Canberra Computer Science Enrichment: A – *Hands-on* – Introduction to Automated Planning

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13. May 2022

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Introduction

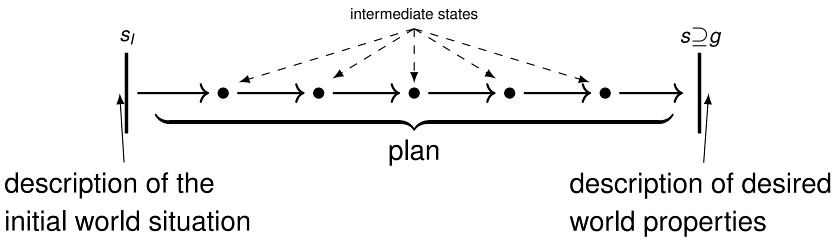
Planning in a Nutshell

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

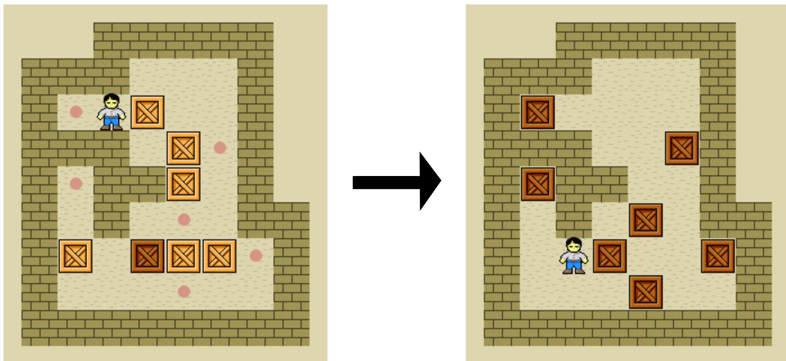
- An initial state s_I – all "world properties" true in the beginning.
- A set of available actions – how world states can be changed.
- A goal description g – all properties we'd like to hold.

What do we want?

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

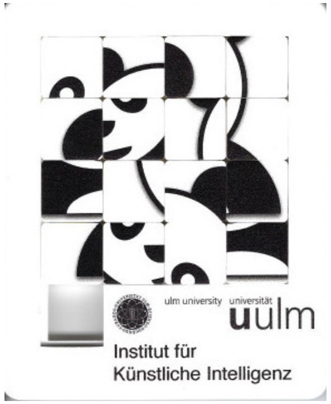


Planning Games like Sokoban



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.)

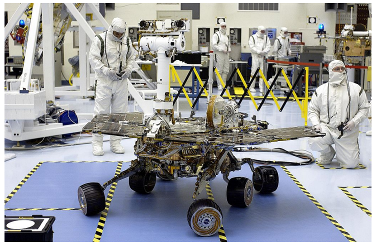
Planning Games like the Sliding Tile Puzzle

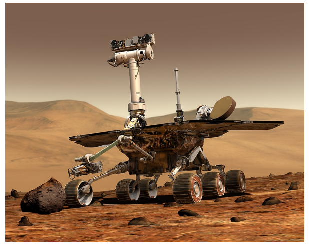


→

Initial State   Goal State

Planning Robots like the Mars Rovers

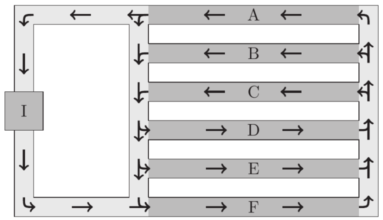




- MAPGEN (Mixed Initiative Activity Planning Generator) is a ground-based decision support system for Mars Exploration Rover mission operations and science teams that begins to give content to the notion of autonomous planetary exploration.
- The paradigm is to enable the person using the software to 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/*

Planning Automated Factories like a Greenhouse



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

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Further reading:
- M. Helmert and H. 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 Scanalyzer Domain in PDDL (see paper above).

