo. "Hybrid Planning Heuristics Based on Task Decomposition Graphs". In: ***SoCS 2014***

Heuristic Search: Further Work Related to HTN Heuristics

- Based on landmarks, i.e., tasks/methods/facts that are required in any solution.
- Encode delete- and ordering-relaxed HTN problem as Integer Linear Program (ILP).
- Encode search node (relaxed) into a non-hierarchical planning problem (and then use existing heuristics from that setting).

D. Höller and **P. Bercher**. “Landmark Generation in HTN Planning”. In: ***AAAI 2021***

D. Höller, **P. Bercher**, and G. Behnke. “Delete- and Ordering-Relaxation Heuristics for HTN Planning”. In: ***IJCAI 2020***

D. Höller, **P. Bercher**, G. Behnke, and S. Biundo. “HTN Planning as Heuristic Progression Search”. In: ***JAIR*** (2020)

– as above –. “On Guiding Search in HTN Planning with Classical Planning Heuristics”. In: ***IJCAI 2019***

– as above –. “A Generic Method to Guide HTN Progression Search with Classical Heuristics”. In: ***ICAPS 2018***

Planning-Based Assistance

Introduction: Planning-based Assistance Systems

Approach: Model the environment and task as planning problem.

- Then, automatically generate solution plans,
- choose user-friendly (i.e., meaningful) order for detailed instructions,
- repair plans if required (to deal with execution errors), and
- explain tasks or background knowledge.

Assembly Assistant: Problem Illustration

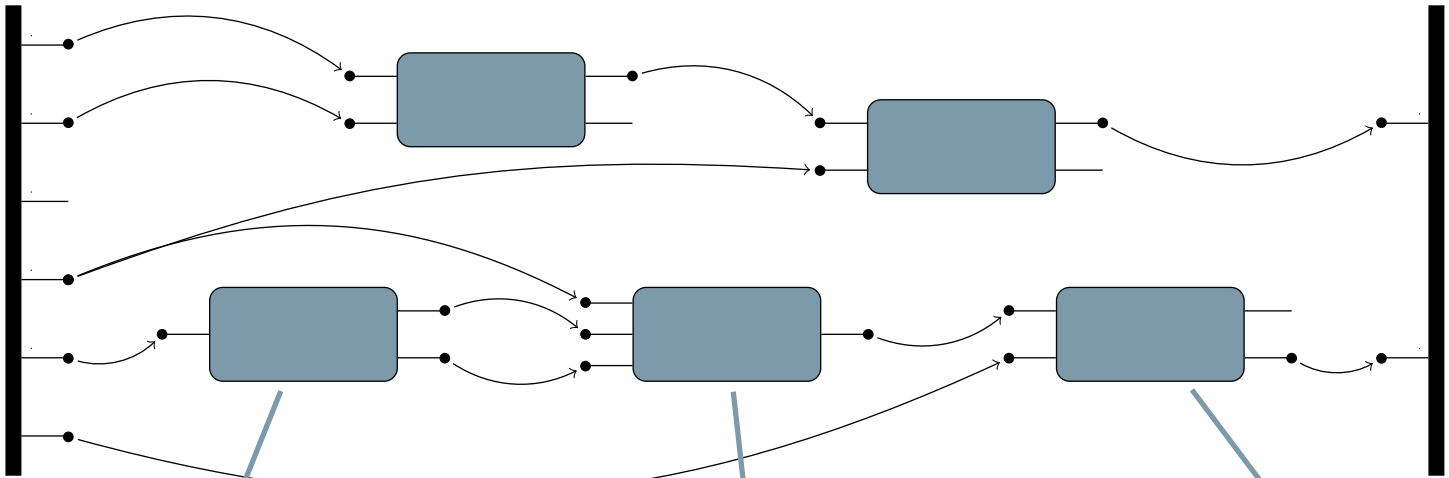
Sink devices:

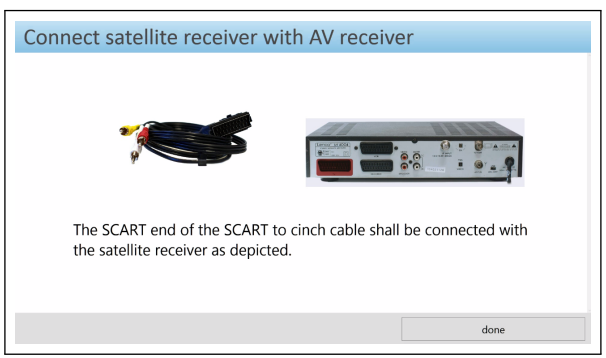
- Television (requires video)
- Amplifier (requires audio)

