Chapter: *Introduction to (Non-Hierarchical) Planning*

Dr. Pascal Bercher

Institute of Artificial Intelligence,
Ulm University, Germany

Winter Term 2018/2019

(Compiled on: February 20, 2019)

ulm university universität uulm

Overview:

Where and When?

Lecture	Tuesday	14:15 - 15:45 Uhr	(O27/R 2202)
	Thursday	16:15 - 17:45 Uhr	(O27/R 2202)

Exercises Replace every 4th lecture, see Moodle

Consultation Hours Right after the lectures and by appointment
`pascal.bercher@uni-ulm.de`

Exam

Grades

- Exam gives 6 ECTS if passed.
- Scoring at least 50% of the exercise points improves the exam grade by one step (0.3 or 0.4, respectively).

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Dates

- The exam may be written or oral, depending on the number of participants.
- Exams: We agree on this *now* or *very soon*.

Literature

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- Most of the lecture's content is *state of the art*! It is way too recent to be in any textbook.
- The suggested text books and lectures mainly provide detailed explanations as well as examples about the basics.

Literature, cont'd I

Text Books

- S. Russell, P. Norvig: *Artificial Intelligence – A Modern Approach*, Prentice Hall, 2010. (Much on non-hierarchical planning, but only approx. 10/1300 pages about hierarchical planning.)

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- M. Ghallab, D. Nau, P. Traverso: *Automated Planning and Acting*, Cambridge University Press, 2016. (Only a very few pages are on hierarchical planning.)

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Planning Research in the Scientific Landscape

Most important planning and AI conferences:

- ICAPS, the Int. Conf. on Planning and Scheduling.
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Most important AI journals:

- Artificial Intelligence (AIJ, AI Journal).
- Journal of Artificial Intelligence Research (JAIR).

Literature, cont'd IV

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- ICKEPS, the International Competition on Knowledge Engineering for Planning and Scheduling.
- For a comprehensive list, see: `http://www.icaps-conference.org/index.php/Main/Competitions`

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- Even after putting the slides online the first time, they might still get updated. Ensure to use the newest version when studying for the exam!

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Just a bit more formally...

Planning is the reasoning process required to generate a *plan* – a sequence of action that transforms a given state of a system into a desired one.

Domain-Independent Approach

- We want to define a large *class of problems*, i.e., a range of different problems with certain properties.
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  - Verification tools exist that test solutions for their actual correctness (redundant if the planning software is definitely bug-free).

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  Though differences must not always be large as shown in one real-world application: Malte Helmert and Hauke Lasinger. "The Scanalyzer Domain: Greenhouse Logistics as a Planning Problem". In: *Proc. of the 20th Int. Conf. on Automated Planning and Scheduling (ICAPS 2010)*. AAAI Press, 2010, pp. 234–237

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- Many more...

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What is being researched?

- Plan generation:

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- Plan generation:
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Planning in the Research Landscape, cont'd I

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- Plan generation:
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  - Divide problem into independent sub problems.

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  - Detect (i.e., prove) the unsolvability.
  - Provide certificates that serve as verifiable unsolvability proofs.

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  - How hard are the problems?

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  - How hard are the problems?
  - What can be expressed by our formalisms?

Planning in the Research Landscape, cont'd I

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  - Algorithms. ***(covered in lecture)***
  - Reductions to other problems. ***(covered in lecture)***
  - Heuristics. ***(covered in lecture)***
  - Divide problem into independent sub problems. *(not covered)*
  - Mixed-initiative plan generation with a human. *(not covered)*
- Unsolvable planning tasks: *(not covered)*
  - Detect (i.e., prove) the unsolvability.
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- Heuristic search. ***(covered in lecture)***
- Complexity analysis. ***(covered in lecture)***
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  - Convey plans to human users.

Planning in the Research Landscape, cont'd I

What is being researched?

- Modeling support.
- Explainable planning.
- Plan and goal recognition.
- Plan Repair.
- Application to real-world settings:
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  - *many* more ...

Planning in the Research Landscape, cont'd I

What is being researched?

- Modeling support. *(not covered)*
- Explainable planning. ***(covered if time)***
- Plan and goal recognition. *(not covered)*
- Plan Repair. ***(covered if time)***
- Application to real-world settings:
  - Plan execution and monitoring. ***(covered if time)***
  - Convey plans to human users. ***(covered if time)***
  - *many* more ...

Planning in the Research Landscape, cont'd II

Properties of Planning Systems

- Planning is done offline versus online (versus mixed-initiatively).