Planning: A *Domain-Independent* Approach

- Automated Planning is a domain-independent approach!
- As mentioned in the beginning, the integral part is:
  - The state descriptions: Which state properties exist?
  - Actions: What can be *done* and how does this change states?
- Planning technology is agnostic against specific applications! (So all previous examples can be modeled as planning problems.)
- Research bases on an abstract high-level description language. Example action in a domain controlling Satellites:

```
(:durative-action turn_to
 :parameters (?s - satellite ?d_new - direction ?d_prev - direction)
 :duration (= ?duration 5)
 :condition (and (at start (pointing ?s ?d_prev))
                 (over all (not (= ?d_new ?d_prev))))
 :effect (and (at end (pointing ?s ?d_new))
              (at start (not (pointing ?s ?d_prev))))
)
```

Domain-Independence: Pros vs. Cons

Advantages of Domain-independence:

- Use (well-tested) standard solvers:
  - Cost-effective: only write the model, not new software
  - Most likely there are less bugs
- Optimality guarantees of solutions (find the cheapest).
- Exploit further planning technology, e.g., automated support for:
  - Model can be checked for problems.
  - Existing techniques for proving unsolvability can be used.
  - Plan explanation techniques can be exploited.
  - Verify correctness of solutions.

Disadvantages of Domain-independence:

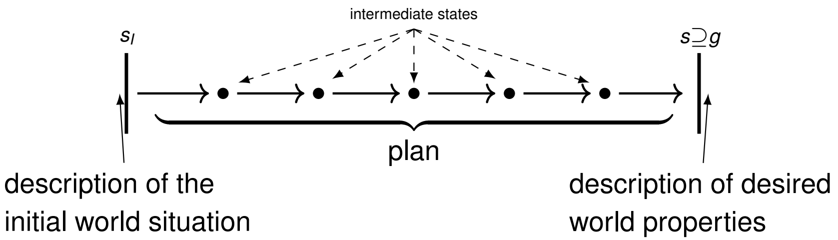
- You need a planning expert to model the domain. (But we will have many more in just like 60 minutes!)
- Potential inefficiency: a domain-specific *might* be more efficient than a domain-independent one.

AI Planning Problems

Problem Definition: Assumptions made in Classical Planning

We focus on the "base case" of AI planning: *Classical Planning*

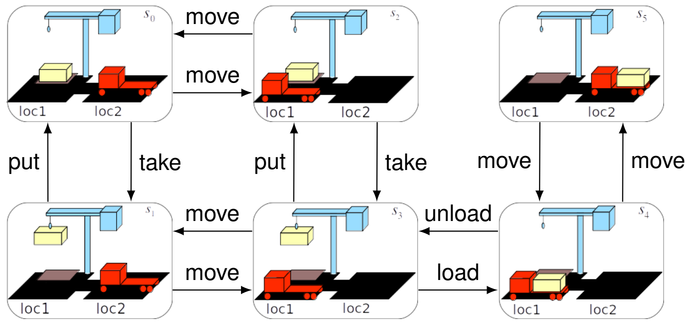
- *Discrete:* only instantaneous state changes (no time)
- *Deterministic:* outcomes of actions are known and unique
- *Fully observable:* no hidden information anywhere
- *Single-agent:* "the planner" controls all actions



Problem Definition: Formalism

A classical planning problem $\mathcal{P} = \langle V, A, s_I, g \rangle$ consists of:

- V is a finite set of *state variables*.



Title: Lecture Slides for Automated Planning

Source: `http://www.cs.umd.edu/~nau/planning/slides/chapter01.pdf`

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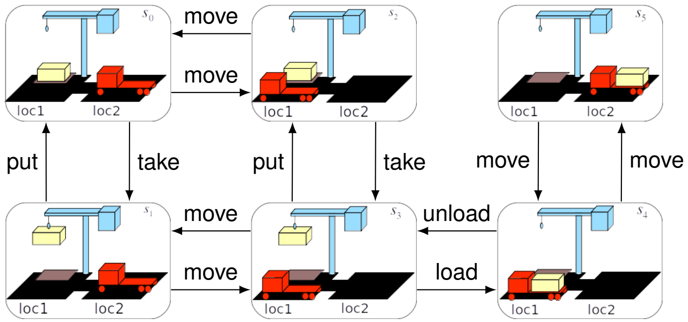

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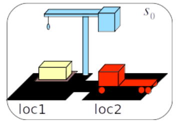
$V = \{$CrateAtLoc1, CrateInCrane, CrateInTruck, TruckAtLoc1, TruckAtLoc2$\}$

Problem Definition: Formalism

A classical planning problem $\mathcal{P} = \langle V, A, s_I, g \rangle$ consists of:

- V is a finite set of *state variables*.
  - *States* are sets consisting of state variables (also called *facts*).