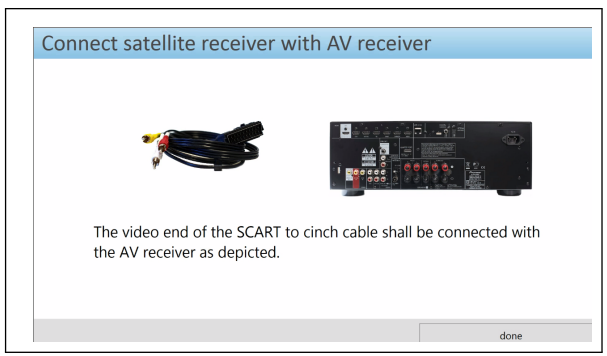
Source devices:

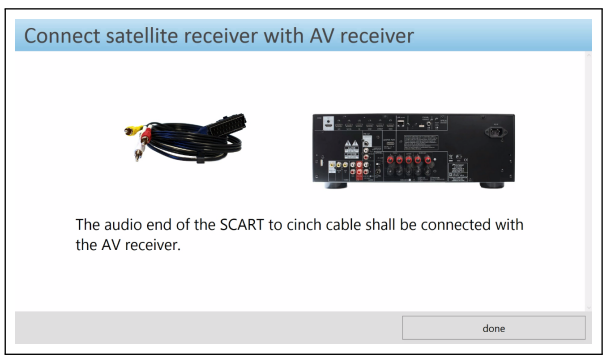
- Blu-ray player
- Satellite receiver
  (both produce audio & video)

Assembly Assistant: Solution Plan

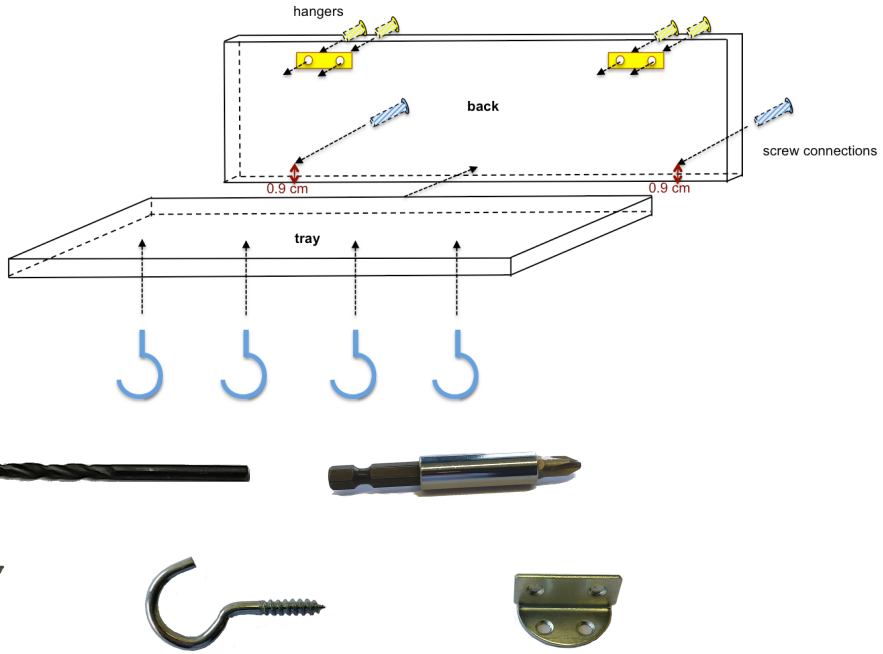








Do It Yoursef (DIY) Assistant: Problem Illustration



The material:

- Boards (need to be cut first)
- Electrical devices, e.g., drills, saws
- Attachments like drill bits and materials like nails

G. Behnke, **P. Bercher** et al. “New Developments for Robert – Assisting Novice Users Even Better in DIY Projects”. In: ***ICAPS 2020***