Planning in the Research Landscape, cont'd II

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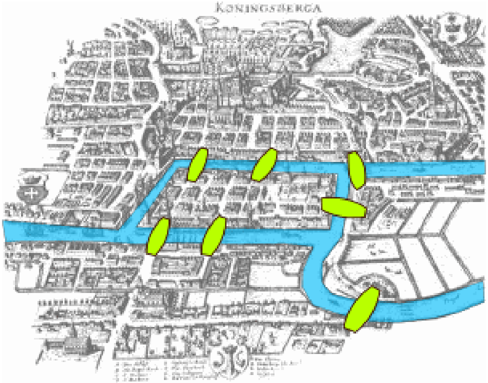
  - Minimize makespan (time to execute when accounting for parallelism).

Combinatorial Problems, e.g., Seven Bridges of Königsberg



Title: *The Problem of the Seven Bridges of Königsberg*

Source: https://commons.wikimedia.org/wiki/File:Konigsberg_bridges.png

Riddles, e.g. Dining Philosophers

There are five philosophers, five meals, and five forks.

Picture:

Title: *An illustration of the dining philosophers problem*

Source: `https://commons.wikimedia.org/wiki/File:An_illustration_of_the_dining_philosophers_problem.png`

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- They all want to have eaten

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Games, e.g., Solitaire

Games, e.g., Sliding Tile Puzzle, 15 Puzzle, n^2-1 Puzzle

2	1	4	8
9	7	11	10
6	5	15	3
13	14	12	

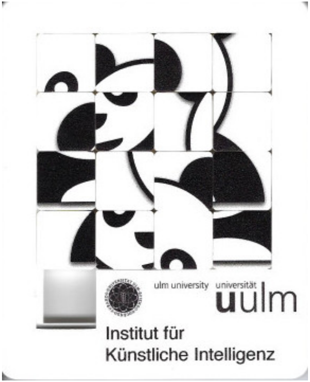
Problem

→

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	

Solution

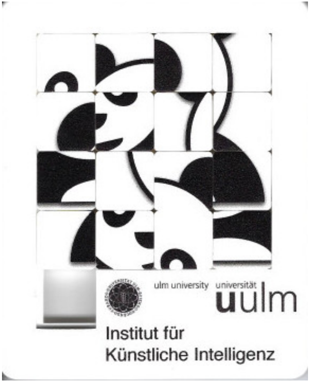
Games, e.g., Sliding Tile Puzzle, 15 Puzzle, n^2-1 Puzzle