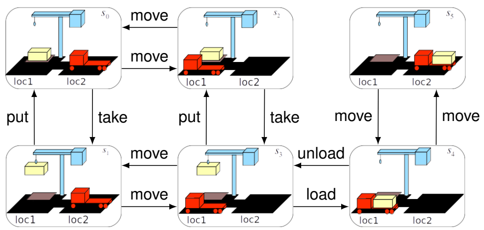
This state s_0 is formalized as: $\{$*CrateAtLoc1*, *TruckAtLoc2*$\}$

  - We assume the *closed world assumption*, where all variables not mentioned in a state s do not hold. In contrast to the open world assumption where it's unknown whether they hold or not).
    - E.g., *TruckAtLoc2* $\in s_0$, so it's currently true in state s_0.
    - E.g., *CrateInCrane* $\notin s_0$, so it's currently false in that state s_0.
  - $S = 2^V$ is called the *state space*. (The set of all states.)

Problem Definition: Formalism

A classical planning problem $\mathcal{P} = \langle V, A, s_I, g \rangle$ consists of:

- A is a finite set of actions. Each action $a \in A$ is a tuple $(pre, add, del, c) \in 2^V \times 2^V \times 2^V \times \mathbb{R}^+$ consisting of a *precondition*, *add and delete list*, and action costs. For convenience, we write $pre(a)$, $add(a)$, $del(a)$, and $c(a)$.



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take	pre:	{CrateAtLoc1}		**put**	pre:	{CrateInCrane}
	add:	{CrateInCrane}			add:	{CrateAtLoc1}
	del:	{CrateAtLoc1}			del:	{CrateInCrane}

Problem Definition: Formalism

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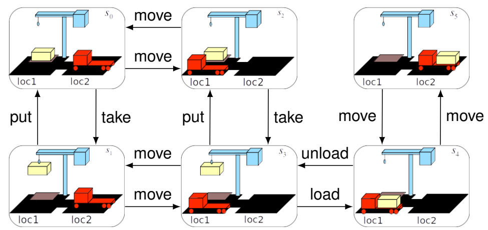

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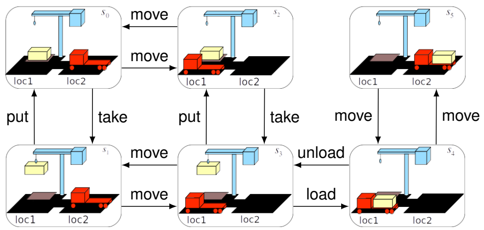
moveLeft	pre:	{TruckAtLoc2}		**moveRight**	pre:	{TruckAtLoc1}
	add:	{TruckAtLoc1}			add:	{TruckAtLoc2}
	del:	{TruckAtLoc2}			del:	{TruckAtLoc1}

Problem Definition: Formalism

A classical planning problem $\mathcal{P} = \langle V, A, s_I, g \rangle$ consists of:

- A is a finite set of actions. Each action $a \in A$ is a tuple $(pre, add, del, c) \in 2^V \times 2^V \times 2^V \times \mathbb{R}^+$ consisting of a *precondition*, *add and delete list*, and action costs. For convenience, we write $pre(a)$, $add(a)$, $del(a)$, and $c(a)$.



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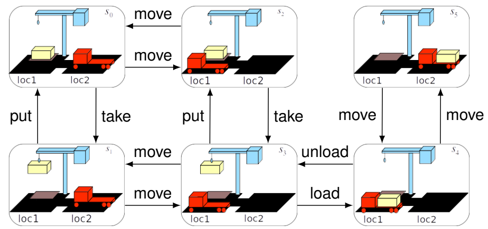
load	pre:	{CrateInCrane, TruckAtLoc1}	**unload**	pre:	{CrateInTruck, TruckAtLoc1}
	add:	{CrateInTruck}		add:	{CrateInCrane}
	del:	{CrateInCrane}		del:	{CrateInTruck}

Problem Definition: Formalism

A classical planning problem $\mathcal{P} = \langle V, A, s_I, g \rangle$ consists of:

- $s_I \in S$ is the initial state (complete state description).
- $g \subseteq V$ is the *goal description*.
  - Each state $s \in S$ with $s \supseteq g$ is called a goal state.
  - We abbreviate the set of goal states with $G = \{s \in S \mid s \supseteq g\}$



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$s_I = \{\text{CrateAtLoc1, TruckAtLoc2}\} = s_0$
$g = \{\text{CrateInTruck, TruckAtLoc2}\}$, thus: $G = \{s_5\}$ since $s_5 \supseteq g$.

