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

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Introduction

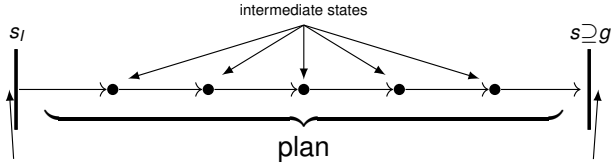
Planning in a Nutshell

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?

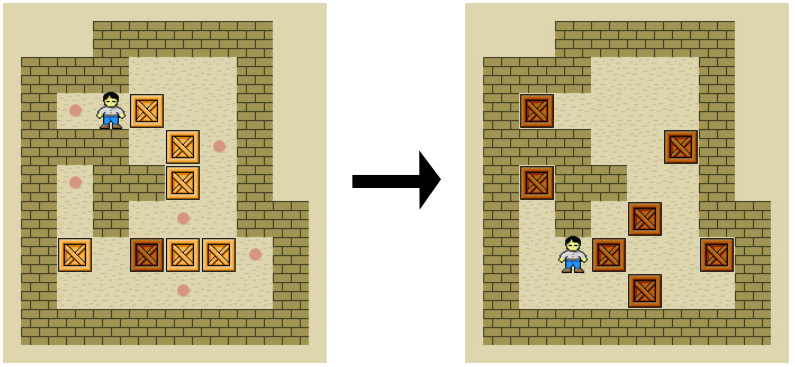
→ Find a *plan* that transforms s_I into g.



description of the initial world situation

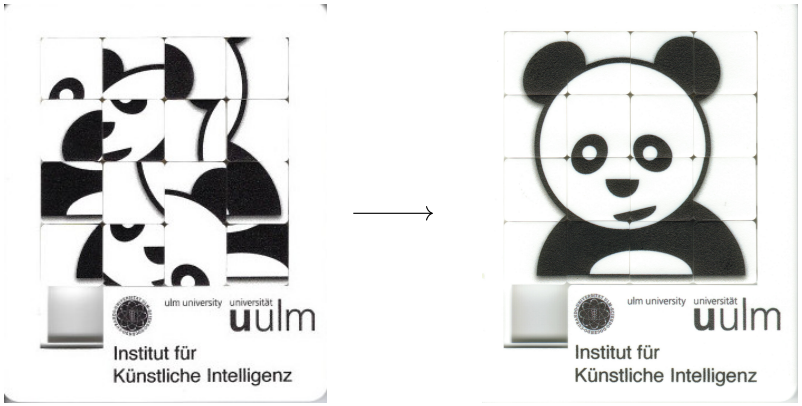
description of desired world properties

Planning Games like Sokoban



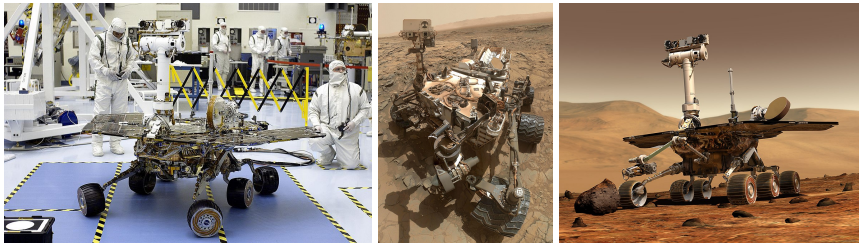
Title: A Sokoban puzzle and its solution
Source: `https://en.wikipedia.org/wiki/Sokoban`
Puzzle Author: Carlos Montiers Aguilera
Graphics Author: Borgar Þorsteinsson and Pascal Bercher.
The graphic has been modified multiple times (e.g., conversion from animated gif into this one.)

Planning Games like the Sliding Tile Puzzle



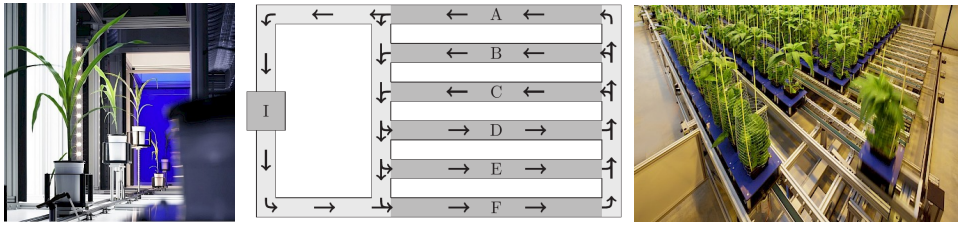
Initial State Goal State

Planning Robots like the Mars Rovers



- The mixed-initiative planning system *MAPGEN* was used to generate rovers' plans offline.
- These are then executed by the rovers (i.e., they do not run planners).