$\longrightarrow$

Problem

Games, e.g., Sliding Tile Puzzle, 15 Puzzle, n^2-1 Puzzle

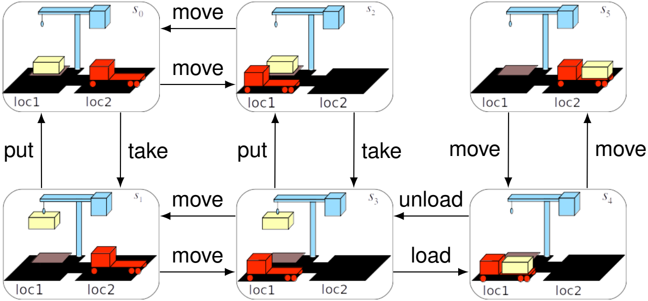


Problem

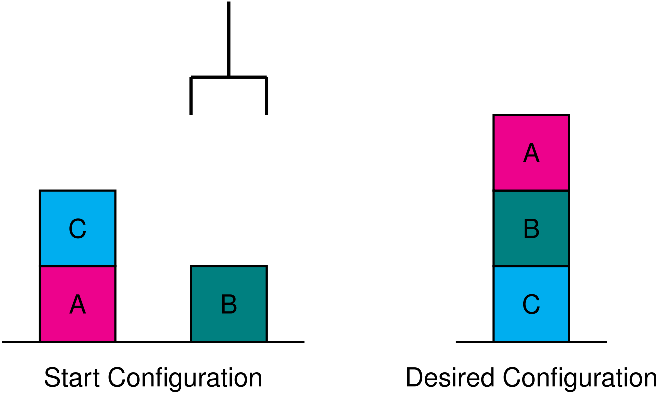
$\longrightarrow$

Solution

Cranes in a Harbor

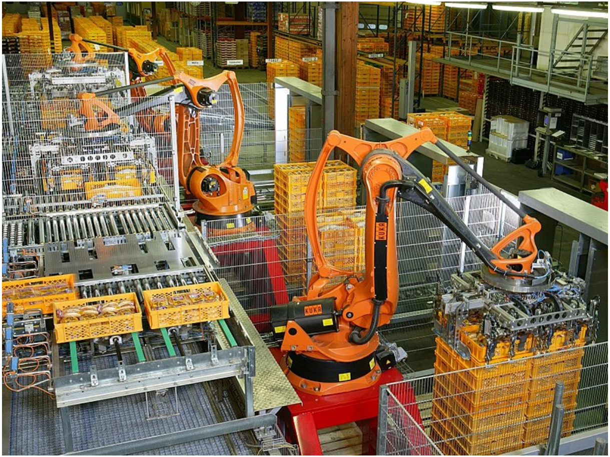


Blocksworld



Standard Planning Benchmark in the IPC and *every* planning lecture.

Automatic Factories, Industry 4.0



Source: https://en.wikipedia.org/wiki/File:Factory_Automation_Robotics_Palettizing_Bread.jpg

Greenhouse

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

Further reading:

- Malte Helmert and Hauke Lasinger. "The Scanalyzer Domain: Greenhouse Logistics as a Planning Problem". In: *Proc. of the 20th Int. Conf. on Automated Planning and Scheduling (ICAPS 2010)*. AAAI Press, 2010, pp. 234–237
- The IPC Scanalizer Domain in PDDL (see paper above).

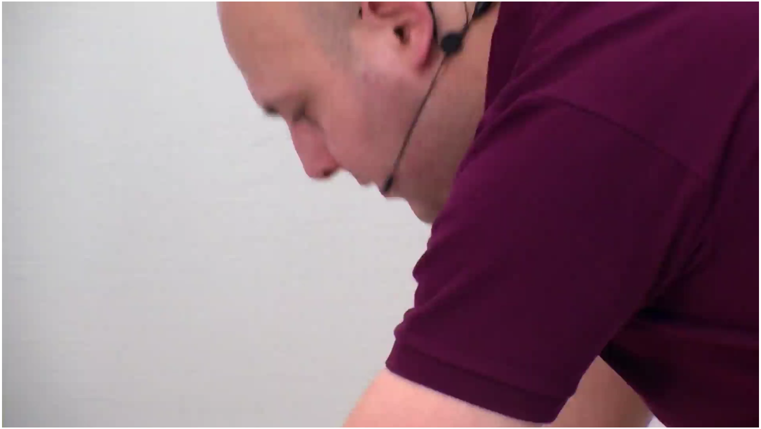
Home Theater Assembly Assistant

Four devices:

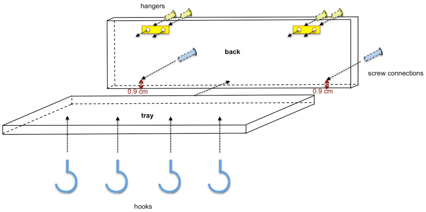
- Television (requires video)
- Blu-ray player
- Satellite receiver
- audio/video receiver (requires audio)

Home Theater Assembly Assistant, cont'd I (Step-by-Step Instructions)

Home Theater Assembly Assistant, cont'd II (Explanations)



Do-It-Yourself (DIY) Assistant

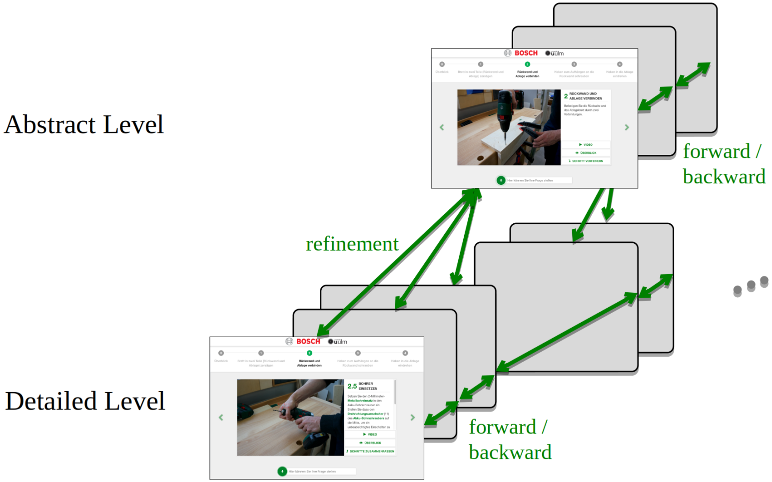


The material:

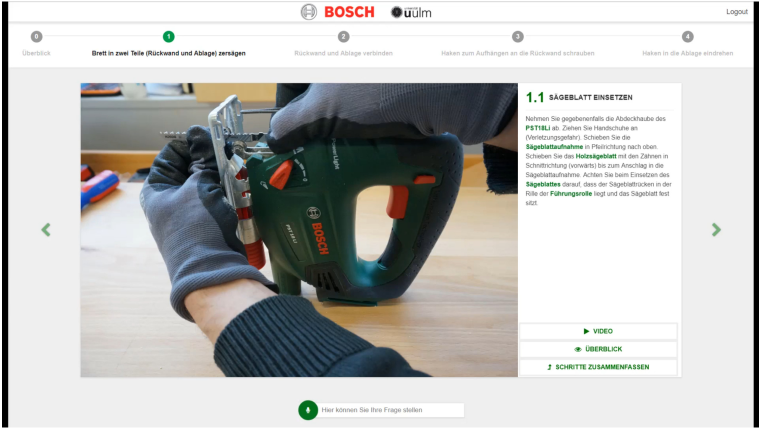
- Boards (need to be cut first)
- Electrical devices like drills and saws
- Attachments like drill bits and materials like nails

Do-It-Yourself (DIY) Assistant, cont'd I (Different Levels of Abstraction)

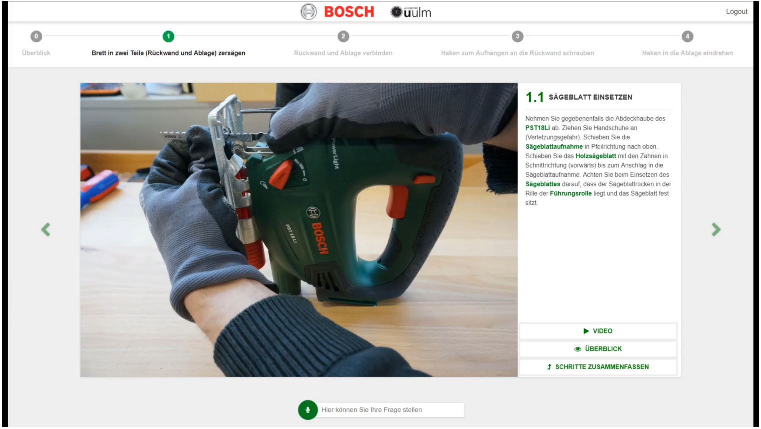
Presentation of instructions on different levels of abstraction:



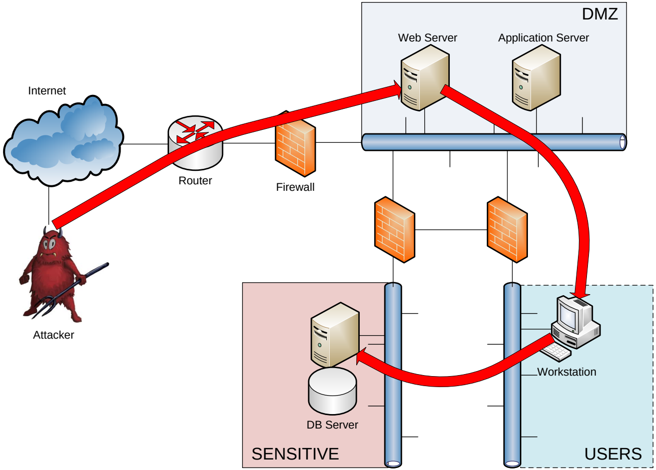
Do-It-Yourself (DIY) Assistant, cont'd II (Step-by-Step Instructions)



Do-It-Yourself (DIY) Assistant, cont'd III (Explanations)



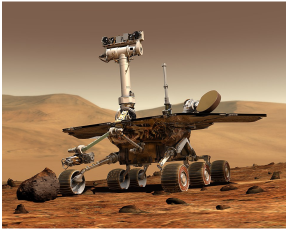
Network Intrusion



Source: https://fai.cs.uni-saarland.de/teaching/winter17-18/planning-material/planning01-about-this-course-post-handout.pdf

Mars Rover





Source:
- left https://commons.wikimedia.org/wiki/File:KSC-03PD-0786.jpg
- middle https://commons.wikimedia.org/wiki/File:Curiosity_Self-Portrait_at_%27Big_Sky%27_Drilling_Site.jpg
- right https://commons.wikimedia.org/wiki/File:NASA_Mars_Rover.jpg

Further reading:
- Pascal Bercher and Daniel Höller. "Interview with David E. Smith". In: *Künstliche Intelligenz* 30.1 (2016). Special Issue on Companion Technologies, pp. 101–105. DOI: 10.1007/s13218-015-0403-y
- Every paper about *MAPGEN* (for references, see also article above).