Problem Definition: Formalism, cont'd I

- An action $a \in A$ is called *applicable* (or executable) in a state $s \in S$ if and only if $pre(a) \subseteq s$.
- If $pre(a) \subseteq s$ holds, its application results into the successor state $\gamma(a, s) = (s \setminus del(a)) \cup add(a)$. $\gamma : A \times S \to S$ is called the *state transition function*.

→ Example: The action...

take	pre:	{CrateAtLoc1}
	add:	{CrateInCrane}
	del:	{CrateAtLoc1}

... is applicable in state $s_0 = \{CrateAtLoc1, TruckAtLoc2\}$ resulting into $\{TruckAtLoc2, CrateInCrane\}$.

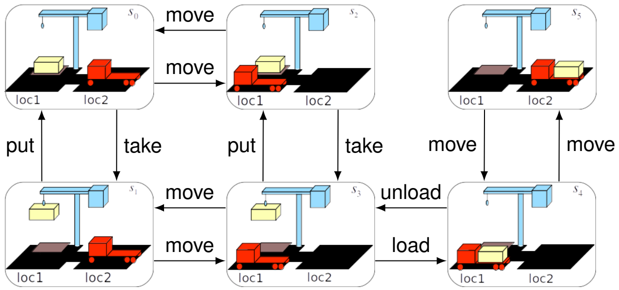
Problem Definition: Formalism, cont'd I

- An action $a \in A$ is called *applicable* (or executable) in a state $s \in S$ if and only if $pre(a) \subseteq s$.
- If $pre(a) \subseteq s$ holds, its application results into the successor state $\gamma(a, s) = (s \setminus del(a)) \cup add(a)$. $\gamma : A \times S \to S$ is called the *state transition function*.
- 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 denotes the resulting state of applying $a_0, \ldots, a_i$ to $s_0 = s_I$.
  - This means: Each action is applicable in its predecessor state.
- We extend the state transition function to work on action sequences as well, i.e., $\gamma : A^* \times S \to S$. (Definition omitted.)

Problem Definition: Formalism, cont'd II

Solution:

- An action sequence $\overline{a}$ consisting of 0 or more actions is called a *plan* or *solution* to a classical planning problem if and only if:
  - $\overline{a}$ is applicable in s_I.
  - $\overline{a}$ results into a goal state, i.e., $\gamma(\overline{a}, s_I) \supseteq g$.



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Solution: **take**, **moveLeft**, **load**, **moveRight**

Problem Definition: Formalism, cont'd II

This is everything about the classical planning formalism! I.e.,

- Formal definition of the "planning problem".
- Formal definition of any "plan", i.e., solution.
  Most notably, this includes the definition of action application.

Questions so far?

State Transition Systems

What's a State Transition System?

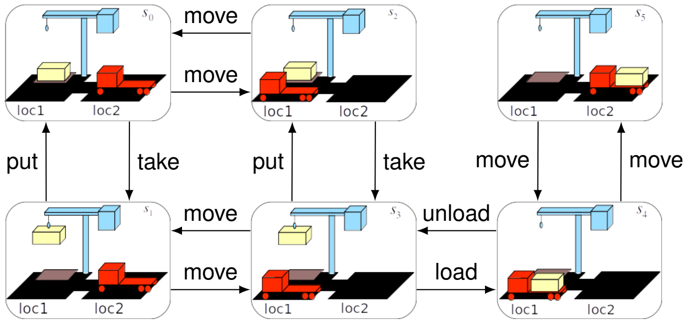
- State transition systems are the "underlying semantics" of classical planning problems.
- They *explicitly* show all states and how they can be traversed by actions.
- We use them to give an intuition on how hard solving planning problems can become (and how easy it is to model them)!

Example for a State Transition System

A *state transition system* is

- just a graph consisting of states and labeled edges
- with a designated initial state and designated goal states

as seen before:



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Formal Definition of State Transition System

Definition (State Transition System)

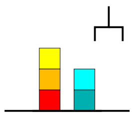
A state transition system is a 6-tuple (S, L, c, T, I, G), where

- S is a finite set of states.
- L is a finite set of transition labels.
- $c : L \to \mathbb{R}^+$ is a cost function.
- $T \subseteq S \times L \times S$ is the transition relation.
- $I \in S$ is the initial state.
- $G \subseteq S$ is the set of goal states.

So where's the difference to a planning?

$\rightarrow$ Classical planning problems $\mathcal{P} = \langle V, A, s_I, g \rangle$ are *compact representations* of state transition systems!

Size Increase of the State Space in Blocksworld



- *We have:* n blocks, 1 gripper, and two actions, each takes a top-most block with the gripper and
  - puts it immediately onto some other top-most block
  - or onto the table, respectively.
- *We want:* transform the initial towers into another, given set of towers.