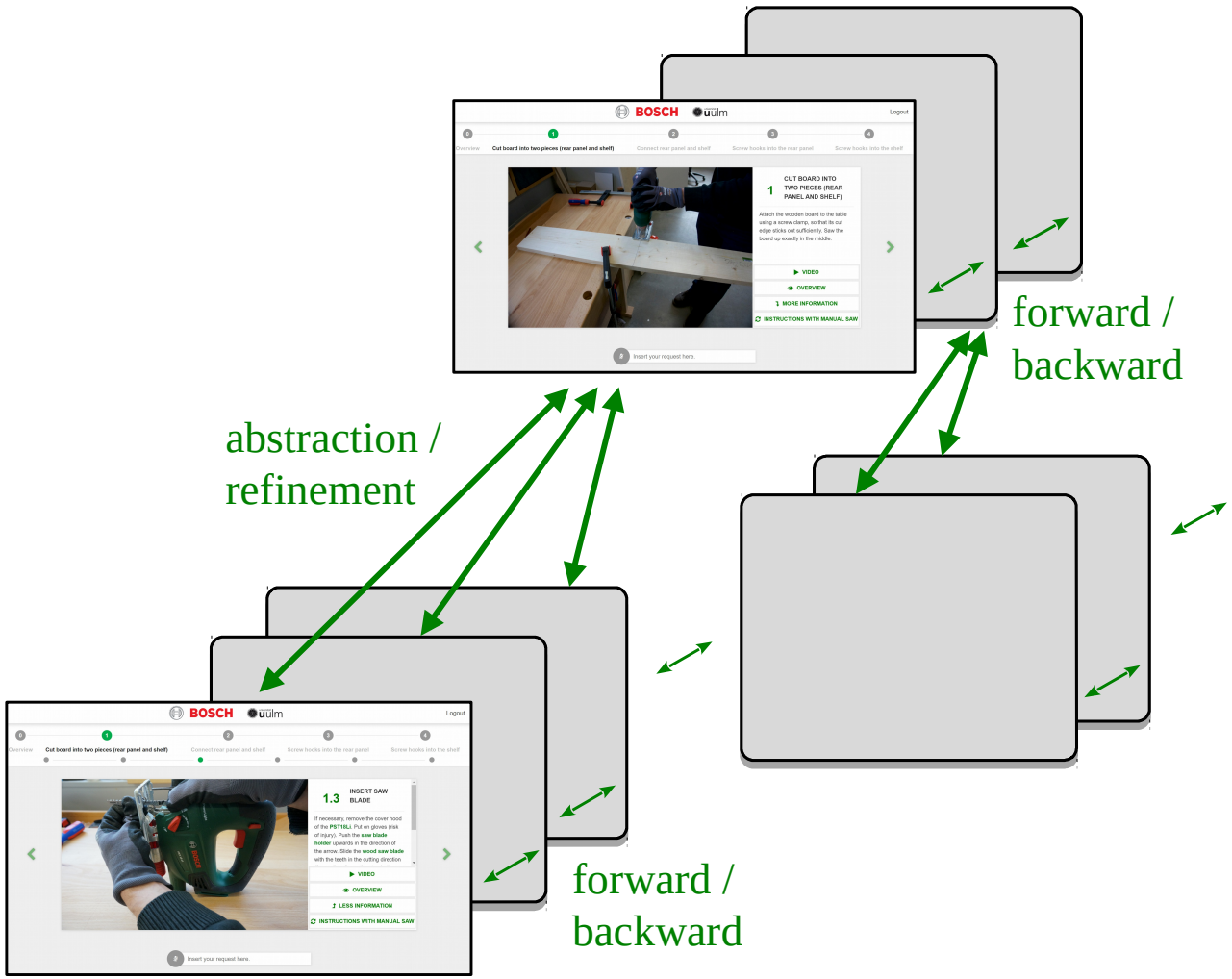
M. Kraus, M. Schiller, G. Behnke, **P. Bercher**, M. Dorna, M. Dambier, B. Glimm, and S. Biundo, W. Minker. “Was that successful? On Integrating Proactive Meta-Dialogue in a DIY-Assistant System using Multimodal Cues”. In: ***ICMI 2020***

G. Behnke, M. Schiller, M. Kraus, **P. Bercher**, M. Schmautz, M. Dorna, M. Dambier, W. Minker, B. Glimm, and S. Biundo. “Alice in DIY wonderland or: Instructing novice users on how to use tools in DIY projects”. In: ***AI Communications*** (2019)

– as above –. “Instructing Novice Users on How to Use Tools in DIY Projects”. In: ***IJCAI-ECAI 2018***

Do It Yoursef (DIY) Assistant: Exploit Task Hierarchy

Presentation of instructions on different levels of abstraction:



Summary

Main Research Interests

Problem classes:

- (Non-hierarchical) Partial Order Causal Link (POCL) Planning
- Hierarchical Task Network (HTN) Planning

Research areas:

- Complexity investigations
  (of various interesting problems)
- Heuristic search
  (algorithms, heuristics, etc.)
- Practical applications
  (or questions related to it)

} from theory to practice!