Not Enough?

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- and more!

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A *solution* (or *plan*) is any sequence of actions transforming the initial state into a goal state.

Historical Remarks

The best-known classical planning formalism is the *STRIPS formalism*.

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Today, STRIPS ordinarily refers to (a restricted fragment of) STRIPS' description language.

The STRIPS Formalism

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- We have only *positive* preconditions, i.e., actions do not pose constraints on what properties do *not* hold in the state of their application.

The STRIPS Formalism, cont'd I

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- $s_I \in S$ is the initial state (complete state description).
- $g \subseteq V$ is the goal description (encodes a set of goal states).

The STRIPS Formalism, cont'd II

Action application:

- An action $a \in A$ is called *applicable* (or executable) in a state $s \in S$ if and only if $pre(a) \subseteq s$. Often, this is given by a function: $\tau(a, s) \Leftrightarrow pre(a) \subseteq s$.

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- An action sequence $\bar{a} = a_0, \ldots, a_{n-1}$ is applicable in a state s_0 if and only if for all $0 \leq i \leq n-1$ a_i is applicable in s_i, where for all $1 \leq i \leq n$ s_i is the resulting state of applying $a_0, \ldots, a_i$ to $s_0 = s_I$. Often, the state transition function is extended to work on action sequences as well $\gamma : A^* \times S \to S$.

The STRIPS Formalism, cont'd III

Solution:

An action sequence $\bar{a}$ consisting of 0 (empty sequence) or more actions is called a *plan* or *solution* to a STRIPS planning problem if and only if:

The STRIPS Formalism, cont'd III

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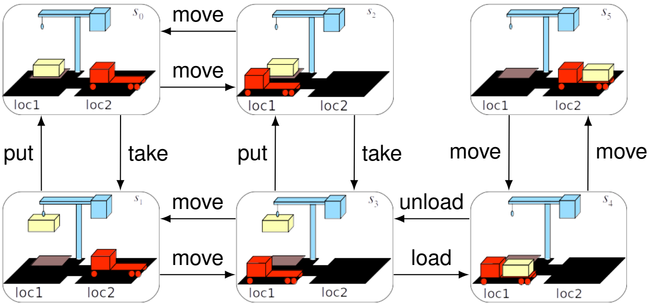
- $\bar{a}$ results into a goal state, i.e., $\gamma(\bar{a}, s_I) \supseteq g$.

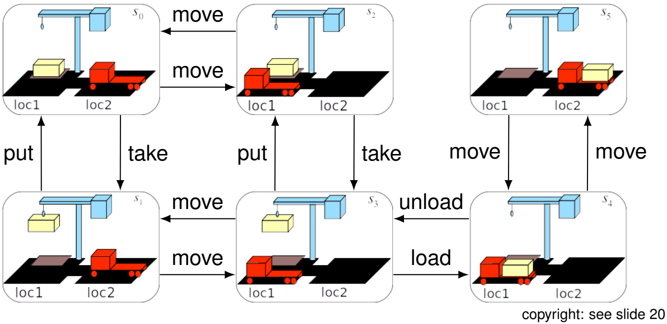
Example – Exercise!



copyright: see slide 20

Exercise:
Model a classical planning problem $\mathcal{P} = \langle V, A, s_I, g \rangle$ with the actions and states as indicated above.

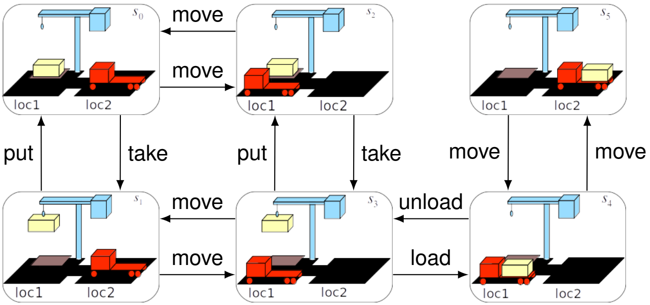
Example – Exercise!