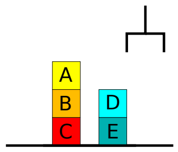
blocks	states	blocks	states
1	1	10	58,941,091
2	3	11	824,073,141
3	13	12	12,470,162,233
4	73	13	202,976,401,213
5	501	14	3,535,017,524,403
6	4,051	15	65,573,803,186,921
7	37,633	16	1,290,434,218,669,921
8	394,353	17	26,846,616,451,246,353
9	4,596,553	18	588,633,468,315,403,843

Size of Planning Problems vs. State Transition Systems

- We can thus see that planning problems are much more compact representations of state transition systems.
- Compare, e.g., the size of blocksworld domain with $n = 5$ blocks (which will have only a few actions) to the state size of > 501.
- *Exercise!* We will model this simple blocksworld problem!
- We give some details here, but then use an online PDDL (Planning Domain Description Language) editor.

A Hands-on Exercise: Modeling Blocksworld

Propositional Model: Required State Variables



- We have 5 blocks called *A*, *B*, *C*, *D*, *E*.
- Actions can use the gripper to:
  - take a top-most block from a tower of size ≥ 2, or
  - take a block that lies on the table (tower of size 1).
- Actions can also use the gripper to:
  - place its block onto another top-most block, or
  - place the block in it onto the table.

So, which state variables do we need?

- *AisTopMost*, *BisTopMost*, etc. – to check whether we can grab it
- *AonB*, *AonC*, etc. – so we can make the next block top-most
- *AonTable*, *BonTable*, etc. – for the lowest block in each tower
- *holdingA*, *holdingB*, etc. – to know what the gripper is holding
- *gripperFree* – so we know whether we can take a block

Propositional Model: Modeling the Stack Actions

- Now we model putting one block on another:
  - Say we have block *A* in the gripper.
  - We need support (i.e., an action) for each other block $b \in \{B, C, D, E\}$ since that one could be on top.
  - Now let's do it!
    - Open `editor.planning.domains`
    - Choose *File*, then *Load*. Choose *groundBlocksworldDomain.pddl* from the zip for this course that can be downloaded from "`tinyurl.com/CCSE-2022-S1-planning`".
    - Before you do the exercise, take a look at the actions *take-A-from-table* and *place-A-on-table*.
- Solution:

```
(:action stack-A-onto-B
   :precondition (and (holdingA) (BisTopMost))
   :effect (and (not (holdingA)) (gripperFree)
                (AonB) (AisTopMost)
                (not (BisTopMost))))
```

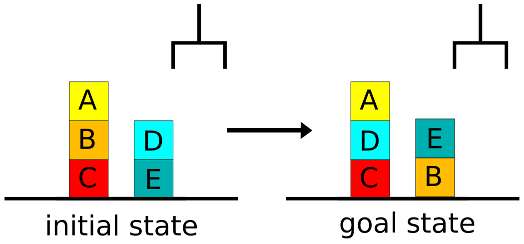

Propositional Model: Modeling the Unstack Actions

- Now we model removing one block from another:
  - Say we want to take block *A* into the gripper.
  - We need support (i.e., an action) for each other block $b \in \{B, C, D, E\}$ since that one could be beneath *A* – we need this since we need to state that this one will be at top next.
  - Back to `editor.planning.domains`!
- Solution:

```
(:action unstack-A-from-B
   :precondition (and (gripperFree)
                      (AonB) (AisTopMost))
   :effect (and (not (gripperFree)) (holdingA)
                (not (AonB)) (not (AisTopMost))
                (BisTopMost)))
```

Propositional Model: Modeling the Initial State

- We now take a look at the problem definition.



- (Same as *groundBlocksworldProblem-Instance1.pddl*)

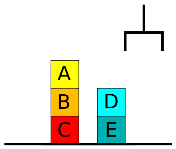
```
(define (problem blocksworld-prob1)
  (:domain blocksworld-ground)
  (:init (AisTopMost) (AonB) (BonC) (ConTable)
         (DisTopMost) (DonE) (EonTable))
  (:goal (and (AisTopMost) (AonD) (DonC) (ConTable)
              (EisTopMost) (EonB) (BonTable))))
```

Is this correct? No! The gripper being initially empty is missing!