Appendix: Complexity Results

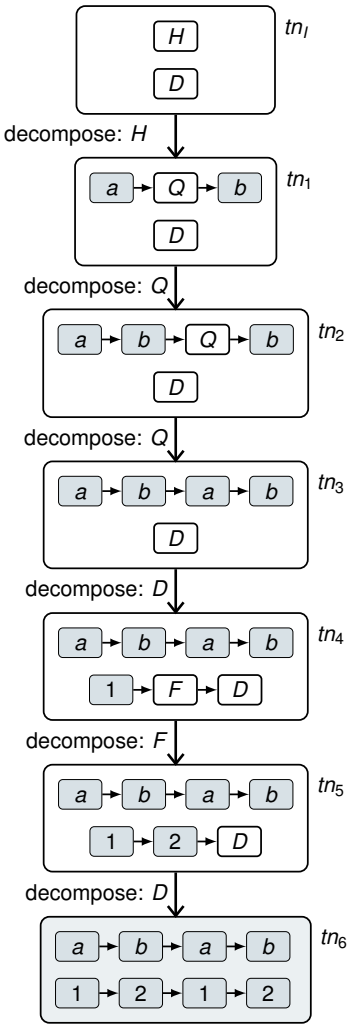
Plan Existence Complexity Results: HTN Planning versus Classical Planning

Theorem: HTN planning is **undecidable** *(Erol et al., 1994/1996)*

- In HTN planning, we can only "manipulate" task networks via decomposition: Pick a decomposition method (from the model) and replace its compound task by it.
- But what if we allowed the insertion of actions (primitive tasks) arbitrarily, just as in classical planning?
  - Will the problem become easier?
  - What are the consequences?
- We call the resulting formalism:
  TIHTN Planning: HTN Planning with Task Insertion

P. Bercher et al. "A Survey on Hierarchical Planning – One Abstract Idea, Many Concrete Realizations". In: ***IJCAI 2019***
R. Alford, **P. Bercher**, and D. Aha. "Tight Bounds for HTN planning with Task Insertion". In: ***IJCAI 2015***
T. Geier and **P. Bercher**. "On the Decidability of HTN Planning with Task Insertion". In: ***IJCAI 2011***

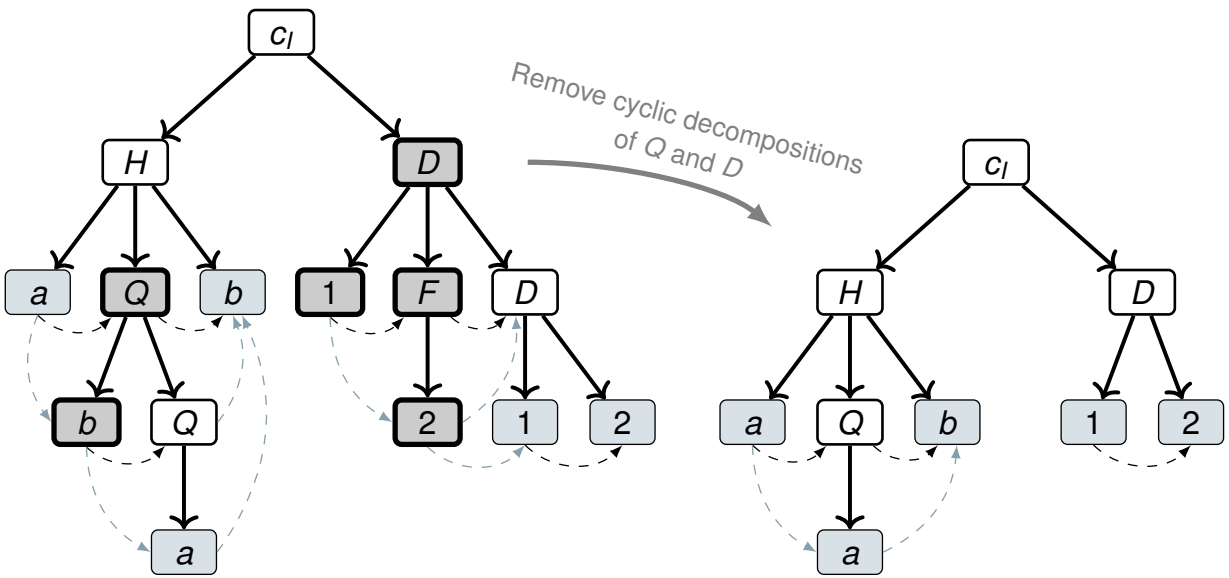
Plan Existence Complexity Results: HTN Planning with Task Insertion



Lemma: TIHTN planning doesn't need cyclic decompositions!