STRIPS planning problem:

- V: {CrateAtLoc1, HoldCrate, TruckAtLoc1, TruckAtLoc2, CrateInTruck}
- A: {take, put, moveLeft, moveRight, load, unload} (see following slides)
- s_I: {CrateAtLoc1, TruckAtLoc2}
- g: {CrateInTruck, TruckAtLoc2}

Example – Exercise!



copyright: see slide 20

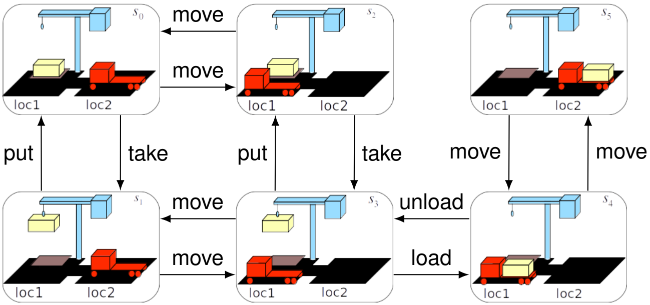
take

pre: {CrateAtLoc1}
add: {HoldCrate}
del: {CrateAtLoc1}

put

pre: {HoldCrate}
add: {CrateAtLoc1}
del: {HoldCrate}

Example – Exercise!

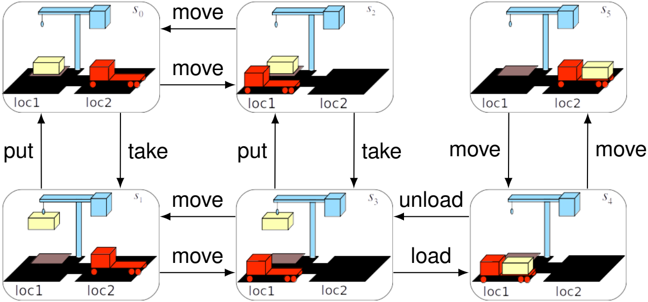


copyright: see slide 20

moveLeft
pre: {TruckAtLoc2}
add: {TruckAtLoc1}
del: {TruckAtLoc2}

moveRight
pre: {TruckAtLoc1}
add: {TruckAtLoc2}
del: {TruckAtLoc1}

Example – Exercise!



load

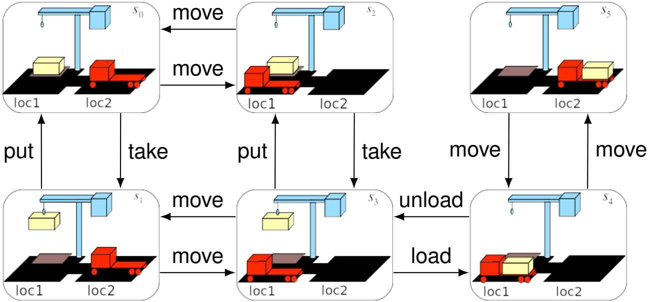
pre: {HoldCrate, TruckAtLoc1}
add: {CrateInTruck}
del: {HoldCrate}

unload

pre: {CrateInTruck, TruckAtLoc1}
add: {HoldCrate}
del: {CrateInTruck}

State Transition System

Every classical planning problem is a compact representation of a *state transition system*, i.e., of how states are transformed into each other.



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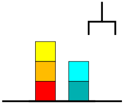
Size Increase of the State Space in Blocks World



- *n* blocks, 1 gripper.
- A single action either takes a block with the gripper or puts a block we are holding onto some other block/the table.

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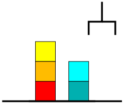

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blocks	states
1	1
2	3
3	13
4	73
5	501
6	4051
7	37633
8	394353
9	4596553

blocks	states
10	58941091
11	824073141
12	12470162233
13	202976401213
14	3535017524403
15	65573803186921
16	1290434218669921
17	26846616451246353
18	588633468315403843

State Transition System, cont'd I

Definition (State Transition System)

A state transition system is a 6-tuple (S, L, c, T, I, G), where

- S is a finite set of states.

State Transition System, cont'd I

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- $G \subseteq S$ is the set of goal states.

State Transition System, cont'd II

Some further terminologies:

- A transition system is called *deterministic* if for all states s and labels l there is at most one state s', such that $(s, l, s') \in T$. Otherwise, it's called *non-deterministic*.

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- A state s is called *dead-end* if no goal state is reachable from s.
- A transition system is called *solvable* if some goal state is reachable.

Questions

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Which of the following transition systems has a *reachable* dead-end? (We assume that the states of the transition system are *world states* encoding the respective current situation.)

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2. 15-Puzzle?
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4. Yes. If all philosophers take their right fork, they starve do death.

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- How to define executability if, due to the partial order, there are many possible linearizations?
  - → In terms of *causal links* or by checking the linearizations.