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!
- 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.
  - Check 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.

Notation

Math Recap: Sets versus Lists

We will heavily base upon *sets*.

- Sets are invariant against repetition.
  - E.g., $\{a, a, b, b, b, c\} = \{a, b, c\}$.
- Sets are invariant against re-ordering.
  - E.g., $\{a, b, a, b, c, b\} = \{a, a, b, b, b, c\}$.
  - Thus, we also get $\{a, b, a, b, c, b\} = \{a, a, b, b, b, c\}$
    $= \{a, b, c\} = \{a, c, b\}$
    $= \{b, a, c\} = \{b, c, a\}$
    $= \{c, a, b\} = \{c, b, a\}$
- Therefore, sets are fundamentally different from lists!
  - Lists are also called *sequences* or *tuples*.
  - E.g., the list (a, b, c) is different from both (a, c, b) and (a, a, b, c)

Math Recap: Set Notation

- The empty set $\{\}$ is usually *always* denoted by the symbol $\emptyset$.
- In contrast, the empty list (i.e., empty sequence) is denoted by ε.
- Let X be a finite set. Then, 2^X denotes its "power set" that contains all subsets.
  - E.g., if $X = \{a, b, c\}$, then
    $2^X = \{\{a, b, c\}, \{a, b\}, \{a, c\}, \{b, c\}, \{a\}, \{b\}, \{c\}, \emptyset\}$
- The "cardinality" of a set X is the number of its elements and denoted by $|X|$. Cardinality is *not* recursive!
  - E.g., if $X = \{a, b, c\}$, then $|X| = 3$.
  - Regarding non-recursiveness: if, e.g., $X = \{\{a, b\}, c\}$, then $|X| = 2$, because it has two elements, not three.
- Note that for all possible X it holds that $|2^X| = 2^{|X|}$.
  - E.g., if $X = \{a, b, c\}$, then $|2^X| = 2^{|X|} = 2^3 = 8$

Math Recap: Set Notation, cont'd

- We write $a \in X$ if a is contained in X, i.e., an *element* of X. We say $a \notin X$ if a is not contained in X. Again, this is *not* recursive!
  - E.g., if $X = \{\{a, b\}, c\}$, then only $\{a, b\} \in X$ and $c \in X$, but $a \notin X$ and $b \notin X$. Also $\{c\} \notin X$.
- We write $Y \subseteq X$ if Y is a (not necessarily strict) subset of X. We write $Y \not\subseteq X$ if this does not hold.
  - E.g., $\{a, b, c\} \subseteq \{a, b, c\}$ (in fact, $X \subseteq X$ for all sets X).
  - E.g., $\{a, c\} \subseteq \{a, b, c\}$.
  - E.g., if $X = \{\{a, b\}, c\}$, then $\{c\} \subseteq X$ and $\{\{a, b\}\} \subseteq X$, but $\{\{a, c\}\} \not\subseteq X$ and $\{a, b\} \not\subseteq X$.
- Let X, Y, Z be sets. Then $X \times Y \times Z$ is the cross product of these sets. It's the set of tuples with one element from each set.
  - Formally, $X \times Y \times Z = \{(x, y, z) \mid x \in X, y \in Y, z \in Z\}$
  - One normally uses standard math notation, e.g., $X^2 = X \times X$. We use X^n for exactly n times X, and X^* for *all* numbers in $\mathbb{N} \cup \{0\}$.

Math Recap: Set Operations

- We write $X \cup Y$ for *unifying two sets* X and Y, i.e., $X \cup Y$ contains all elements of both sets.
  - Formally: $X \cup Y = \{z \mid z \in X \text{ or } z \in Y\}$
- We write $X \cap Y$ is the *set intersection*, i.e., $X \cap Y$ contains all elements that are contained in both sets.
  - Formally: $X \cap Y = \{z \mid z \in X \text{ and } z \in Y\}$
- We write $X \setminus Y$ for *set subtraction*, i.e., $X \setminus Y$ contains all elements that are contained in X, but not ("minus the ones") in Y.
  - Formally: $X \setminus Y = \{z \in X \mid z \notin Y\}$