T. Geier and **P. Bercher**. "On the Decidability of HTN Planning with Task Insertion". In: ***IJCAI 2011***

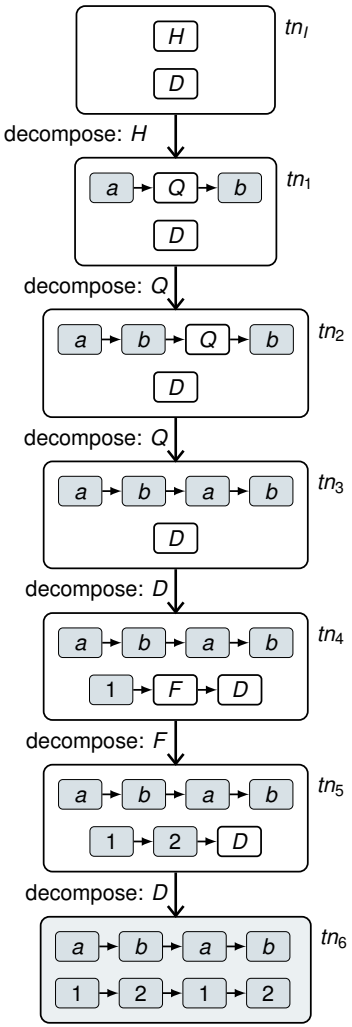
Restrict to *acyclic* decompositions, re-fill with task insertion!



The acyclic tree missed the actions b, 1, 2

But we can just re-insert them via task insertion!

Plan Existence Complexity Results: HTN Planning with Task Insertion



Theorem: TIHTN planning is in **NEXPTIME**

R. Alford, **P. Bercher**, and D. Aha. "Tight Bounds for HTN planning with Task Insertion". In: ***IJCAI 2015***

T. Geier and **P. Bercher**. "On the Decidability of HTN Planning with Task Insertion". In: ***IJCAI 2011***

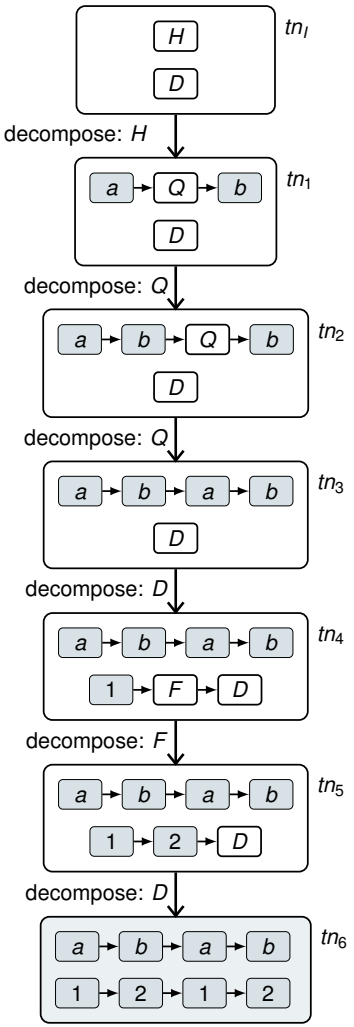
1. Step: Guess an acyclic decomposition:

A tree with acyclic decompositions describes at most $b^{|C|+1}$ decompositions.

(C = set of compound tasks)
(b = size of largest task network in the model)

Verify in $O(b^{|C|+1})$ whether the tree describes a correct sequence of decompositions.