Additional Definitions

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Let $\prec \subseteq X \times X$ be a strict partial order. Then, a linearization of $\prec$ is a sequence $x_1, \ldots, x_n$ of X's elements that does not contradict the ordering constraints.

Partial Plans (Definition)

Definition (Partial Plan)

Given a planning problem $\langle V, A, s_I, g\rangle$, a *partial plan* is a tuple $(PS, \prec, CL)$ consisting of:

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  - consists of two plan steps $ps, ps' \in PS$ and a state variable $v \in V$ that occurs both in $add(ps)$ and in $pre(ps')$.
  - implies $(ps, ps') \in \prec$ and there is no ps'' with $ps'' \xrightarrow{v} ps' \in CL$ (unique supporter).

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Recap on Partial Orders

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antisymmetric if $x \prec y$, then not $y \prec x$,
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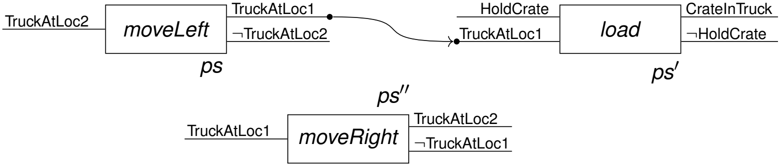
Example for Causal Links and Causal Threats

Consider the following partial plan from the *Cranes in the Harbor* domain. The causal link $ps \xrightarrow{\text{TruckAtLoc1}} ps'$ documents the achievement of the precondition of ps' by ps.



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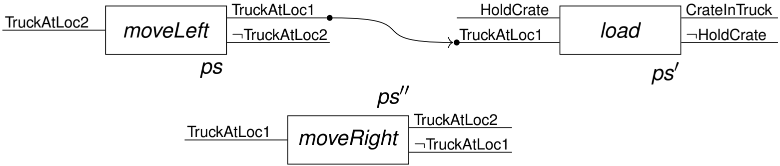

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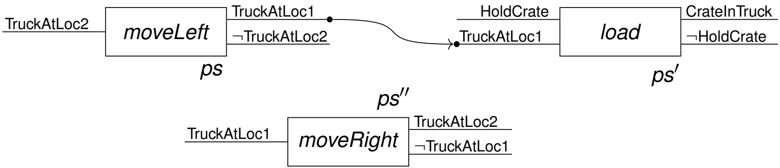

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→ ps'' could be ordered between ps and ps'.
Thus: it *threatens* the causal link.

Causal Threats

Definition (Causal Threat)

Let $(PS, \prec, CL)$ be a partial plan. A *causal threat* consists of the plan steps $ps, ps' \in PS$, a causal link $ps \xrightarrow{v} ps'$, and the *threatening plan step* $ps'' \in PS$ if and only if

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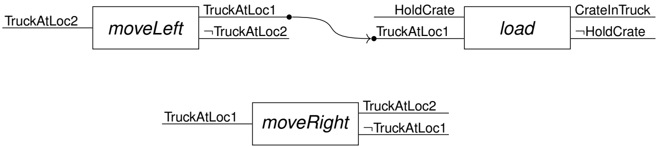
Note:

In case we allow negative preconditions, the definition of causal threats needs to be extended.

Encoding Initial State and Goal Description

How to represent the initial state and goal description?



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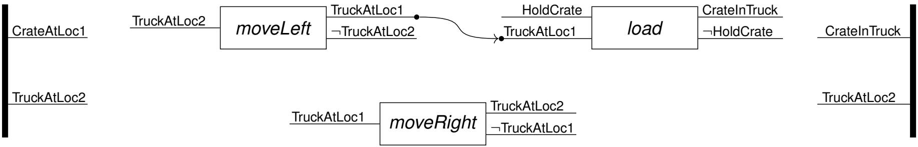

- We represent these states as artificial actions:
  - *Initial State.* For s_I introduce an action $a_I \notin A$ with $pre(a_I) = del(a_I) = \emptyset$ and $add(a_I) = s_I$.
  - *Goal Description.* For g introduce an action $a_g \notin A$ with $pre(a_g) = g$ and $add(a_g) = del(a_I) = \emptyset$.
  - *Ordering Constraints.* Enforce that a_I is the very first action and a_g is the very last.

Encoding Initial State and Goal Description, cont'd

How to represent the initial state and goal description?

- Please note that according to the definition of partial plans (cf. sl. 46) the set of plan steps *PS* is defined as a set of plan steps $l{:}a$, where l is a unique *label* symbol and $a \in A$ is an action.