AI Planning Problems

Problem Definition: Assumptions made in Classical Planning

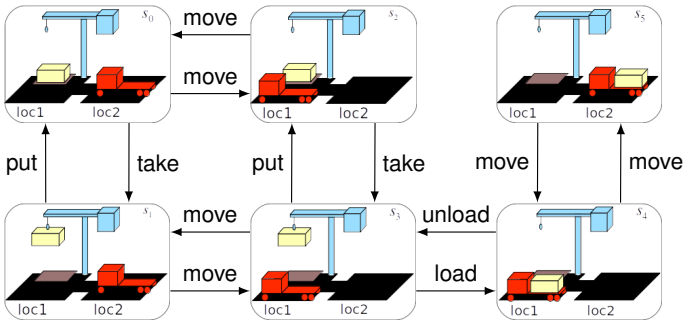
We focus on the "base case" of AI planning: *Classical Planning*

- *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

Author & License: Dana S. Nau (BY-NC-SA 2.0 generic)

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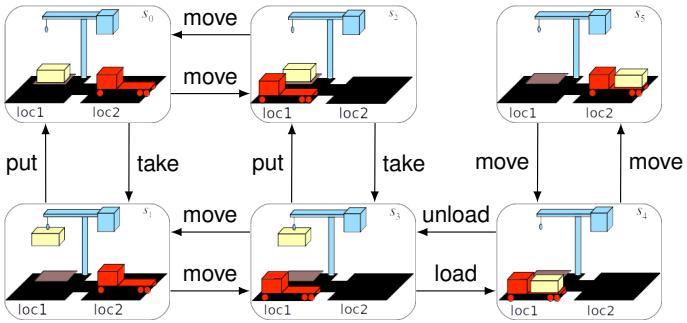


$V = \{$CrateAtLoc1, CrateInCrane, CrateInTruck, TruckAtLoc1, TruckAtLoc2$\}$

Problem Definition: Formalism

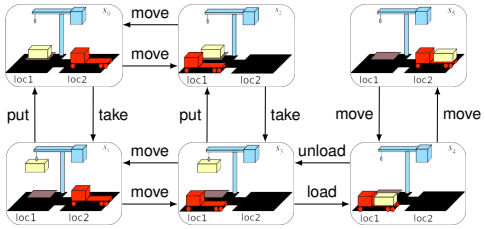
A classical planning problem $\mathcal{P} = \langle V, A, s_I, g \rangle$ consists of:

- V is a finite set of *state variables*.
  - *States* are sets consisting of state variables (also called *facts*).
  - We assume the *closed world assumption*, i.e., all variables not mentioned in a state s do not hold in that state (in contrast to: it's not known whether they hold or not).
    E.g., if $a \in s$ then a is true (does hold) in s, but if $a \notin s$ then a is false (does not hold) in s.
  - $S = 2^V$ 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 $c(a)$.



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

Problem Definition: Formalism

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

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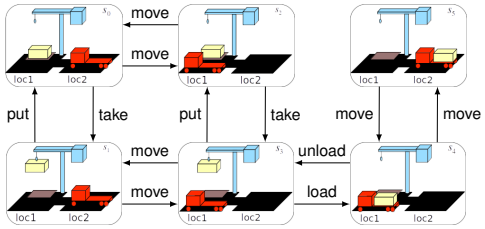

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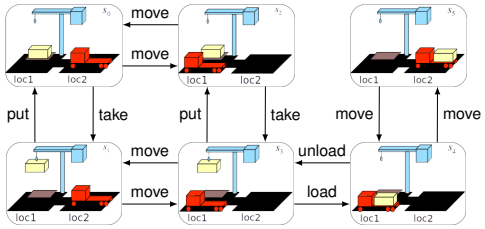
moveLeft		**moveRight**	
pre:	{TruckAtLoc2}	pre:	{TruckAtLoc1}
add:	{TruckAtLoc1}	add:	{TruckAtLoc2}
del:	{TruckAtLoc2}	del:	{TruckAtLoc1}

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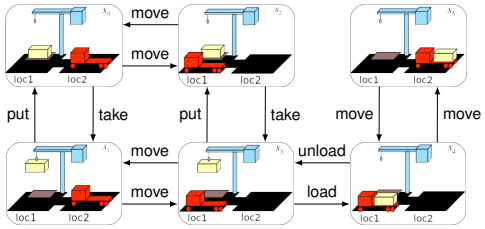
load		**unload**	
pre:	{CrateInCrane, TruckAtLoc1}	pre:	{CrateInTruck, TruckAtLoc1}
add:	{CrateInTruck}	add:	{CrateInCrane}
del:	{CrateInCrane}	del:	{CrateInTruck}

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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$s_I = \{\text{CrateAtLoc1}, \text{TruckAtLoc2}\} = s_0$
$g = \{\text{CrateInTruck}, \text{TruckAtLoc2}\}$, 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*.