Plan Existence Complexity Results: HTN Planning with Task Insertion



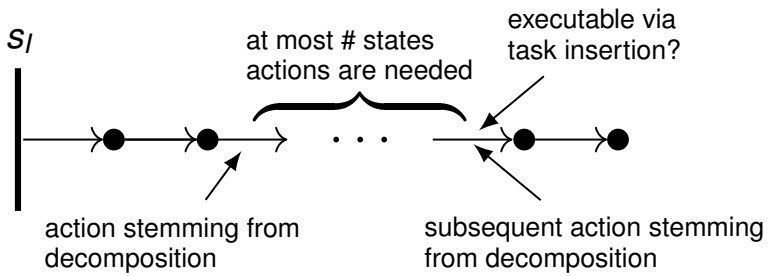
Theorem: TIHTN planning is in **NEXPTIME**

R. Alford, **P. Bercher**, and D. Aha. "Tight Bounds for HTN planning with Task Insertion". In: ***IJCAI 2015***

T. Geier and **P. Bercher**. "On the Decidability of HTN Planning with Task Insertion". In: ***IJCAI 2011***

2. Step: Guess the actions and orderings to be inserted.

The (guessed) decomposition tree results into a task network with at most $\leq b^{|C|+1}$ tasks.



Between each two actions, at most $2^{|V|}$ actions need to be inserted to achieve the next precondition.

($|V|$ = number of state variables, $2^{|V|}$ = number of states)

Plan Existence Complexity Results: Overview

Restrictions on Hierarchy	Task Networks Totally Ordered?	Task Insertion?	Complexity Class
Arbitrary	yes	yes	**PSPACE**
Arbitrary	yes	no	**EXPTIME**
Arbitrary	no	yes	**NEXPTIME**
Arbitrary	no	no	**undecidable** and **semi−decidable**
Tail-Recursive	yes	yes	**PSPACE**
Tail-Recursive	yes	no	**PSPACE**
Tail-Recursive	no	yes	**NEXPTIME**
Tail-Recursive	no	no	**EXPSPACE**
Regular	yes	yes	**PSPACE**
Regular	yes	no	**PSPACE**
Regular	no	yes	**PSPACE**
Regular	no	no	**PSPACE**
Acyclic	yes	yes	**PSPACE**
Acyclic	yes	no	**PSPACE**
Acyclic	no	yes	**NEXPTIME**
Acyclic	no	no	**NEXPTIME**
No Hierarchy	yes	yes	**PSPACE**
No Hierarchy	yes	no	in **P**
No Hierarchy	no	yes	**PSPACE**
No Hierarchy	no	no	**NP**

Results from the table:

P. Bercher et al. “More than a Name? On Implications of Preconditions and Effects of Compound HTN Planning Tasks”. In: ***ECAI 2016***

R. Alford, **P. Bercher**, and D. Aha. “Tight Bounds for HTN planning with Task Insertion”. In: ***IJCAI 2015***

R. Alford, **P. Bercher**, and D. Aha. “Tight Bounds for HTN Planning”. In: ***ICAPS 2015***

T. Geier and **P. Bercher**. “On the Decidability of HTN Planning with Task Insertion”. In: ***IJCAI 2011***

When ignoring orderings and delete effects:

D. Höller, **P. Bercher**, and G. Behnke. “Delete- and Ordering-Relaxation Heuristics for HTN Planning”. In: ***IJCAI 2020***

Loosely related: *Expressivity*

D. Höller, G. Behnke, and **P. Bercher**, and S. Biundo. “Language Classification of Hierarchical Planning Problems”. In: ***ECAI 2014***

D. Höller, G. Behnke, and **P. Bercher**, and S. Biundo. “Assessing the Expressivity of Planning Formalisms through the Comparison to Formal Languages”. In: ***ICAPS 2016***

Further Complexity Investigations

We investigated the computational complexity of related tasks:

- Is task/method/fact *t*/*m*/*f* a landmark, i.e., required in any solution? (As hard as the base problem)
- Is fact *f* a required precondition or guaranteed effect of a compound task? (As hard as the base problem)
- Plan verification (is a given task network a solution?) for a combination of HTN and POCL planning. (**NP-complete**)
- Can we perform change(s) X to a given solution – to obtain a solution again? (from **NP-complete** upwards)

D. Höller and **P. Bercher**. "Landmark Generation in HTN Planning". In: ***AAAI 2021***

C. Olz, S. Biundo, and **P. Bercher**. "Revealing Hidden Preconditions and Effects of Compound HTN Planning Tasks – A Complexity Analysis". In: ***AAAI 2021***

P. Bercher, D. Höller, G. Behnke, and S. Biundo. "More than a Name? On Implications of Preconditions and Effects of Compound HTN Planning Tasks". In: ***ECAI 2016***

G. Behnke, D. Höller, and **P. Bercher**, and S. Biundo. "Change the Plan – How hard can that be?" In: ***ICAPS 2016***