Lifted Model: A "Lifted" Blocksworld Model

- We have seen that modeling still requires many actions!
  - Each stack and unstack action requires $n * (n - 1)$ different variants when there are n blocks! (I.e, $5 * 4 * 2 = 40$ actions just for stack and unstack for $n = 5$ blocks).
  - Also the number of existing state variables (defined in the domain file) was quadratic! (36 for $n = 5$ blocks)
  - (Although that's much better than the exponential search space increase (> 501 states for $n = 5$), we can still improve on that!)
- We will now regard *lifted* planning problems, where one can specify variables. This leads to an even more compact representation! (In general, this gives an exponential size decrease.)

Lifted Model: Required State Variables



- We have 5 blocks called A, B, C, D, E.
- Actions can use the gripper to:
  - take a top-most block from a tower of size ≥ 2, or
  - take a block that lies on the table (tower of size 1).
- Actions can also use the gripper to:
  - place its block onto another top-most block, or
  - place the block in it onto the table.

Which ~~state variables~~ predicates do we need? Let $?b$ and $?b'$ be variables.

- *topMost(?b)* – to check whether we can grab $?b$
- *on(?b,?b')* – so we can make $?b'$ the next top-most block
- *onTable(?b)* – for the lowest block in each tower
- *holding(?b)* – to know what the gripper is holding
- *gripperFree()* – so we know whether we can take a block

$\rightarrow$ The problem instance lists all blocks as "objects"

Lifted Model: Modeling the (Lifted) Unstack Action

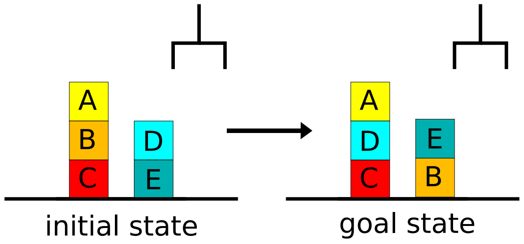
- Now we model removing one block from another:
  - Say we want to take block $?b$ into the gripper.
  - We need support (i.e., an action) for each other block $?b' \in \{A, B, C, D, E\}$ since that one could be beneath $?b$ – we need this since we need to state that $?b'$ one will be at top next.
  - Again, do it!
    - Choose *File*, then *Load*. Choose *liftedBlocksworldDomain.pddl*.
    - You can again check the syntax by looking at the other actions.
- Solution:

```
(:action unstack
   :parameters (?b1 ?b2 - block)
   :precondition (and (gripperFree)
                      (on ?b1 ?b2) (topMost ?b1))
   :effect (and (not (gripperFree)) (holding ?b1)
                (not (on ?b1 ?b2)) (not (topMost ?b1))
                (topMost ?b2)))
```

Lifted Model: Solving Blocksworld

Now, solve it!

- Load the file *liftedBlocksworldProblem-Instance1.pddl*.
- Use the *Solve* button and select the right files.



1. (unstack A B)
2. (place-on-table A)
3. (unstack B C)
4. (place-on-table B)
5. (unstack D E)
6. (stack D C)
7. (take-from-table A)
8. (stack A D)
9. (take-from-table E)
10. (stack E B)

Lifted Model: Size of the Lifted Model

How large does this (very compact) model become (now)? (*n* blocks)

- Propositional model:
  - $O(n^2)$ many actions and state variables.
- Lifted model:
  - Only $4 \in O(1)$ actions and $5 \in O(1)$ predicates.
  - $n \in O(n)$ blocks (as a simple list in the problem instance).

→ Every blocksworld problem can be modeled with just 4 actions and listing the *n* blocks. (Instead of specifying the state transition system, which grows exponentially.)

Summary and Outlook

Summary: What did we do today?

- We've learned the formal foundations of *Classical Planning* problems.
- We've learned how they can be modeled using the *Planning Domain Description Language (PDDL)*.
- We took a brief glance at the website planning.domains, which features (among others) a tool for:
  - Modeling planning problems in PDDL.
  - Running a solver on these models.

Outlook: What *didn't* we do today?

- There are (so!) many extensions of the classical model, e.g.,
  - Uncertainty! Partial observability and probabilistic effects.
  - Time (how long do actions take, and what happens when?).
  - Resource consumption and production.
  - Complex state trajectory constraints.
  - Hierarchies among the actions. (My *main* research area!)
- How so actually solve planning problems? (My research area!)
- Complexity analysis: How hard is it to solve a problem? (My favorite research area!)
- So much more, e.g.,
  - Proving unsolvability.
  - Plan explanations or explaining unsolvability.
  - Modeling support.