$\rightarrow$ Example: The action...

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

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

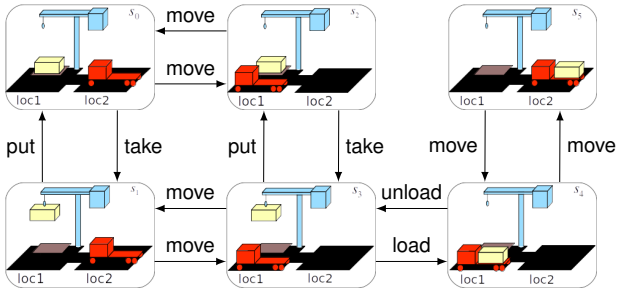
Problem Definition: Formalism, cont'd I

- 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 $\overline{a} = a_0, \ldots, a_{n-1}$ 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?

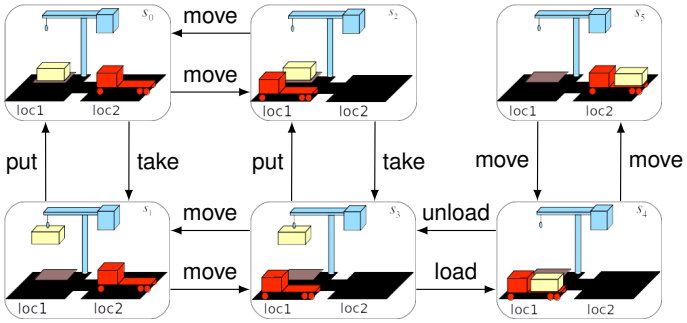
- State transition systems are the "underlying semantics" of classical planning problems.
- They *explicitly* show all states and how they can be traversed by actions.
- We use them to give an intuition on how hard solving planning problems can become (and how easy it is to model them)!

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)

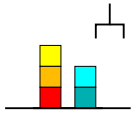
A state transition system is a 6-tuple (S, L, c, T, I, G), where

- 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?

$\to$ Classical planning problems 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.

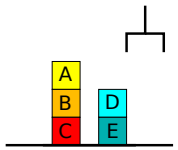
blocks	states	blocks	states
1	1	10	58,941,091
2	3	11	824,073,141
3	13	12	12,470,162,233
4	73	13	202,976,401,213
5	501	14	3,535,017,524,403
6	4,051	15	65,573,803,186,921
7	37,633	16	1,290,434,218,669,921
8	394,353	17	26,846,616,451,246,353
9	4,596,553	18	588,633,468,315,403,843

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.

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 my website.
    - 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))))
```

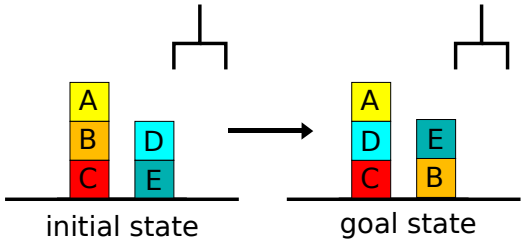
Propositional Model: Modeling the Unstack Actions

- 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*)

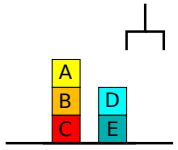
```
(define (problem blocksworld-prob1)
  (:domain blocksworld-ground)
  (:init (AisTopMost) (AonB) (BonC) (ConTable)
         (DisTopMost) (DonE) (EonTable))
  (:goal (and (AisTopMost) (AonD) (DonC) (ConTable)
              (EisTopMost) (EonB) (BonTable))))
```

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

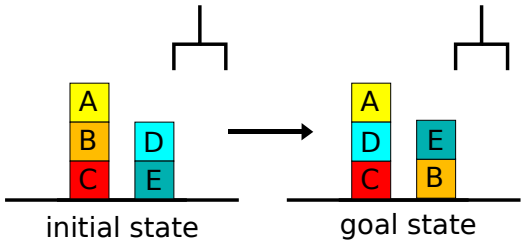
- Now we model removing one block from another:
  - Say we want to take block $?b$ into the gripper.
  - We need support (i.e., an action) for each other block $?b' \in \{A, B, C, D, E\}$ since that one could be beneath b – we need this since we need to state that $?b'$ one will be at top next.
  - Again,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

$\rightarrow$ 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 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.