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- *Causal Threats* (as defined above).
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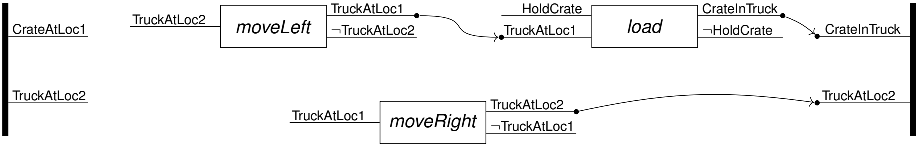
Flaws, cont'd

Which flaws does this partial plan possess?



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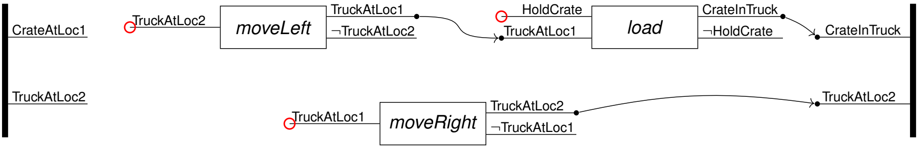

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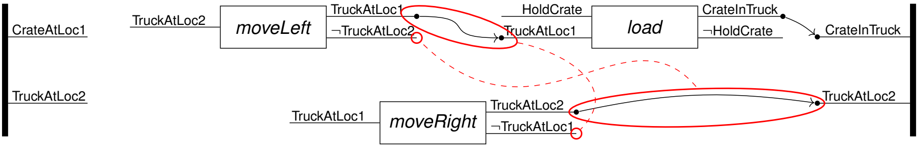

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- Solutions are partial plans rather than action sequences.

Linearizations of POCL Solutions

Theorem

Let $\mathcal{P} = \langle V, A, P_I \rangle$ be a POCL planning problem with initial state s_I and goal description g. Let $P = (PS, \prec, CL)$ be a plan for $\mathcal{P}$.

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Exercise!

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By example (next slide), which was provided by Kambhampati, published by: David McAllester and David Rosenblitt. "Systematic Nonlinear Planning". In: *Proc. of the 9th National Conf. on Artificial Intelligence (AAAI 1991)*. AAAI Press, 1991, pp. 634–639

Linearizations of POCL Solutions, cont'd II

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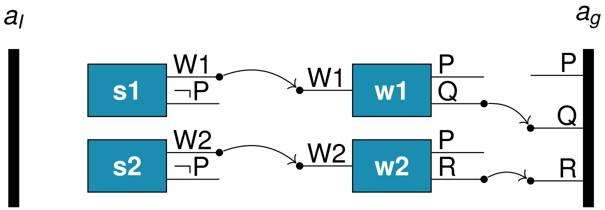

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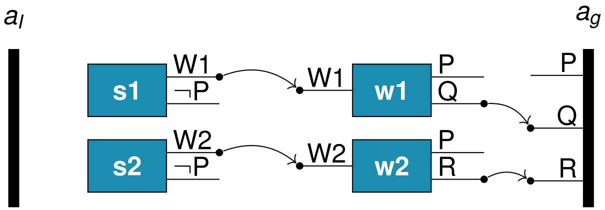

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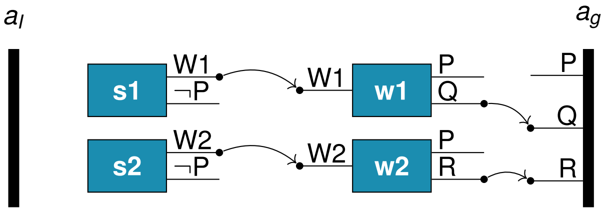

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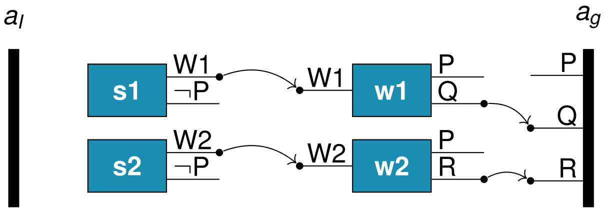

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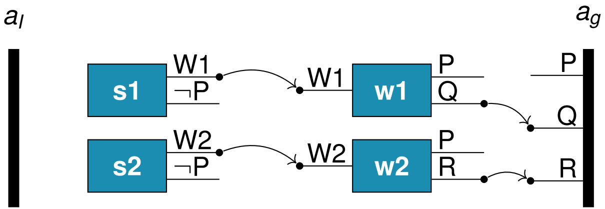

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